Neutrons at COSY
A Workshop at
Kernforschungsanlage Jülich

February 22 - 23, 1988

Editors
Detlef Filges and Hartwig Freiesleben
Spezielle Berichte der Kernforschungsanlage Jülich – Nr. 443
Institut für Reaktorentwicklung and CANU Jül-Spez-443

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Neutrons at COSY

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INTRODUCTION

For many years neutrons were considered important both as a useful probe in nuclear physics research and as an initiator and catalyst for fission, fusion and other applications. As a result knowledge about neutrons, especially below 20 MeV, received organized world-wide attention. Research with neutrons at medium energies, say 50 MeV to several GeV, has not consistently received attention and no systematic evaluations exist. But there is a large and considerable interest today because medium energy neutrons are very important in basic science and technology.

Therefore, the aim of this workshop was to provide an overview of the present status and the research which should be carried out in this field in future and which kind of experiments should be performed at the COSY facility:

- state-of-the-art about medium energy neutron experiments and existing facilities
- planned experiments
- needs for experiments doing research with neutrons at COSY (detectors, accelerator requirements, time structure etc.)
- what will be a first experiment to measure neutrons at COSY.

The interest in this workshop is documented by a large number of participants. In this report copies of the viewgraphs of the talks are provided. Further ideas and comments to the topic are welcome.

We would like to thank the Vorstand of the KFA for financial support and Mrs. U. Banken for the organization of the workshop.
SUMMARY OF THE WORKSHOP AND THE DISCUSSION

From the papers presented at the workshop emerge the request for experimental facilities in the following research areas:

1. Neutron time-of-flight measurements at an external beam line

Such experiments require an optimum time structure which can — with present state-of-the-art — be only achieved with an \( h = 60 \) cavity at the expense of intensity. The frequency of the external beam pulses should be lower than 5 MHz to avoid ambiguities in n-TOF measurements. In order to provide enough open space for n-TOF measurements the primary beam should be extracted after passing the electron-cooling system which, of course, is not needed for these experiments. The ingenuity of the experimentators is called for developing a tagged neutron beam and advanced neutron detectors.

The "neutron community" requests the COSY-design group to foresee a slow beam extraction in the indicated area. to study further possibilities for improving the COSY time structure (acceleration with \( h > 60 \)) and to develop methods to decrease the frequency of external pulses to the desired value.

2. Neutrons from an internal target

This topic deserves further considerations. An internal (e.g. deuterium, lithium etc.) target will produce a neutron beam. If this target is installed downstream close to a C-magnet, the yoke of which is directed towards the center of the ring, a neutron beam at \( 0^\circ \) is available for some applications. Under the same conditions, experiments, e.g. few body studies, which require neutron detection in the exit channel become feasible at \( 0^\circ \) or finite angles with as little material as possible between target and detector. By this arrangement precision neutron experiments become feasible which utilize the cooled beam.

The "neutron community" therefore requests the COSY-design group to foresee enough space for installation of an internal target at which neutron measurements are possible. The ideal position is just downstream of the electron-cooling device.
3. External neutron beam for neutron induced reaction studies

An external neutron beam would render possible a broad range of experimental investigations. However, COSY is not the machine to provide the necessary primary beam currents for producing a secondary neutron beam - at least not with its present injector. Therefore, the "neutron community" postpones further discussions in this context, they might be taken up again if high beam currents become available.
Participation List  Workshop "Neutrons at COSY"

W. Amian, KFA-IRE
W. Bernnat, Uni Stuttgart, IKE
P. Cloth, KFA-IRE
P. Dragovitsch, KFA-IRE
V. Drüke, KFA-IRE
J. Ernst, Uni Bonn
D. Filges, KFA-IRE
H. Freiesleben, Uni Bochum
R. Hecker, KFA-IRE
U. Herpers, Uni Köln
F. Hinterberger, Uni Bonn
K. Kilian, KFA-IKP
J. Krug, Uni Bochum
H. Machner, KFA-IKP
S. Martin, KFA-ASI/COSY
M. Mattes, Uni Stuttgart
T. Mayer-Kuckuk, Uni Bonn
R. Michel, Uni Hannover
H.P. Morsch, KFA-IKP
Hj. Müller, TU Graz
H. Nann, KFA-IKP
R.D. Neef, KFA-IRE
W. Oelert, KFA-IKP
N. Paul, KFA-IRE
S.M. Qaim, KFA-ICH1
E. Rössle, Uni Freiburg
H. Schaal, KFA-IRE
H. Schieck, Uni Köln
U. Schmidt-Rohr, MPI Heidelberg
O.W.B. Schult, KFA-IKP
W. Scobel, Uni Hamburg
H. Seyfarth, KFA-IKP
J. Speth, KFA-IKP
Y. Terrien, Saclay
Program

Monday, February 22, 1988

9:15  Coffee
9:30  S. Martin, KFA-ASI  COSY - status report
     (time-structure etc.)
10:30 H. Nann, IUCF/KFA-IKP  The IUCF neutron time-of-flight
     facility
11:30 W. Amian, KFA-IRE  The LANL neutron time-of-flight
     facility
12:30  Lunch
14:00 Y. Terrien, Saclay  Neutron beams at SATURNE, techniques
     and experiments
15:00 D. Filges, KFA-IRE  On the necessity to measure high energy
     neutrons for scientific applications
15:45  Coffee
16:00 P. Dragovitsch, KFA-IRE  Calculational models for the determi-
     nation of double differential cross
     sections of (p,xn) and (n,xn) reactions
16:45 H. Freiesleben, Uni Bochum  A detector for high-energy neutrons
17:30 V. Drüke, KFA-IRE  Remarks on possible time (energy)
     errors in previous time-of-flight
     measurements with high-energy neutrons
18:30  Social event

Tuesday, February 23, 1988

9:15  R. Michel, Uni Hannover  Importance of high-energy neutrons
     produced by cosmic radiation in extraterrestrial matter
10:00 W. Scobel, Uni Hamburg  TOF spectroscopy of neutrons from (p,n)
     reactions with $E_p<160$ MeV
10:45  Coffee
11:00 H. Machner, KFA-IKP  Energy spectra of secondary particles
     produced by high-energy protons
11:45 S.M. Qaim, KFA-ICH1  Complex-particle emission in neutron
     induced nuclear reactions
12:30  Lunch
14:00 J. Krug, Uni Bochum  Few-nucleon reactions with neutrons
14:45  Discussion of next steps (all)
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<td>Complex-particle emission in neutron induced nuclear reactions</td>
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<td>Few-nucleon reactions with neutrons</td>
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</table>
1.

S. Martin, U. Pfister

Kernforschungsanlage Jülich

ASI

COSY - status report and beam properties
with special emphasis of the time structure
h = 1 cavity

- Time structure seems to be possible for internal and external beam.

- Extraction rate:
  - Numbers of particles in the ring per 0.01--10 sec.
\( h = 60 \) acceleration

**Numbers of particles vs. phase**

<table>
<thead>
<tr>
<th>( N )</th>
<th>( eV )</th>
<th>( \theta_s )</th>
<th>( \Delta \theta )</th>
<th>( A L )</th>
<th>( \Delta t )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 4 \times 10^7 )</td>
<td>200</td>
<td>14°</td>
<td>251°</td>
<td>2.13 m</td>
<td>7.4 ( \text{ns} )</td>
</tr>
<tr>
<td>( 10^7 )</td>
<td>200</td>
<td>46°</td>
<td>135°</td>
<td>1.15 m</td>
<td>4.0 ( \text{ns} )</td>
</tr>
<tr>
<td>( 10^8 )</td>
<td>200</td>
<td>73°</td>
<td>51°</td>
<td>0.43 m</td>
<td>1.5 ( \text{ns} )</td>
</tr>
<tr>
<td>( 10^9 )</td>
<td>200</td>
<td>83°</td>
<td>21°</td>
<td>0.18 m</td>
<td>0.62 ( \text{ns} )</td>
</tr>
<tr>
<td>( 10^8 )</td>
<td>200</td>
<td>87°</td>
<td>9°</td>
<td>0.08 m</td>
<td>0.2 ( \text{ns} )</td>
</tr>
</tbody>
</table>

\( \Delta t = 3.06 \text{ m} \), \( T = 3.76 \text{ ns} \)

- Options for maintaining of time structure

- with \( h = 60 \) cavity and \( N = 10^{10} \) particles, \( \Delta t = 1.5 \text{ ns} \) to bump the external beam use

- bumper data: kick = 1 mrad

- \( B \cdot L = 0.011 \text{ Tm} \)
- \( N \cdot I = 100 \text{ A} \)
- rise time = 25 - 100 \( \text{sec} \)
- \( \delta \phi = 11 \text{ Tm} \)
- \( \delta \rho = 12 \text{ mm} \)

Switch 100A with 1 MHz at 1/50 of \( N \) the particles in ring till the target, the rest is lost.

Rep. rate \( \sim 1 \text{ \( \mu \text{sec} \)} \)
The IUCF neutron time-of-flight facility
The IUCE Neutron Time-of-Flight Facility

Energy Resolution

\[ \frac{\Delta T}{T} = \gamma (\gamma + 1) \left[ \left( \frac{\Delta x}{x} \right)^2 + \left( \frac{\Delta t}{t} \right)^2 \right]^{\frac{1}{2}} \]

with \( \gamma = (1 - \beta^2)^{-\frac{1}{2}} \) = Lorentz contraction factor
\( T = \) kinetic energy of the neutron
\( \Delta x = \) uncertainly in the neutron flight path
\( \Delta t = \) uncertainly in the neutron time-of-flight

\[ \frac{\Delta T}{T} = \gamma (\gamma + 1) \left( \frac{\Delta x}{x} \right)^2 \left( \frac{\Delta t}{t} \right)^2 \]

= \gamma (\gamma + 1) (\Delta t)^* \]

with \( (\Delta t)^* = \) overall time dispersion
\( = \) observed time width of a peak in a time-of-flight spectrum
Sources contributing to overall time resolution

- Intrinsic time resolution of the neutron detector
- Beam burst width
- Time spread in the neutrons arising from the finite target thickness
- Time spread in the neutrons from the finite thickness of the detectors
- Time spread in the neutrons from the energy spread of the beam
requirements for high-precision neutron spectroscopy:

- Long flight paths of at least 100 m are desirable
- Good time resolution: $\Delta T < 1 \text{ ns}$

technical problems to be solved:

- Long flight paths cannot reasonably be swung around the target; another method of changing the angle of observation must be used.
- At large distances the solid angle subtended by detectors is very small. $\Rightarrow$ Detectors must be large.
- The accelerator time reference must be stabilised as well as possible.
The IUCF cyclotron floor plan

p-beam properties

energy

$\Delta E/E$

$\frac{I_p}{p}$

20 - 200 MeV

$1 \times 10^{-3}$ FWHM

20 - 500 nA

10 - 150 nA \{ pulse selected \}

time structure:

microscopic

0.5 ns

macroscopic

1 RF pulse in 2, 3, 4, 5, 6 or 7 and in 35 to 300

RF frequency

$\sim 30$ MHz
Scale of reference for detector size

(A) typical solid state detector:
  area: $A = 50 \text{ mm}^2$
  distance from target: $r = 12 \text{ cm}$
  $\Rightarrow \Delta \Omega = 1 \text{ msr}$

(B) neutron detector
  solid angle: $\Delta \Omega = 1 \text{ msr}$
  distance from target: $r = 100 \text{ m}$
  $\Rightarrow A = 10 \text{ m}^2$

Basic configuration of a large-volume neutron detector

thickness: $10.2 \text{ cm}$ in direction of incident neutrons

```
\begin{align*}
\text{TOP} & \\
\text{L} & \\
\text{BOTTOM} & \\
\text{PMT} & \\
\text{PLastic scintillator} & \text{NE-102} & \text{LIGHT PIPE}
\end{align*}
```

PMT = photomultiplier (Amperex XP 2041)

use of mean-timing method to derive time signal: average of photon transit time from scintillation event to the ends of the long scintillator is independent of the position of the event.

$$\begin{align*}
t_R &= \frac{L}{c} + \left( \frac{1}{2} - x \right) \frac{c}{c} + (c - E_x) + \delta t_R \\
L &= \frac{L}{c} + \left( \frac{1}{2} + x \right) \frac{c}{c} + (c + E_x) + \delta t_L
\end{align*}$$

$\uparrow$ $\uparrow$ $\uparrow$

TOF light transit discriminator delay

The optimum light pipe length is slightly larger than one-half of the scintillator length because of the finite 12.5 cm diameter aperture of the photocathodes.
Large volume neutron detectors

0.154 m x 1.016 m x 0.101 m
0.508 m x 1.016 m x 0.101 m

<table>
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<tr>
<th>Scintillator</th>
<th>Light pipe length</th>
<th>Intrinsic time dispersion</th>
<th>Position resolution</th>
</tr>
</thead>
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<tr>
<td>0.254 m x 1.016 m</td>
<td>0.305 m</td>
<td>235 ± 5 ps</td>
<td>41 ± 3 mm</td>
</tr>
<tr>
<td>0.508 m x 1.016 m</td>
<td>0.610 m</td>
<td>300 ± 7 ps</td>
<td>46 ± 4 mm</td>
</tr>
</tbody>
</table>

Scintillator thickness: 0.102 m
Measuring the time-of-flight

start signal to TAC: neutron detector
stop signal for TAC: from RF signal of the cyclotron, corrected for phase drifts

phase drift = changes in time of arrival of beam burst at the target relative to a fixed phase on the RF signal from the cyclotron, caused by instabilities of the magnetic fields

Block diagram of phase drift compensator

- scattered protons are detected with a fast scintillator counter
- proton signal triggers a discriminator which generates a pulse of a width of about \( \frac{1}{2} \) the RF period
- this pulse opens a diode bridge current gate
- if opening time is centered around the crossover point of the RF sine wave, the net charge passing through the gate is zero
- if there is a phase drift, the net charge is no longer zero
- output of the gate is integrated in time, and integrated output is used as an error signal into a phase shifter
Beam burst width and phase drift

Flight path: $x = 24$ m
with phase compensation

time dispersion due to:
  - effective detector thickness: $(0.59 \pm 0.04)$ ns
  - target thickness $(38 \text{ mg/cm}^2)$: $0.17$ ns
  - beam energy spread: $\sim 0$
  - time spread of beam: $(0.45 \pm 0.06)$ ns

Overall time dispersion and energy resolution

Spectrum measured with two $0.154 \text{ m} \times 1.016 \text{ m} \times 0.102 \text{ m}$ detectors
Flight path: $x = 90.9$ m
phase drift compensated

Overall time resolution: $700 \text{ ps}$
Overall energy resolution: $320 \text{ keV}$

Contribution from target thickness $(40 \text{ mg/cm}^2)$: $280 \text{ keV}$
Energy spread of proton beam: $135 \text{ keV}$
Neutron detector efficiency:

(A) direct measurement method

\[ 7\text{Li}(p,n)^7\text{Be} \]

e.g. \( d + d \rightarrow ^3\text{He} + n \)
deetect \(^3\text{He}\) and \( n \) in coincidence.

(B) secondary measurement method

\[ 7\text{Li}(p,n)^7\text{Be} \]
e.g. \( d + d \rightarrow ^3\text{He} + n \)
measure first differential cross section for \(^3\text{He}\) production,
then measure separately the number of neutrons at appropriate
conjugate angle, and use differential cross section for \(^3\text{He}\) production to calculate neutron efficiency.

(C) indirect method

2.9. use neutron yields of the \(^7\text{Li}(p,n)^7\text{Be}\) (g.s. \( T = 0.4\) MeV)
reaction measured under the same experimental
conditions.

2.9. use isospin Clebsch-Gordan ratio of \((p,n)\) and \((p,p')\)
transitions from self-conjugate \((T=0)\) target nuclei
to \( T=1 \) analog states

\[ \frac{\sigma(p,n)}{\sigma(p,p')} = 2 \]

(D) computational method using Monte-Carlo techniques

\[ ^7\text{Li}(p,n)^7\text{Be} \text{ TOTAL REACTION CROSS SECTION} \]

\[ \ln \sigma = -1.13 \ln E_p + 7.05 \]
actual measurement of neutron detector efficiency

use neutron yields of the $^7\text{Li}(p,n)^7\text{Be}$ (q.s. + 0.93 MeV) reaction at several bombarding energies

use $(p,n)$ and $(p,p')$ analog transition cross sections

interpolate for all other neutron energies using Monte-Carlo technique
The IUCF stripper loop

used to vary pulse structure of the beams over wide range while
simultaneously increasing beam brightness

H⁻ beam is injected using both inflection magnets #1 and #2 and
stripped to p of the same energy

Neutron polarimeters

utilize the analyzing power of elastic n-p scattering,
\[ \text{i.e. } 1^1H(n,\mu)1^1H \]

analyzing power: \[ A_y = \frac{L-R}{L+R} \]

figure of merit: \[ A_y^2 \sigma \]

Stored beam is extracted by a pulsed electrostatic deflector (#1)
whose output is triggered by a variable width pulser at an adjustable
sub-harmonic of the cyclotron RF frequency.

extracted beam is directed back into beam line by a DC electrostatic
deflector (#2) and a small steering and focusing magnet.
then beam is bunched with an f/2 subharmonic buncher before
entering the injector cyclotron.
The Kent State University polarimeter

n-p at 130 MeV

\( \sigma(\theta) \)

\( A_y(\theta) \)

\( A_y^2(\theta) \)

\( \theta_{\text{Lab}} \)
improvement of performance

replace the NE-102 plastic scintillator scatterers with mineral-oil scintillator BC-517L from Bicron, Inc.

BC-517L has k/C ratio of 2.01 and density 0.86 g/cm³
If density is 38% higher than in NE-102
C density is 25% less than in NE-102

⇒ improvement in figure of merit: 40-50%

efficiency of polarimeter: ~ 0.17%

measured parameters:
(1) time-of-flight from the target to one of the scatterers
(2) time-of-flight between the scatterer and a side detector
(3) pulse-height in the scatterer
(4) pulse-height in the side detector
(5) position of the interaction in the scatterer
(6) position of the interaction in the side detector
100 MeV $^{14}_C(p,n)^{14}_N$ at $0^\circ$

Counts/1000

Neutron Energy (MeV)

Counts/1000

Neutron Energy (MeV)

The IUCF - LANL - ORNL - OSU - OU neutron polarimeter

charged particle veto
3.

W. Amian

Kernforschungsanlage Jülich

IRE

The LANL neutron time-of-flight facility
The Los Alamos
Neutron Time-of-Flight Facility

W. Amian, KFA/IRE
H. Atwater, Los Alamos
D. Filges, KFA/IRE
C. Goulding, Los Alamos
D. Holtkamp, Los Alamos
P. Lisowski, Los Alamos
M. Meier, Los Alamos
G. Morgan, Los Alamos
C. Moss, Los Alamos
N. Paul, KFA/IRE
H. Robinson, Los Alamos
G. Russell, Los Alamos
J. Ullman, Los Alamos
E. Whitaker, Los Alamos
- Neutron Time of Flight (NTOF)
  (p,n) studies
  600 m flight path
  neutron polarimeter
  neutron spin precession system in FP
  beam swinger
  1 – 2 MeV resolution at 800 MeV

- Medium Resolution Spectrometer (MRS)
  (p,p') and (n,p) studies
  QD(−Q) spectrometer
  Li(p,n) neutron source
  1 MeV resolution at 800 MeV

- high intensity polarized H⁻ ion source
  optically pumped
  10 nA to 1 μA average beam current

• beam bumber
The WNR/LANSCE Facility

- **LANSCE (Target 1)**
  high-current area fed by the PSR for neutron experiments in the thermal and epithermal energy range (condensed matter neutron scattering)
  30 μA (up to 200 μA)

- **Target 2**
  low-current, low-return room for fast neutron TOF experiments and general external proton beam capability
  100 nA

- **Target 4**
  high-intensity fast-neutron white source for nuclear physics applications
  4 μA
NEUTRON FLUX 15 DEG

Target Material: 7.6 cm long, Ti-7178Al
3.0 cm diam
Experimental Program at Target 4

- Radiative capture: \((n,\gamma_s)\)
- Gamma production: \((n,x\gamma)\)
- Charged particle production: \((n,xp), (n,xd), ...\)
- Charge exchange reaction: \((n,p)\)
- High energy fission cross sections: \((n,f)\)
LANSCHE STATUS  27-NOV-87 12:40

AVERAGE CURRENT TO TARGET 26.9 nA
REP RATE 15 Hz  PULSE WIDTH 250 ns

SCHEDULED CURRENT 30 nA  MICROAMPERE HOURS SINCE MIDNIGHT 0.00
EXPERIMENTAL HALL STATUS CLOSED  NEXT SCHEDULED ENTRY 15:00

WNR STATUS 27-NOV-87 12:41

AVERAGE CURRENT TO TARGET 323 nA
REPRATE 25Hz  MICROPULSE SPACING 3.2 us
BEAM GATE LENGTH 820 us  BEAM ON

TARGET IN USE  LINE D BEAM PLUG STATUS 3 OUT 4 OUT 5 OUT 6 OUT
ERI STATUS CLOSED  NEXT SCHEDULED ENTRY 15:00
Beam Intensities at WNR

<table>
<thead>
<tr>
<th></th>
<th>1984</th>
<th>1987</th>
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<tbody>
<tr>
<td>Macro rate</td>
<td>12</td>
<td>40</td>
</tr>
<tr>
<td>Macro length</td>
<td>700</td>
<td>750</td>
</tr>
<tr>
<td>Micro separation</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Pulse rate</td>
<td>2,000</td>
<td>30,000</td>
</tr>
<tr>
<td>Average current</td>
<td>10</td>
<td>1,500</td>
</tr>
<tr>
<td>Protons per micro puls</td>
<td>$2 \times 10^7$</td>
<td>$3 \times 10^8$</td>
</tr>
</tbody>
</table>

*Non-relativistic:*

$$
\frac{dT_n}{T_n} = 2 \sqrt{\frac{ds^2}{z^2} + \frac{dt^2}{t^2}}
$$

i.e. for $ds=0$ the energy resolution is two times the time resolution

*Relativistic:*

$$
\frac{dT_n}{T_n} = \frac{1}{s} \left( s^2 + \frac{c^2}{c^2 - 1} \right) \sqrt{\frac{ds^2}{s^2} + \frac{dt^2}{t^2}}
$$

$$
\tau = T_n / 939.5731 \quad \text{1, } T_n \text{ in MeV}
$$

$c = 2.997 \text{ cm/sec} = \text{speed of light}$

for high-relativistic particles the resolution is quadratic in energy
WNR Micropulse Time Width Measurement

800 MeV Proton Beam

To Beam Dump

Quartz Cerenkov Radiator

Mirror

Streak Camera

Measurement Parameters
22 ps/channel resolution
100 pulse average

Result:
132 ps FWHM

Target-2 Data
Drift distance $l$ [m]

Time dispersion for fixed $\Delta p/p = 5 \times 10^{-4}$ [ns]

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>HRS</th>
<th>WNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>256</td>
<td>652</td>
<td>799</td>
</tr>
<tr>
<td>500</td>
<td>408</td>
<td>555</td>
</tr>
<tr>
<td>800</td>
<td>108</td>
<td>255</td>
</tr>
</tbody>
</table>

Los Alamos
**WNR HIGH RESOLUTION (pA) FACILITY**

- $E_p = 600$ MeV
- $\Delta E_p = 25$ MeV  
  ($\Delta t = 500$ ps, $l = 213$ m)
- $E_\gamma = 0$ to 770 MeV
- $\theta = 0$ to $10^\circ$

**PHYSICS ISSUES**

- EFFECTIVE INTERACTION STRENGTH
- SEARCH FOR MISSING G-T STRENGTH
- GIANT RESONANCE STUDIES
- $\Delta$ PRODUCTION SYSTEMATICS

Los Alamos
DEAD TIME EFFECTS AT HIGH INSTANTANEOUS COUNT RATE

- two different types of counting losses encountered
  - random losses due to long processing times of the electronics; spectrum non-distorting
  - loss of all subsequent signals after the arrival of the first event, i.e., at high event rates slow particles would never have a chance to be recorded; spectrum distorting

- corrections
  - random losses: easy, relate only to beam bursts for which the system was ready to record on arrival of a particle
  - loss of subsequent events: dependent on pulse height (time of arrival), only the first (fastest) event in channel i is recorded, any subsequent events at j > i are lost

- simplified correction factor for loss of subsequent events:

\[ M_i = N_t \cdot \ln \left( 1 - \frac{N_i}{N_t - \sum_{j=1}^{i-1} N_j} \right) \]

\[ M_i = \text{corrected number of counts in channel } i \]
\[ N_i = \text{number of counts in channel } i \]
\[ N_t = \text{total number of beam bursts corrected for system busy time} \]

(assuming constant beam current)
PilotU Detector 12x12x2.54 cm
Neutrons of 30.60 to 35.07 MeV

Light Response [MeVee]

PilotU Detector 12x12x2.54 cm
Neutrons of 4.30 to 5.16 MeV

Light Response [MeVee]
ATTENUATION OF THE NEUTRON FLUX

- materials in the flight paths:
  
<table>
<thead>
<tr>
<th>Material</th>
<th>7.5°</th>
<th>30°</th>
</tr>
</thead>
<tbody>
<tr>
<td>air</td>
<td>0.060</td>
<td>0.098</td>
</tr>
<tr>
<td>Al windows</td>
<td>0.019</td>
<td>0.019</td>
</tr>
<tr>
<td>veto detector</td>
<td>0.015</td>
<td>0.015</td>
</tr>
<tr>
<td>uranium filters</td>
<td>0.401</td>
<td>0.233</td>
</tr>
</tbody>
</table>

15m of the flight paths evacuated

- transmission of uranium and polyethylene filters measured from 1 to 800 MeV and cross sections generated

- all other corrections done using ENDF cross-section data

- conservatively 10% uncertainty assumed below 20 MeV and 20% above
Differential Cross Section
[barns / sr (MeV/c)]

Momentum [MeV/c]

\[
p + N \
\downarrow \quad \text{quasi-elastic charge exchange}
\]

\[
p + n \rightarrow p + n
\]

\[
p + n \rightarrow p + n + \pi^0
\]

\[
p + n \rightarrow n + n + \pi^+
\]

\[
p + p \rightarrow p + n + \pi^+
\]

\[
\text{trianuclear cascade}
\]

\[
N^*
\]

\[
evaporation
\]
4.

Y. Terrien

Centre D'Etudes Nucleaires Saclay

Neutron beams at SATURNE:
techniques and experiments
SATURNE National Laboratory

Beams

- $\vec{p}$
  - $100 \rightarrow 2,900$ MeV
  - $10^{10}$ / burst
- $d$
  - $100 \rightarrow 2,300$ MeV
  - $2 \times 10^{10}$
- $\vec{n}$
  - $\rightarrow 1,150$ MeV
  - $10^6$ / target

H. I.
- $\rightarrow 1$ GeV/A
- $\leq 20$ Ne

Polarization:

- $\vec{p}$
  - $\sim 90\%$ ($\leq 1$ GeV)
  - $\sim 75\%$ ($\sim 2$ GeV)

- $d$
  - $\sim 66\%$ Vector polarization
  - $\sim 85\%$ Tensor polarization
  - Very stable; no resonances

When MIMAS (May 1987)

Intensity $\times 10^{-20}$ at least

Heavier H. I.
Figure 3 - Plan de Saturne avec Mimas
\( n \) beam at Saturne

DPhN Saclay E83852

Intensity of the neutron flux:
\[ I_n^{\text{max}} \approx 1.5 \times 10^{-5} \text{ neutrons/cm}^2/\text{burst} \]
\[ \approx 5 \times 10^6 \text{ m}/\text{cm}^2/\text{burst} \]
(at 800 MeV; varies \( \approx (P_n)^2 \))

this is with MIMAS

\[ E_n = \frac{E_d}{2} \approx 1.15 \text{ GeV} \]

\( E_d \approx 25 \text{ to } 50 \text{ MeV} \)

from \( E_n \approx 400 \text{ to } 1150 \text{ MeV} \)

\[ \Delta E_n \approx \pm 0.8 \times 10^{-3} \text{ sr} \]

Polarisation
\[ P_n \approx P_n^\text{Be} \approx 0.60 \]
\( (\approx 0.58 \text{ pract.}) \)
NEUTRON-PROTON
SMALL TRANSFER
ELASTIC SCATTERING
$T_n = 400-1100$ MeV

L.N.P.I.-Gatchina
A.V. Dobrovolsky
A.V. Khanzadeev
G. Korolev
G.E. Petrov
E.M. Spiridonko
A.A. Vorobyov

J.C. Lugol
J. Saudinos
B. Silverman
Y. Terrien
F. Wellers

Physical motivations

Knowledge of NN interaction

- Phase shift analyses (P.S.A.)
- Input for microscopic calculations of nuclear reactions

$p-p\ T=1$ well known
$n-p\ T=0,1$ very few experiments
CATHODE
-15 kV

\( V_{A1}, V_{A2}, V_{C}, V_{D} \rightarrow T_R \)
\( t_c - t_B(t_A) \rightarrow \theta_R \)
\( t_B(t_A) - t_{\text{cath}} \rightarrow Z_R \)

Gas: \( H_2, \text{CH}_4, \text{He} \)

\( V_{\text{cathode}} \) vs. time

\( Z_R/W \)

\( t_{\text{cath}} \)

\( V_{\text{anode}} \sim T_R \)

\( Z \sim X_R \) (recoil track projection on Z-axis \( \Rightarrow \theta_R \))

\( \Delta \theta = 0.3 \text{ rad} \)
Counting rate (IUAR)

Beam: a few $10^5$ 1/m²
Calculation: $10^3$/hour
Computer: $10^2$/hour
Elastic event: 5-10 hours

A burst 1 second 600 km
8.0 seconds 700 km
4.0 seconds 40 km

(with gas = CH₄
at 15 atm.)

A nodes correlations

Gas CH₄
**np elastic (Saturne)**

- np (this exp.) INAR
- pp (ref. 9) Qachina

- Relative monitoring accuracy $< 2\%$
- Absolute calibration $3 \rightarrow 6\%$

(Comments: comparison of $^{4}\text{He}$, well known, with $^{4}\text{He}$ measured using this monitor.)

**Monitor**

- Very clean spectra
- $C\,(n,p)$ dominating
Absolute normalization of neutron beam

\[ \frac{d\sigma}{dt} (n^{4}{\text{He}}) \frac{?}{?} \frac{d\sigma}{dt} (p^{4}{\text{He}}) \]

\[ \downarrow \]

relative meas.
with Ikar and neutron beam

\[ \text{absolute meas. already exist} \]

If \( ? = \text{YES} \), \( \implies \text{monitor calibration} \)

\[ f_{^{6}{\text{He}}} - f_{^{4}{\text{He}}} \sim (f_{pp} - f_{pn}) \left( S_{\text{He}} - S_{\text{He}} \right) \]

\[ \text{small} \quad = 0 \]

if \( R_{p} = R_{n} \)

in \( ^{4}\text{He} \)

\[ ? = \text{YES} \pm 1.2\% \]

(Simple full-order Glauber model estimation - Jour. de Phys. 46 (1985) 1873)
THE NUCLEON-NUCLEON PROGRAM

The aim: To reconstruct the NN scattering matrix in the SATURNE energy range 0.5-3 GeV.

The means:
- Measure complete sets of spin dependent experiments in pp elastic and np elastic scattering.
- Using:
  - Polarized beams (p\(^+\), n\(^-\)), 3 L directions.
  - Polarized target.
  - Neut. polarimeter.
  - Measure spin-dependent total cross sections.

Proton polarized target (PPT)
- Bunsen, \(\frac{1}{2}\) unit (cm\(^3\)), or cubic 70 cm\(^3\)
- Polarization in a 25 kgauss solenoid.
- \((\text{He}_3-\text{He}_4)\) dilution cryostat \(\rightarrow \) "frozen spin" \(\rightarrow\) 20-30 mK.
- Holding field: 3 kgauss.
- Relaxation time 2 in 60 days.
- Polarization in 90\% (NMR).
- Max. p rate on the target: \(2.10^8/s\).

\[ N^3 = \left( \right) \]

And \( N^3 = \left( \right) \)

5 complex amplitudes \(a, b, c, d, e\), functions \((\Theta, \phi)\):
\[
\begin{align*}
    c &= \frac{a}{|b|} \\
    m &= \frac{a}{|b|} \\
    n &= \frac{a}{|b|} \\
\end{align*}
\]
\[ \Delta \sigma_L^{(\text{sat})} - \Delta \sigma_L^{(\text{arg})} = \frac{2\pi}{k} \text{Im} \left[ \sigma^{(0)}(\theta) + 2(\theta) \right] \]

\[ \Delta \phi^{(\text{sat})} - \Delta \phi^{(\text{arg})} = \frac{2\pi}{k} \text{Im} \left[ \sigma^{(0)}(\theta) - 2(\theta) \right] \]
### Table: Residual Ring

<table>
<thead>
<tr>
<th>Residual Ring</th>
<th>Residual Ring</th>
<th>Residual Ring</th>
<th>Residual Ring</th>
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<th>Residual Ring</th>
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</thead>
<tbody>
<tr>
<td>1 Ind</td>
<td>2 Ind</td>
<td>3 Ind</td>
<td>4 Ind</td>
<td>5 Ind</td>
<td>6 Ind</td>
</tr>
<tr>
<td>1 Ind</td>
<td>2 Ind</td>
<td>3 Ind</td>
<td>4 Ind</td>
<td>5 Ind</td>
<td>6 Ind</td>
</tr>
<tr>
<td>ゴスク</td>
<td>ノルスク</td>
<td>デスク</td>
<td>2 Ind</td>
<td>3 Ind</td>
<td>4 Ind</td>
</tr>
</tbody>
</table>

### Diagram: N - K (Beam C (a))

- N - K beam
- Free N beam

### Text:

3 pre-triggers:

\[ PP = TPD.TD.SH.TG1.UH \]

- \[ (n \text{ right}) \] TPD = (TD1+TD+SH) \[ TGD \] WH = neutron converter
- \[ (n \text{ left}) \] TNG = TGD,TD,SH \[ (TH+WH) \] PCE = charge exchange in carbon

+ polarimeter for recoil p.
# $N - p$ with free polarized neutrons

(produced by deuteron beam)

## Data Summary

<table>
<thead>
<tr>
<th>Measured Observable</th>
<th>$\theta_{cm}$ (deg)</th>
<th>Pro-</th>
<th>Avail.</th>
<th>Published</th>
</tr>
</thead>
<tbody>
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<td>0.63</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>$A_{0004}$ (PTE only)</td>
<td>0.80</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>$A_{0004}$ (PTE only)</td>
<td>0.88</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>$A_{0004}$ (PTE only)</td>
<td>0.98</td>
<td>X</td>
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<td>$A_{0004}$ (PTE only)</td>
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<tr>
<td>$A_{0000}$</td>
<td>0.810</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

### Notes

- **SACLAY 1987 - Neutron Counter**
- **SACLAY 1987 - Charge Exchange Detector**
- **LAMPF 1987 - One Arm Spectrometer**
- **PSA Saclay - Geneva - Predictions**
\( n - p \) free polarized neutrons (continuation)

<table>
<thead>
<tr>
<th>Measured Observable</th>
<th>Energy (GeV)</th>
<th>Proceed</th>
<th>Available</th>
<th>PUBLISHED</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>Noske</td>
<td></td>
<td></td>
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<tr>
<td>Rescattering</td>
<td>0.88 GeV</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Nonsk</td>
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</tr>
<tr>
<td>Nosk</td>
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</tr>
<tr>
<td>Dos'sok</td>
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</tr>
<tr>
<td>Poxo</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

\( \Delta S_L \)

\( \Delta S_T \)

\( A_{oono}(p-p) \)

\( 0.744 \text{ GeV} \)

\( 0.794 \text{ GeV} \)

\( \theta_{CM} (\text{deg}) \)

\( \Phi \text{QUASI ELASTIC MEASUREMENTS (}^3\text{He BEAM)} \)

\( P=p \quad \text{beam, and polarized } p \quad \text{target} \)

\( \text{PSA} \quad \text{mainly from elastic data} \)
Figure 2

\[ A_{oonn}(p-p) \]

\[ A_{oonn}(p-p) \]

\[ A_{oosk}(p-p) \]

\[ A_{oosk}(p-p) \]

\[ \theta_{CM}(\text{deg}) \]

\[ \theta_{CM}(\text{deg}) \]

\[ \text{This Exp.} \]

\[ \text{PSA} \]

\[ \text{AWL-265 (Amor et al)} \]

\[ \text{P.S.A. (Saclay-Gendre: Bystricky, Lchar & Leluc)} \]
Afo nono measured in this angular region above 110 MeV.

The sight, 0.744 GeV, is in agreement with other measurements at other energies by M. Karolak.

Fig. 4
Future...

- $\bar{\nu}\nu$: elastic completed in SS?
- $A(\bar{\nu},\nu)$: starts in June SS
- $\bar{\nu}\nu \rightarrow pp\pi^-$ in SG.

Spin response function in $A(\bar{\nu},\nu)$ reaction:

1. Do nuclei behave like a Fermi gas in the quasi-elastic region?

\[
\begin{align*}
S_E &= \sum_i <f^i e^{iQ \cdot R^i} | i> \\
S_T &= \sum_i <f^i \pi^+ \pi^- e^{iQ \cdot R^i} | i> \\
S_L &= \sum_i <f^i \pi^+ \pi^- e^{iQ \cdot R^i} | i>
\end{align*}
\]

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{f1}
\caption{\textit{\textbf{12C (e,e')}}}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{f2}
\caption{\textit{\textbf{gas of Fermi}}}
\end{figure}

Why $(\bar{\nu},\nu)$? Mechanism under control.

Selectivity $\Delta T = 1$

Complements $(\bar{\nu}^F, \nu^F)$ and $(\bar{\nu}, \nu)$

If beams exist at SATURATE.
Separation in hadron scattering

In PWIA, for $\Delta S = 1$ transition:

\[
i_0 = (c^2 + b^2 + f^2) X_T^2 + e^2 X_L^2
\]

\[
i_0 D_{NN} = (c^2 + b^2 - f^2) X_T^2 - e^2 X_L^2
\]

\[
i_0 D_{NP} = (c^2 - b^2 + f^2) X_T^2 - e^2 X_L^2
\]

\[
i_0 D_{PQ} = (c^2 - b^2 - f^2) X_T^2 + e^2 X_L^2
\]

\[
i_0 D_{NN} = i_0 D_{NP} = 2 \text{ Re } (b c^*) X_T^2
\]

\[
i_0 D_{PQ} = -i_0 D_{NP} = 2 \text{ Im } (b c^*) X_T^2
\]

$D_{ij}$ : parameters in Wolfenstein

\[
M(q) = A + \mathcal{E} \sigma^b \vec{\tau} \vec{\tau}_u + C (\vec{\tau}^u \vec{\tau}^u) + E \sigma^b \sigma^u + F \sigma^u \sigma^u
\]

$\langle \vec{N} | \vec{P}, \vec{Z} \rangle = \langle \vec{\tau} \vec{\tau}_u, \vec{\Delta} \vec{\Delta}_u, \vec{B} \vec{A}_u \rangle$

PWIA valid?  


In PWIA, exact relations between observables and form factors

$^{12}$C ($\vec{N}, \vec{p}$)  

$T_n = 400$ MeV
TABLE I. Isospin decomposition of reaction cross sections.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Reaction cross section in terms of $\sigma_{\text{tot}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \rightarrow d\pi^+$</td>
<td>$\sigma_{10}$</td>
</tr>
<tr>
<td>$pp \rightarrow pp\pi^0$</td>
<td>$\sigma_{11}$</td>
</tr>
<tr>
<td>$pp \rightarrow pn\pi^+$</td>
<td>$\sigma_{10} + \sigma_{11}$</td>
</tr>
<tr>
<td>$np \rightarrow d\pi^0$</td>
<td>$(\frac{1}{2})\sigma_{10}$</td>
</tr>
<tr>
<td>$np \rightarrow np\pi^0$</td>
<td>$(\frac{1}{2})[\sigma_{10} + \sigma_{01}]$</td>
</tr>
<tr>
<td>$np \rightarrow nn\pi^+$</td>
<td>$(\frac{1}{2})[\sigma_{11} + \sigma_{01}]$</td>
</tr>
<tr>
<td>$np \rightarrow pp\pi^-$</td>
<td>$(\frac{1}{2})[\sigma_{11} + \sigma_{01}]$</td>
</tr>
<tr>
<td>$pp \rightarrow \text{inelastic}$</td>
<td>$\sigma_{10} + 2\sigma_{11} = \sigma_{\text{tot}}$</td>
</tr>
<tr>
<td>$np \rightarrow \text{inelastic}$</td>
<td>$(\frac{1}{2})[\sigma_{10} + \sigma_{10} + 2\sigma_{11} + 3\sigma_{01}]$</td>
</tr>
<tr>
<td></td>
<td>$= (\frac{1}{2})[\sigma_{\text{tot}} + \sigma_{\text{tot}}]$</td>
</tr>
<tr>
<td></td>
<td>where $\sigma_{\text{tot}} = 3\sigma_{01}$</td>
</tr>
</tbody>
</table>

(Rosenfeld, Phys. Rev. 96 (1954) 139)
Final State Interaction

\( p p \rightarrow p n \pi^+ \)

\( ^3S_0, ^3S_1 \)

\[ \begin{array}{c}
N \\
\text{↓} \\
\text{↓} \\
N \\
\end{array} \]

\[ \begin{array}{c}
N \\
\text{↓} \\
\text{↓} \\
N \\
\end{array} \]

\[ \begin{array}{c}
N \\
\text{↓} \\
\text{↓} \\
N \\
\end{array} \]

\[ \begin{array}{c}
N \\
\text{↓} \\
\text{↓} \\
N \pi \\
\end{array} \]

I = 1, \quad \Delta \text{ dominant}

= 0 \quad \times \quad \text{(isospin)}

N^*_\pi \text{ possible}

NN \rightarrow NN \pi

Dubach, Kloet and Silbar
P. R. C 33 (86) 373

Much weaker effects
on spin observables

\( p p \rightarrow f p \pi \)

\( p p \rightarrow \gamma \pi \)

> 800 MeV
Conventional

Quark or gluon exchange

Hwang (CEBAF meeting)
ARCOLE

$\bar{p}p \rightarrow \bar{p}p\pi^+$

Diagram:

- C: chamber à fils (MVPD)
- S: scintillateur
- : cible $H_2$ liquide (liquid target)

Histogram:

$\bar{p}p \rightarrow pp\pi^+$ events

Correlation function:

$\text{CORR} = f(p, q, q', q''')$

9 variables needed: $p, q, q', q''$, (coordinates)
6 actually measured:
- $p$, $q$, $q'$ and invariant relation $(p, q, q', q'')$

$\rightarrow$ correlation function
Present geometry
- large phase-space cut

Future (~ mid 1988)
- Cylindrical 6 MWPC
- Plane MWPC
  (helical cathode strips, read out)
5.

D. Pilges

Kernforschungsanlage Jülich

IRE

On the necessity to measure high energy neutrons for scientific applications
On the necessity to measure high energy neutrons for scientific applications

D. Filges
KFA-IRE

Neutrons below 20 MeV for many years a useful probe:
- nuclear physics research
- fission- and fusion technology
- other applications
Table 1
Comparison of calculated inelastic cross-sections ( barn per atom) for $^1\text{H}$, $^1\text{Al}$, $^{38}\text{Fe}$ and $^{205}\text{Pb}$ for incident neutrons and protons.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Incident neutrons</th>
<th>Incident protons</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1\text{H}$</td>
<td>$^1\text{Al}$</td>
<td>$^{38}\text{Fe}$</td>
</tr>
<tr>
<td>100.0</td>
<td>0.36</td>
<td>0.44</td>
</tr>
<tr>
<td>200.0</td>
<td>0.21</td>
<td>0.39</td>
</tr>
<tr>
<td>300.0</td>
<td>0.19</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Table 2
Comparison of calculated secondary yields per inelastic collision for incident neutrons and protons of 600 MeV.

<table>
<thead>
<tr>
<th>Incident neutrons</th>
<th>Incident protons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron yield</td>
<td>$^1\text{H}$</td>
</tr>
<tr>
<td>1.98</td>
<td>2.96</td>
</tr>
<tr>
<td>Proton yield $^4$</td>
<td>1.11</td>
</tr>
<tr>
<td>Heavy ion yield $^4$</td>
<td>0.73</td>
</tr>
<tr>
<td>Pion yield $^4$</td>
<td>0.24</td>
</tr>
<tr>
<td>$\sigma_{\text{n}}/\sigma_{\text{p}}$</td>
<td>1.12</td>
</tr>
</tbody>
</table>

$^4$ Sum of $d$, $^3\text{He}$, $^3\text{He}$.

$^4$ Sum of $\pi^+$, $\pi^-$.

Table 3
Comparison of 20 MeV neutron elastic cross-sections, mean cosine of scattering angles and recoil energy of ions as calculated by HETC [4], by Randt’s formula [10] and by MACK [11] from ENDF/B-IV Data [9].

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$\sigma_0$ (barn per atom)</th>
<th>Mean cosine of scattering angle</th>
<th>Recoil energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HETC</td>
<td>ENDF</td>
<td>HETC</td>
<td>ENDF</td>
</tr>
<tr>
<td>$^1\text{H}$</td>
<td>0.97</td>
<td>0.84</td>
<td>0.956</td>
</tr>
<tr>
<td>$^4\text{He}$</td>
<td>0.96</td>
<td>0.96</td>
<td>0.961</td>
</tr>
<tr>
<td>$^6\text{Li}$</td>
<td>1.03</td>
<td>1.07</td>
<td>0.962</td>
</tr>
<tr>
<td>$^7\text{Be}$</td>
<td>1.18</td>
<td>1.17</td>
<td>0.974</td>
</tr>
<tr>
<td>$^1\text{Al}$</td>
<td>0.97</td>
<td>0.91</td>
<td>0.980</td>
</tr>
</tbody>
</table>

Neutrons: 20 MeV up to several GeV (medium energy)

- Very little and no systematic measurements.
- Neutrons are difficult to measure and neutrons are a challenge for experimentalists.
- Requirements from technology application.
- Considerable interest today because medium energy neutrons are very important in many applications in basic science and technology.

But: Considerable interest today because medium energy neutrons are very important in many applications in basic science and technology.

Important:
- Multiplicity
- Larger average path for high energy inelastic collisions = large attenuation length
- Uranium
Approximate nominal values for nuclear mean-free-paths for some materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Density $\text{g/cm}^3$</th>
<th>$\lambda_n$ $\text{cm}$</th>
<th>Nuclear mean-free-path $\lambda_n$ $\text{g/cm}^2$</th>
<th>cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0.001205</td>
<td>85</td>
<td>705</td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td>7.8</td>
<td>130</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Pb</td>
<td>11.3</td>
<td>195</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>16.7</td>
<td>205</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Normal Concrete</td>
<td>2.4</td>
<td>90</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>Heavy Concrete</td>
<td>3.5-4.3</td>
<td>90</td>
<td>21-26</td>
<td></td>
</tr>
</tbody>
</table>

$\lambda_n$ = mean-free-path for high energy nonelastic collisions

$\lambda_n = 33 \lambda^{1/3} \text{g/cm}^2$
Examples where medium energy neutrons are needed

- **nuclear data**
  - high energy cross sections
  - secondary particle spectra

- **radiation effects**
  - e.g. material damage, activation

- **model/code development**
  - nuclear interaction models
  - high energy event generators and transport codes

- **basic science and technology**
  - detector development for future nuclear and high energy physics experiments (e.g. high energy physics calorimeter)
  - basic studies on cosmic ray effects
  - target design
  - accelerator shielding
  - radiation damage to electronics in space
  - radiation protection of personnel in space
Nuclear Data

Worldwide effort to go beyond the limits of ENDF-data bases

gay: To evaluate cross sections above 20 MeV

to about several GeV

High Energy Nuclear Cross Section Data

- Applications and types of data
- Incident energy range (s)
- Current experimental data and theoretical methods
- Data base development

Applications

- Target and Detector Development
  - Particle emission (neutron) and gamma-ray emission
  - Neutron and charged particle induced inclusive reaction data (d, t, α, He-3 and recoil products, others)
- Higher energy shielding needs
  - Thick target neutron and gamma production from charged-particle reactions
  - Neutron transport
- Accelerator beam components activation
  - Neutron induced and charged particle radionuclide cross sections
  - Neutron therapy?

Data situation marked by sparseness of relevant experimental data

Theoretical models used to produce majority of utilized data
### Table 1
Summary of Reported \((p,xn)\) Measurements

<table>
<thead>
<tr>
<th>(E_p) (MeV)</th>
<th>Targets</th>
<th>Target Type</th>
<th>Neutron Energy Range (MeV)</th>
<th>Angles (°)</th>
<th>Method</th>
<th>Quantity Determined</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>Al, Cu, Pb, U</td>
<td>thin</td>
<td>15-140</td>
<td>0</td>
<td>TOP</td>
<td>Diff. in Yield</td>
<td>P.R. Bowen, Nucl. Phys. 30(62) 475</td>
</tr>
<tr>
<td></td>
<td>H, Ce, Al, Cu, Co, Bi</td>
<td>thick</td>
<td>30-170</td>
<td>0, 10, 45</td>
<td>TOP</td>
<td>Diff. in Yield</td>
<td>J.W. Machtler, Phys. Rev. C6 (1972) 1496</td>
</tr>
<tr>
<td>190</td>
<td>Cu, Al, Ag, Au, U</td>
<td>thin</td>
<td>0-12</td>
<td>45, 135</td>
<td>emulsion</td>
<td>Diff. in Cross Sect.</td>
<td>E.E. Cross, UCRL-13309 (59)</td>
</tr>
<tr>
<td></td>
<td>C, Al, Co</td>
<td>thin</td>
<td>100-450</td>
<td>0, 10, 20, 45</td>
<td>TOP</td>
<td>Diff. in Yield</td>
<td>N. Takahashi, Int. Conf. Neutr. Cross Sect. for Technology (1975)</td>
</tr>
<tr>
<td>660</td>
<td>U</td>
<td>thin</td>
<td>100-450</td>
<td>0</td>
<td>TOP</td>
<td>Diff. in Yield</td>
<td>R.G. Vasil'kov, Sov. Jour. Nucl. Phys. 7 (1964) 40; E. Enberg, 44(78) 92, No. 4</td>
</tr>
<tr>
<td>660</td>
<td>Al, Cu, Sn, Pb, U</td>
<td>thin</td>
<td>20-500</td>
<td>50</td>
<td>TOP</td>
<td>Diff. in Yield</td>
<td>R.D. Heyde, Phys. Rev. C8 (1973) 2412</td>
</tr>
<tr>
<td>740</td>
<td>U</td>
<td>thick</td>
<td>20-500</td>
<td>50</td>
<td>TOP</td>
<td>Diff. in Yield</td>
<td>C.G. Cassapakis, Phys. Lett. 61B (1975) 26</td>
</tr>
<tr>
<td>800</td>
<td>Be, C, Al</td>
<td>thin</td>
<td>100-800</td>
<td>120</td>
<td>TOP</td>
<td>Diff. in Cross Sect.</td>
<td>B.E. Bonner, Phys. Rev. C18 (1978) 1438</td>
</tr>
<tr>
<td>470-720</td>
<td>Pb, U</td>
<td>thick</td>
<td>470-720</td>
<td>0</td>
<td>TOP</td>
<td>Diff. in Cross Sect.</td>
<td>J.S. Fraser, Physics in Canada 21, No. 3 (1955) 61</td>
</tr>
<tr>
<td>1000-1470</td>
<td>Al, Cu, In, Pb, U</td>
<td>thin</td>
<td>0.5-400</td>
<td>0, 30, 45, 120</td>
<td>TOP</td>
<td>Diff. in Cross Sect.</td>
<td>S.D. Hove, unpublished, Thesis 1980</td>
</tr>
<tr>
<td>545</td>
<td>C, Al, Fe, Pb, H, In, Ta, Pb, U</td>
<td>thin</td>
<td>0.5-685</td>
<td>30, 90, 150</td>
<td>TOP</td>
<td>Diff. in Cross Sect.</td>
<td>S.D. Hove, unpublished, Thesis 1980</td>
</tr>
</tbody>
</table>

Medium Energy Nuclear Data

Overview for Nuclear Data Requirements

<table>
<thead>
<tr>
<th>Type of Data</th>
<th>Needs/Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>(d^2\rho/da))</td>
<td>proton, charged particle, neutron, (\gamma)-production, target, structure materials, (\gamma)-production, target, structure materials, high energy etc.</td>
</tr>
<tr>
<td>Integral high energy reactions</td>
<td>from protons, charged particles, target, and structure materials, high energy, etc.</td>
</tr>
<tr>
<td>Intensity high energy distributions</td>
<td>target, and structure materials, materials in outer space</td>
</tr>
<tr>
<td>Gas production</td>
<td>- activetion products, radionuclides</td>
</tr>
<tr>
<td>Transmission</td>
<td>- altion products, radionuclides</td>
</tr>
</tbody>
</table>

\(\rho = n_{(p,e)\gamma,\text{cascade}}\) (Where emitted particle type \(n = (p,e)\gamma,\text{cascade})\).
Experimental Data (continued)

- New LAMPF measurements - (LANL/KFA-IRE Collaboration) Meir et al- Neutron emission, forward angles; Be,C,Al,Ni,W Ta,Pb,U; 318,800 MeV proton energies

Wilson, Holkamp et al - γ production, 256 and 318 MeV protons; LiH,C,Al,Ti,Ni,Pb,U, macroscopic targets

Laros and Priedhorsky - γ production(relative), 211 MeV p, HPGe detector; targets LiH,C,Al,Ti,Ni,Pb, 238 U, macroscopic

- Indiana University cyclotron - $E_p \rightarrow 200$ MeV

Charged particle and some neutron spectra, angular distributions, residual nucleus production

Experimental Data (Recent)

- Karlsruhe data (1984) - 590 MeV protons, extensive range of targets (C,Al,Fe,Nb,In,Ta,Pb, U); 3-5 angles /target

INCE Model Results — Neutron Emission Spectra

Deficiencies in calculated spectra - At high incident energies INCE results for neutron emission lie lower than experimental results for $E'_n > 10-15$ MeV.

For lower incident energies INCE calculations overpredict neutron spectra at forward angles.
Current methodology used to generate nuclear cross section data for applications

- Intranuclear cascade-evaporation (INCE) model calculations (and particle transport) linked to Monte Carlo transport codes (MCNP, Morse) at $E = 15-20$ MeV (neutrons only)

Problems

- Significant deficiencies in INCE model results in the energy range from $\sim 20-30 \rightarrow 150-200$ MeV (perhaps higher)

- When problems occur it is difficult to separate microscopic nuclear physics (cross sections) effects from macroscopic transport effects

- Inconsistencies between INCE calculations and ENDF/B data

- Costly regeneration of $\sigma$'s for each applied problem
<table>
<thead>
<tr>
<th>Model Type</th>
<th>Code Name</th>
<th>Development Location</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fermi Breakup</td>
<td>FBR</td>
<td>LANL</td>
<td>De-excitation by multiparticle breakup for light nuclei (A ≤ 20).</td>
</tr>
<tr>
<td>Phase Space</td>
<td>PSM</td>
<td>KFA</td>
<td>Uses phase space model to predict energy-angular spectra from light nuclei (A ≤ 12) (developed by KFA Lab, W. Germany).</td>
</tr>
<tr>
<td>Stripping</td>
<td>LHI</td>
<td>SAIC</td>
<td>Allows breakup of beam particle clusters by Sereb theory, used in conjunction with MECC and EVAP.</td>
</tr>
<tr>
<td>High-Energy</td>
<td>ORNL</td>
<td>ORNL</td>
<td>Relies heavily on empirically derived constants, neglects fissioning for subatomic elements (Z &lt; 91).</td>
</tr>
<tr>
<td></td>
<td>RAL</td>
<td>RAL</td>
<td>Based mainly on Fong statistical theory. (developed at Rutherford Appleton Laboratory, U.K.)</td>
</tr>
<tr>
<td>Gamma-Ray</td>
<td>PHT</td>
<td>LANL</td>
<td>Allows several model options for computing gamma-ray spectra from spallation collisions.</td>
</tr>
<tr>
<td></td>
<td>GAMA</td>
<td>SAIC</td>
<td>Spallation gamma-ray de-excitation cascade computed based on electric dipole transitions.</td>
</tr>
<tr>
<td>Pre-Equilibrium</td>
<td>GNASH</td>
<td>LANL</td>
<td>Statistical model, based on Hauser-Feshbach theory, for cross section calculations; emission spectra restricted to isotropy in CM.</td>
</tr>
<tr>
<td></td>
<td>PREANGE</td>
<td>ECN</td>
<td>Based on generalized ejection model, anisotropic emission capability (developed at Netherlands Energy Research Foundation)</td>
</tr>
</tbody>
</table>

**Nuclear Model Codes for High-Energy Radiation Transport**

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Code Name</th>
<th>Development Location</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intranuclear Cascade</td>
<td>MECC</td>
<td>ORNL</td>
<td>Medium energy (20 MeV ≤ E ≤ 3 GeV cascade code for nucleon and pion collisions.</td>
</tr>
<tr>
<td></td>
<td>VEGAS</td>
<td>BNL</td>
<td>Incorporates time-sequencing of events to take into account nucleon depletion during reaction.</td>
</tr>
<tr>
<td></td>
<td>CLUST</td>
<td>LLL</td>
<td>Allows interaction of bound &quot;clusters&quot; of nucleons for both projectile and inside target nucleus.</td>
</tr>
<tr>
<td></td>
<td>ISABEL</td>
<td>Israel</td>
<td>Extension of VEGAS to incorporate nucleus-nucleus collisions and other features.</td>
</tr>
<tr>
<td></td>
<td>INCA</td>
<td>LANL</td>
<td>Cluster model descendant of VEGAS for light target nuclei and low energy, A ≤ 4 particles.</td>
</tr>
<tr>
<td></td>
<td>OMNI</td>
<td>Clarkson</td>
<td>Specialized version for predicting nuclear recoil spectra and single particle electronics upset (developed at Clarkson College).</td>
</tr>
<tr>
<td>Evaporation</td>
<td>EVAP</td>
<td>ORNL</td>
<td>Based on Dostrovsky theory, normally coupled with MECC.</td>
</tr>
<tr>
<td></td>
<td>EFF</td>
<td>BNL</td>
<td>Based on Dostrovsky theory, normally coupled with VEGAS.</td>
</tr>
<tr>
<td></td>
<td>EVA</td>
<td>Israel</td>
<td>Based on Dostrovsky theory, normally coupled with ISABEL.</td>
</tr>
<tr>
<td></td>
<td>JULIAN</td>
<td>BNL</td>
<td>More detailed model of de-excitation than provided by Dostrovsky theory.</td>
</tr>
</tbody>
</table>
Evolution of HETC-Code

(early 1960's) → NTC

(late 1960's) → NMTC

(early 1970's) → HETC

ORNL

Various Users:
In U.S.: AFWL, BNL, CERN, Fermi, DESY, GAC, KEK, LLL, MPI
Outside U.S.: CEA, etc...

At Present: ≥ 6 versions of HETC Code
≥ HETC used at ≥ 20 facilities
GENERAL DESIGN CHARACTERISTICS

- HERMES consists of a set of programs which solve radiation transport problems under different physical conditions (i.e., energy-range).
- Each program can be run separately.
- Each program can use particle sources generated by other programs.
- Each program submits particles to other programs for further treatment.
- Each program submits its estimation results for further use in combined statistical analysis.
- Each program uses the same problem description.
- Each program has access to library modules:
  - interpretation of problem description input (CMD)
  - tracing particles through the shared geometry setup (CG)
  - basic statistic procedures (STATLIB)
  - data management routines (CMD) etc.

Organization of HERMES
### STRUCTURE OF SUBMISSION FILES

<table>
<thead>
<tr>
<th>Item</th>
<th>Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>VERB</td>
<td>char8</td>
<td>situation id</td>
</tr>
<tr>
<td>2</td>
<td>KEY</td>
<td>integer</td>
<td>situation key</td>
</tr>
<tr>
<td>3</td>
<td>ISEED</td>
<td>integer</td>
<td>current random seed</td>
</tr>
<tr>
<td>4</td>
<td>IRUN</td>
<td>integer</td>
<td>problem number</td>
</tr>
<tr>
<td>5</td>
<td>IRAT</td>
<td>integer</td>
<td>current batch number</td>
</tr>
<tr>
<td>6</td>
<td>IRHS</td>
<td>integer</td>
<td>current history number</td>
</tr>
<tr>
<td>7</td>
<td>NNUO</td>
<td>integer</td>
<td>number of neutrons submitted (NET)</td>
</tr>
<tr>
<td>8</td>
<td>NPUO</td>
<td>integer</td>
<td>number of ( v^+ ) submitted (NET)</td>
</tr>
<tr>
<td>9</td>
<td>NNUC</td>
<td>integer</td>
<td>number of exited nuclei submitted (NET)</td>
</tr>
<tr>
<td>10</td>
<td>JOB</td>
<td>char8</td>
<td>Time stamp to identify the job</td>
</tr>
<tr>
<td>11</td>
<td>DATE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>TIME</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>dummy</td>
<td></td>
<td>dummy words to get same record length on IBM and CRAY/XMP</td>
</tr>
<tr>
<td>14</td>
<td>dummy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>dummy</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 1.** Submission trigger record format

<table>
<thead>
<tr>
<th>VERB</th>
<th>KEY</th>
<th>situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOR</td>
<td>-1</td>
<td>Start of run</td>
</tr>
<tr>
<td>SSB</td>
<td>-2</td>
<td>Start of batch</td>
</tr>
<tr>
<td>EOB</td>
<td>-3</td>
<td>End of run</td>
</tr>
<tr>
<td>EOR</td>
<td>-4</td>
<td>End of batch</td>
</tr>
</tbody>
</table>

**Figure 2.** Submission trigger record types

<table>
<thead>
<tr>
<th>Item</th>
<th>Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>VERB</td>
<td>char8</td>
<td>situation id</td>
</tr>
<tr>
<td>2</td>
<td>KEY</td>
<td>integer</td>
<td>=0 for all particle submission records</td>
</tr>
<tr>
<td>3</td>
<td>ISEED</td>
<td>integer</td>
<td>current random seed</td>
</tr>
<tr>
<td>4</td>
<td>A</td>
<td>real</td>
<td>struck nucleus mass number</td>
</tr>
<tr>
<td>5</td>
<td>Z</td>
<td>real</td>
<td>struck nucleus charge number</td>
</tr>
<tr>
<td>6</td>
<td>E*</td>
<td>real</td>
<td>struck nucleus excitation energy</td>
</tr>
<tr>
<td>7</td>
<td>TYP</td>
<td>real</td>
<td>particle type</td>
</tr>
<tr>
<td>8</td>
<td>X</td>
<td></td>
<td>particle site</td>
</tr>
<tr>
<td>9</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>U</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>E</td>
<td></td>
<td>particle energy</td>
</tr>
<tr>
<td>14</td>
<td>WT</td>
<td></td>
<td>particle statistical importance</td>
</tr>
</tbody>
</table>

**Figure 3.** Particle submission record format

<table>
<thead>
<tr>
<th>VERB</th>
<th>KEY</th>
<th>TYP</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>0</td>
<td>1</td>
<td>n (below cut)</td>
</tr>
<tr>
<td>G4M</td>
<td>0</td>
<td>7.</td>
<td>G</td>
</tr>
<tr>
<td>EIO</td>
<td>0</td>
<td>3.</td>
<td>( v^+ )</td>
</tr>
<tr>
<td>NUC=</td>
<td>0</td>
<td>14.</td>
<td>exited nucleus</td>
</tr>
<tr>
<td>E+</td>
<td>0</td>
<td>8.</td>
<td>e^+</td>
</tr>
<tr>
<td>E-</td>
<td>0</td>
<td>9.</td>
<td>e^-</td>
</tr>
<tr>
<td>NU+</td>
<td>0</td>
<td>5.</td>
<td>( \mu^+ )</td>
</tr>
<tr>
<td>NU-</td>
<td>0</td>
<td>6.</td>
<td>( \mu^- )</td>
</tr>
</tbody>
</table>

**Figure 4.** Particle submission record types
CALCULATIONAL METHOD

- HETC code

High energy hadron radiation transport (> 15 MeV)
Uses theoretical models for inelastic/elastic collisions
(Intra-nuclear-cascade-evaporation model)

- EGS code

High energy electron-gamma-shower radiation transport
(Few keV up to several TeV)

- MORSE-code

Monte Carlo Oak Ridge Stochastic Experiment
Low energy (< 100 MeV) neutron/gamma transport
Uses experimental cross section data base

- SIM code

General purpose simultaneous analysis system for detector
Responses of NET/MORSE/EGS and other Monte Carlo codes
By means of definition commands

- DYN code

Neutron dynamic calculations using experimental cross sections
And NET neutron source distributions

NETC is the main code for studying hadronic cascades

A. Particles transported

p, n, x^+, x^-, e^+, e^- (light heavy ions A < 10)

B. Three-dimensional multi-media

C. Information available on

\(^0\) O, D, T, He^3, e, residual nucleus, residual
nuclear excitation energy (\(r\) emission)

D. NETC takes into account

1. \(dE/dx\)
2. decay
3. nonelastic nuclear collisions
4. nonelastic hydrogen collisions
5. elastic proton/neutron nucleus collisions (upto 20 GeV)
6. elastic collisions with hydrogen
7. fission

E. Energy is conserved at each collision site

F. NETC is basically an analog Monte Carlo transport code

G. For the most part, cross sections (total and differential)
are contained within the code or are calculated during transport

H. NETC operates with combinatorial geometry
MORSE

*modified version for calorimeter simulation

Transport Code for Neutrons and Gammas
(Three-Dimensional, Multi-Media)

A. Particle Transported
Neutrons/Gammas

B. MORSE takes into account

1. elastic neutron nucleus including hydrogen collisions
2. nonelastic neutron-nucleus collisions
3. inelastic neutron-nucleus collisions
4. capture and fission
5. gamma production (capture, fission, inelastic, and nonelastic)

C. MORSE is original not an analog Monte Carlo Transport Code
(KFA-IRE modifications to some parts in analog MC)

D. The neutron source is obtained from the HETC results, i.e.,
neutrons produced below cutoff in HETC (< 20 MeV)

E. Multigroup cross sections are obtained from AMPX/HJOY
using ENDFB/V data

F. Produced gamma rays are stored for EGS transport

G. MORSE operates with combinatorial geometry
EGS

Electron, Positron, Gamma Ray Transport Code
(Three-Dimensional, Multi-Media)

A. Particles transported
\[ e^-, e^+, \gamma \]

B. EGS takes into account
1. \( dE/dx \) (small and wide angle scattering)
2. Compton scattering
3. Pair production
4. Bremsstrahlung
5. Annihilation
6. Photoelectric effect
7. etc.

C. Energy is conserved at each collision site

D. EGS is an analog Monte Carlo transport code

E. The electromagnetic source is obtained from the NELC results, i.e.,

\[
\begin{align*}
\gamma^0 & = \gamma^+ + \gamma^- \\
\gamma^\pm & = \gamma^+ + \gamma^- \\
N^+ & = N^+ + \gamma^+ \\
N^- & = N^- + \gamma^-
\end{align*}
\]

F. PEGS provides the necessary cross sections

G. EGS operates with combinatorial geometry
TRANSPORT CODES

- DUBNA CODE
  Barashenkov et al. Dubna, USSR

- RANFT CODE (FLUKA etc)
  (CERN, Karl-Marx-Universität, DDR)

- GHEISHA CODE
  (Feufeldt, DESY und RWTH Aachen, Germany)

- CASIM CODE
  (van Ginneken et al., Fermi Lab, USA)

- ISABEL CODE
  (Yariv, Fraenkel, BNL, LANL and Weizmann-Institut)

- HETC CODE
  (Armstrong, Bertini, ORNL, SAIC, USA)

  Workshop planned in Oct 87
  at Jülich, FRG
Origin of Data for HILO High-Energy Cross Section Library

<table>
<thead>
<tr>
<th>Cross Section</th>
<th>Range (MeV)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>elastic</td>
<td>&lt; 14.9</td>
<td>VITAMIN-C Fusion Library /7/*</td>
</tr>
<tr>
<td>elastic</td>
<td>14.9 - 400</td>
<td>optical model</td>
</tr>
<tr>
<td>nonelastic</td>
<td>&lt; 14.9</td>
<td>VITAMIN-C Fusion Library</td>
</tr>
<tr>
<td>nonelastic</td>
<td>14.9 - 60</td>
<td>optical model and exp.</td>
</tr>
<tr>
<td>nonelastic</td>
<td>60 - 400</td>
<td>intranuclear-cascade evaporation model</td>
</tr>
<tr>
<td>differential</td>
<td>&lt; 14.9</td>
<td>VITAMIN-C Fusion Library</td>
</tr>
<tr>
<td>elastic</td>
<td>14.9 - 400</td>
<td>optical model</td>
</tr>
<tr>
<td>differential</td>
<td>&lt; 14.9</td>
<td>VITAMIN-C Fusion Library</td>
</tr>
<tr>
<td>nonelastic</td>
<td>14.9 - 400</td>
<td>intranuclear-cascade evaporation model</td>
</tr>
</tbody>
</table>

*Based on ENDF/B-IV data

Features of Presently Available High-Energy Multigroup Cross Section Library HILO

Energy Range
- neutrons: thermal to 400 MeV
- γ-rays: $10^{-2}$ MeV to 14.0 MeV

Group Structure
- 66 neutron groups
- 21 gamma-ray groups

Angular Expansion
- $P_5$ expansion for > 14.9 MeV
- $P_3$ expansion for < 14.9 MeV

Elements Available
- H, $^{10}$B, C, N, O, Na, Mg, Al, Si
- S, K, Ca, Cr, Fe, Ni, W, and Pb
Legendre Expansion of Neutron Production cross section

Protons on Fe: $E_p = 1100$ MeV
$E_n = 500 - 550$ MeV

Normalized neutron flux per unit lethargy in the energy range between 10 MeV and 400 MeV at radius 197.5 cm, comparison between HILO-$P_3/S_{16}$ and LASL-$P_3/S_{16}$
MATERIAL DAMAGE AND GAS PRODUCTION

- MOST WORK FOR NEUTRONS $\leq 20$ MeV

- BUT IMPORTANT FOR SPALLATION SOURCES

- THICK TARGET DAMAGE PARAMETERS
  (DAMAGE ENERGY, DISPLACEMENTS, GAS PRODUCTION,
  TRANSFORMATION PRODUCTS ETC.)
  FOR HIGH ENERGY ($\sim 20$ MeV TO $\sim 1$ GeV)
  PROTONS AND NEUTRONS

- LOW ENERGY CHARGED PARTICLES
Table 18. Summary comparison of present calculations with damage parameter calculations based on ENDF data for 20 MeV neutrons.

<table>
<thead>
<tr>
<th>Damage Parameter</th>
<th>Present Calculations</th>
<th>ENDF</th>
<th>Ratio: ENDF/Present</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Al target</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{dam}}^{(b-\text{keV})}$</td>
<td>90</td>
<td>178</td>
<td>2.0</td>
</tr>
<tr>
<td>$\sigma_{\text{dil}}^{(b)}$*</td>
<td>1.4+3</td>
<td>2.0+3</td>
<td>2.0</td>
</tr>
<tr>
<td>$\sigma_{\text{trans}}^{(b)}$**</td>
<td>0.69</td>
<td>0.96</td>
<td>1.4</td>
</tr>
<tr>
<td>$\sigma_{\text{He}}^{(nb)}$</td>
<td>7</td>
<td>44</td>
<td>6.3</td>
</tr>
<tr>
<td><strong>Cu target</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{dam}}^{(b-\text{keV})}$</td>
<td>143</td>
<td>318</td>
<td>2.2</td>
</tr>
<tr>
<td>$\sigma_{\text{dil}}^{(b)}$***</td>
<td>1.9+3</td>
<td>4.2+3</td>
<td>2.2</td>
</tr>
<tr>
<td>$\sigma_{\text{trans}}^{(b)}$**</td>
<td>1.06</td>
<td>1.42</td>
<td>1.3</td>
</tr>
<tr>
<td>$\sigma_{\text{He}}^{(nb)}$</td>
<td>___</td>
<td>12</td>
<td>___</td>
</tr>
</tbody>
</table>

* for a threshold displacement energy of 25 eV
** transmutation cross section taken to be nonelastic cross section
*** for a threshold displacement energy of 30 eV

Table 13. Comparison of Damage Parameters for Copper and Uranium for 800-MeV Protons.

<table>
<thead>
<tr>
<th></th>
<th>Copper Target</th>
<th>U-238 Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Damage Energy</td>
<td>2.6x10^1</td>
<td>8.5x10^1</td>
</tr>
<tr>
<td>Cross Section (b-keV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. DPA Cross Section (b)*</td>
<td>3.6x10^3</td>
<td>1.1x10^4</td>
</tr>
<tr>
<td>3. Helium Production</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- cross section (b)</td>
<td>0.14</td>
<td>1.7</td>
</tr>
<tr>
<td>- APPM/DPA</td>
<td>38</td>
<td>15</td>
</tr>
<tr>
<td>4. Production Energy (MeV)**</td>
<td>2.6</td>
<td>3.5</td>
</tr>
<tr>
<td>- spallation nuclei</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- fission fragment</td>
<td>83</td>
<td></td>
</tr>
<tr>
<td>5. Damage Energy (MeV)**</td>
<td>0.32</td>
<td>1.1</td>
</tr>
<tr>
<td>- spallation nuclei</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- fission fragment</td>
<td>3.1</td>
<td></td>
</tr>
</tbody>
</table>

* assuming a damage energy threshold of 30 eV for both targets
** production and damage energy normalized per produced particle (residual spallation nucleus or fission fragment)
Figure 13. Helium production cross section for copper versus neutron energy from ENDF (n,a) files and as calculated by the VNMC code, from Ref. [2]. Also shown are results of present calculations and those of Coulter, et al. [3] for 800-MeV protons, and the range of various measured data at <400 MeV from the compilation given in Ref. [6].

Figure 12. Displacement cross section as function of neutron energy for copper target. Original figure from Wechsler et al. [2] shows results from SPECTER code ENDF/B-V cross sections) and the high-energy Monte Carlo code VNMC. Also shown are the displacement cross sections from present calculations at 20, 100, 350, and 800 MeV.
Figure 4. Calculated damage and displacement cross sections for neutrons and protons incident on an aluminum target.

Table 16. Damage calculations for neutron of various energies incident on a thin copper target: present calculations compared to the predictions of others.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$E_n$=20 MeV</th>
<th>$E_n$=100 MeV</th>
<th>$E_n$=350 MeV</th>
<th>$E_n$=800 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. $\sigma_{\text{dam}}$ damage cross section (b-keV)</td>
<td>143$^a$</td>
<td>205$^b$</td>
<td>228</td>
<td>282$^d$</td>
</tr>
<tr>
<td>2. $\sigma_{\text{dis}}$, displacement cross section (b)</td>
<td>(2.2x10$^4$)$^c$</td>
<td>(3.0x10$^4$)$^c$</td>
<td>(4.0x10$^4$)$^c$</td>
<td>(5.0x10$^4$)$^d$</td>
</tr>
<tr>
<td>3. $&lt;$T$&gt;$, average energy transfer (keV)</td>
<td>67</td>
<td>145</td>
<td>205</td>
<td>218</td>
</tr>
<tr>
<td>4. Transmutation cross section (b)</td>
<td>1.06</td>
<td>0.78</td>
<td>0.72</td>
<td>0.85$^d$</td>
</tr>
<tr>
<td>5. Helium production cross section (mb)</td>
<td>53$^c$</td>
<td>110$^c$</td>
<td>140$^c$</td>
<td>140$^c$</td>
</tr>
</tbody>
</table>

a. SPECTRE code calculations, based on ENDF/B-V cross sections, from Wechsler et al. /2/.
b. SPECTRE code calculations, based on "extrapolated" cross sections from 20 to 100 MeV, from Greenwood /20/.
c. VMTC calculations, using VEGAS intranuclear cascade code and OIF evaporation code, from Wechsler et al.
d. From Güttler et al. calculations /3/.
e. Statistically meaningful value not obtained.
f. ENDF/B-IV
Physics of Sampling Calorimetry

- High Energy Physics in the TEV Region at HERA, CERN, FERMI

Shower Particles inside the Calorimeters have Energies of all ranges, especially at COSY Energies

Calculations of Calorimeter Responses

- up to 20 MeV main cross sections available from reactor physics and fusion
- in the high energy region (several GeV) applying QCD-Model Simulation
- at medium energies physics models tend to fail with decreasing energy
**Some Important Physics of Sampling Hadron Calorimetry**

- Migration effect of $\gamma$-energy
  - $e/\text{mip} < 1$

- Spallation and evaporation $n'$s including fission

- Fission $\gamma'$s (prompt)

- $n$-capture in Uranium (delayed $\gamma'$s)

**Choice of materials:**
- a) liq. Argon (LA)
- b) LA + CH$_4$
- c) Scintillator
- d) TMS/TMP

**Fig. 31:** The important effects, which are involved in the physics of compensating sampling calorimeters, are visualized schematically. The main emphasis lies on the production of neutrons and gammas in uranium absorber plates.
Compensation \( \rightarrow \frac{e}{h} \leq \Lambda \)
(best resolution)
Compensation by Neutrons

\[ \rightarrow 5 \text{ Towers} \]
\( \rightarrow \text{Scint} \leq 2.5 \text{ mm} \)
\( \rightarrow \text{Air} \leq 0.5 \text{ mm} \)
133 Sandwich

Fig. 1. Setup of TEST35 DU-scintillator calorimeter.

\( \rightarrow \text{TEST-SS} \)
\( \mu = 2 \text{ EUS} \)
beam energy
\( \begin{align*}
\text{and} & \ 5, 7, 9 \text{ keV/}
\end{align*} \)
<table>
<thead>
<tr>
<th>E-HIGH</th>
<th>E-LOW</th>
<th>YIELD</th>
<th>%ERR</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.000E+03</td>
<td>4.000E+03</td>
<td>0.000E+00</td>
<td>0.00</td>
</tr>
<tr>
<td>4.000E+03</td>
<td>3.000E+03</td>
<td>1.613E-03</td>
<td>100.00</td>
</tr>
<tr>
<td>3.000E+03</td>
<td>2.000E+03</td>
<td>1.729E-02</td>
<td>29.41</td>
</tr>
<tr>
<td>2.000E+03</td>
<td>1.500E+03</td>
<td>3.518E-02</td>
<td>21.71</td>
</tr>
<tr>
<td>1.500E+03</td>
<td>1.000E+03</td>
<td>8.872E-02</td>
<td>10.64</td>
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<tr>
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<td>3.71</td>
</tr>
<tr>
<td>1.000E+02</td>
<td>5.000E+01</td>
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<td>2.69</td>
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<tr>
<td>5.000E+01</td>
<td>2.000E+01</td>
<td>4.440E+00</td>
<td>2.85</td>
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<tr>
<td>2.000E+01</td>
<td>1.000E+01</td>
<td>6.110E+00</td>
<td>2.69</td>
</tr>
<tr>
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<td>5.000E+00</td>
<td>5.796E+00</td>
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<td>5.000E+00</td>
<td>2.000E+00</td>
<td>2.606E+00</td>
<td>2.56</td>
</tr>
<tr>
<td>2.000E+00</td>
<td>1.000E+00</td>
<td>2.691E-01</td>
<td>10.96</td>
</tr>
<tr>
<td>1.000E+00</td>
<td>0.000E+00</td>
<td>1.242E-01</td>
<td>12.20</td>
</tr>
</tbody>
</table>

YIELD DETECTOR FOR N

<table>
<thead>
<tr>
<th>E-HIGH</th>
<th>E-LOW</th>
<th>YIELD</th>
<th>%ERR</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.000E+03</td>
<td>4.000E+03</td>
<td>0.000E+00</td>
<td>0.00</td>
</tr>
<tr>
<td>4.000E+03</td>
<td>3.000E+03</td>
<td>1.458E-02</td>
<td>33.39</td>
</tr>
<tr>
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<td>2.000E+03</td>
<td>8.111E-02</td>
<td>11.98</td>
</tr>
<tr>
<td>2.000E+03</td>
<td>1.500E+03</td>
<td>1.125E-01</td>
<td>17.61</td>
</tr>
<tr>
<td>1.500E+03</td>
<td>1.000E+03</td>
<td>1.427E-01</td>
<td>11.59</td>
</tr>
<tr>
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<td>5.000E+02</td>
<td>5.137E-01</td>
<td>6.76</td>
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<td>1.96</td>
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<tr>
<td>5.000E+01</td>
<td>2.000E+01</td>
<td>9.424E+00</td>
<td>2.03</td>
</tr>
<tr>
<td>2.000E+01</td>
<td>1.000E+01</td>
<td>1.372E+01</td>
<td>1.54</td>
</tr>
<tr>
<td>1.000E+01</td>
<td>5.000E+00</td>
<td>2.157E+01</td>
<td>1.83</td>
</tr>
<tr>
<td>5.000E+00</td>
<td>2.000E+00</td>
<td>3.983E+00</td>
<td>1.62</td>
</tr>
<tr>
<td>2.000E+00</td>
<td>1.000E+00</td>
<td>2.997E+00</td>
<td>1.46</td>
</tr>
<tr>
<td>1.000E+00</td>
<td>0.000E+00</td>
<td>2.848E+00</td>
<td>1.66</td>
</tr>
</tbody>
</table>

YIELD FROM INC

P: 1.635E+01, %ERR: 1.57
N: 8.646E-01, %ERR: 1.89

YIELD FROM EVAF

H FROM INC: 4.284E+01, %ERR: 1.30
N FROM EVAF: 1.067E-02, %ERR: 1.55

---

![Yield Chart](image)

- **Yield**: 1 [unit lethargy]
- **Energy**: 0 - 100
- **Neutron**

---

- **P**: 2.500E+01, %ERR: 1.51
- **N**: 1.495E+02, %ERR: 1.42
- **P+**: 1.078E+00, %ERR: 5.84
- **P10**: 1.635E+00, %ERR: 3.55
- **P1-**: 2.440E+00, %ERR: 3.69
- **MUE+**: 5.279E+03, %ERR: 71.00
- **MUE-**: 2.213E+02, %ERR: 23.67
**Figure 39:** Two of the source distributions which are produced by
the HET-code for 5 GeV/c $e^-$ incident on the T35 setup.
They are transformed by succeeding EGS (a) and MORSE (b)
H.C. calculations. The normalized sampling fractions

Table 6.15.2 Contributions to visible energy for T35 with $E_a = 5$ GeV $e^-$ or $e^+$ incident without veto detector

<table>
<thead>
<tr>
<th>energy component</th>
<th>energy deposition [MeV]</th>
<th>fract. shower component $\phi_j$</th>
<th>visible energy [MeV]</th>
<th>norm. sampl. fraction (input:7.6%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(proton, $e^+$, $\mu^+$ recall p from $E_a&gt;15$ MeV) ion</td>
<td>1542.5</td>
<td>31.3%</td>
<td>122.5$^1$</td>
<td>$\phi_e = 0.02$</td>
</tr>
<tr>
<td>$e^+$</td>
<td>444.4$^1$</td>
<td>17%</td>
<td>42.5</td>
<td>$\phi_e = 0.67$</td>
</tr>
<tr>
<td>$h_1$ = $f_{\mu^+} \cdot \mathrm{ion} + f_{e^+} \cdot \phi_{e^+}$</td>
<td></td>
<td></td>
<td></td>
<td>$\phi_{h_1} = 0.43$</td>
</tr>
<tr>
<td>recall p from $E_a&lt;15$ MeV</td>
<td>444.8$^1$</td>
<td>9%</td>
<td>42.5$^1$</td>
<td>$\phi_{p} = 1.27$</td>
</tr>
<tr>
<td>nucl-$\gamma$ (from capt., high energy + fast fission and de-excit.) $\gamma$</td>
<td>657.3$^1$</td>
<td>14.5%</td>
<td>21.0</td>
<td>$\phi_{\gamma} = 0.30^1$</td>
</tr>
<tr>
<td>$e$</td>
<td>458.0</td>
<td>99.6%</td>
<td>250.</td>
<td></td>
</tr>
</tbody>
</table>

1) Brink value of $\phi = 0.85 \times 10^{-3} \mathrm{g/MeV} \cdot \mathrm{cm}^2$
was used to determine the visible energy from proton
recolls
a) fractional shower component $\phi_j$: energy deposition for component $j$ in % of $E_a$
b) $\phi_{\gamma}$ was calculated with the photon option in HERMES, using the EGS code
c) source energy

**Important:**
About 30-50% of visible energy comes from neutrons.
Fit moments:
From 1.153E+02
To 2.691E+02
μ 1.940E+02
σ/μ 16.28% ~ 3.58°
N-fit 1900

Empirical Moments:
μ 1.922E+02
σ 3.843E+01
σ/μ 19.99%
Skewness 4.392E+01
Excess 1.839E+00
Min. 0.000E+00
Max. 3.482E+02
Counts 2000.
0-Counts 1.
Lost 0.

Grouped Moments:
μ 1.923E+02
σ 3.817E+01
σ/μ 19.85%
Median 1.940E+02
Mode 2.060E+02
6.

P. Dragovitsch

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IRE

Calculational models for the determination of double differential cross sections of \((p,xn)\) and \((n,xn)\) reactions
Calculational Models for the Determination of Double Differential Cross Sections of $(p,xn)$ and $(n,xn)$ Reactions

P. Dragovitsch, IRE-KFA

- HETC/KFA-2 of HERMES Code System
- The INC-E Model of HETC
- Computational Procedures
- Statistical Problems
- Calculational Results and Comparison with Experimental Data
- Conclusions and Outlook
CALCULATIONAL METHOD

General Code: HETC (High Energy Radiation Transport Code)
Version: HETC/KFA-2
Setup: Thin-Target

Nuclear Collision
Models Used:
* internuclear cascade
* evaporation

Atomic Collision
Models: not used

Transport Algorithms: not used

Geometry Modules: not used

Nuclear Data Files:
- differential particle–particle cross sections (n–p, p–p, etc.).
- nuclear masses

Target Configuration: bare nucleus, Z, A.

Source Description: proton source,
- monoenergetic,
- equal distributed over the nuclear geometric cross section,
- no angular distribution.

Analysis: Yield–detectors for predefined energy– and angle–bins

Output: Neutron yields per incident proton inside every angle/energy–bin
5. **CROSS SECTIONS NEEDED**:
   - \( N - N \) \( \{ (p,p), (p,n), \ldots \text{ etc.} \} \)
   - \( \pi - N \) \( \{ \pi^- p, \ldots \text{ etc.} \} \)
   - \( \pi \) absorpt. with "cluster"

6. **EXCLUSION PRINCIPLE**:
   - reject outcome if state is filled

7. **OUTCOME OF INC**:
   - \( E, \pi \) of emitted particles: \( \nu, p, \pi^+, \pi^0, \pi^- \)
   - residual \( E^* \)
   - \( A', \zeta' \) of residual nuclei \( \) Input for EVAP

8. **EVAPORATION** (Weisskopf Theory)

Assumptions:
- Complete energy equilibration before first emission
- Reequilibration of excitation energies between successive evaporations
- Maxwelian energy distribution of emitted particle
- Isotropic angular distribution in Center of Mass

\[ \frac{dN}{d\Omega} (p,xn) \text{ for Al} \]
\[ E_p = 800 \text{ MeV} \]
\[ \Theta_n = 7.5^\circ \]

I. Evaporation
II. Transition
III. Intranuclear cascade
IV. Small angle structure
V. Quasi elastic peak

---

**Graph**

- **MICROBARN/MEV**
- **ENERGY (MEV)**
- **EVP**
- **INC**
- **range of pre-equilibrium emission**
Target: P3-208  projectile: p  energy: 318 MEV

Cross section [b/unit lethargy/sr]

Energy [MeV]

- Experimental
- HET/C (low statistic) 30000 source
- HET/C (high statistic) 240000

Statistical of the computational procedures of cross section calculations with HET/C/KFA-2
Target: PB-208  projectile: p  energy: 800 MEV

angle: 7.5 degree
- experimental
- HETC (high statistic)

Target: PB-208  projectile: p  energy: 318 MEV

angle: 7.5 degree
- experimental
- HETC (high statistic)
Double Differential (p,xn) – Cross Sections
   Present Status

a) HET-Calculations

Al-27:  50, 80, 100, 160, 200, 250, 318 and 800 MeV
Zr-90:  80, 160, 318 and 800 MeV
Pb-208: 80, 160, 318 and 800 MeV

b) Experimental Results: (evaluated)

Be-9:  318 MeV; 7.5 and 30 deg.
C: 318 and 800 MeV; 7.5 and 30 deg.
Al-27: 318 and 800 MeV; 7.5 and 30 deg.
Ni: 318 MeV; 7.5 and 30 deg.
Ta: 318 MeV; 7.5 and 30 deg.
W: 318 MeV; 7.5 and 30 deg.
Pb: 318 and 800 MeV; 7.5 and 30 deg.
U: 318 and 800 MeV; 7.5 and 30 deg.

c) Finished measurements:
Be, BeO, B, BN, C, Al, Fe, Zr, U-238
at 7.5°, 30°, 60°, 150°
for 173, 256 and 800 MeV incident p-energy

d) Planned measurements (1988):
    at 7.5°, 30°, 60°, 120°, 150° for 600 MeV
    at 0° for 600 and 800 MeV

Conclusions:

* For the first time statistical reliable Monte Carlo
calculations of double differential cross sections
for p-induced n-emission have been performed

* This was done for a wide range of target nuclides
  and proton-energies

* The results are in good and often in excellent
  agreement with experimental data

* Discrepancies can only be observed in ranges of
  pre-equilibrium emission

* A large data base is given for

  → comparison with future experimental results

  → comparison with other nuclear models
  (Intension: Find a sufficient pre-equilibrium
  model which can be included in HETC)
7.

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Institut für Experimentalphysik

A detector for high-energy neutrons
PROPOSAL FOR THE CONSTRUCTION OF A LARGE NEUTRON DETECTOR AT SIS

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TH. W. Elze, H. Klinger, H. Spies, K. Stelzer
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R. Kulessa
Jagiellonian University Krakow, Poland

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T. Matulewicz
Warsaw University Poland

\( E(NE^{124}) = \text{10%/cm} \) for \( E = 200-500 \text{ MeV} \)

general problem in neutron spectroscopy and small solenoidal angle, higher \( \eta \) and \( \phi \).

inclusive experiments

exclusive experiments

\( T_i, \Theta, \Phi, \Delta \Theta, \Delta \Phi \)

\( \Theta, \Phi, \Delta \Theta, \Delta \Phi \) measured to be
Requirements to be met by a neutron detection system

1. High efficiency, close to 100% within the solid angle covered

2. Sufficient granularity for reliable determination of multiplicities and correlations (possibility of tracking)

3. High momentum and energy resolution in the whole SiS energy range

4. Coverage of a large angular range with very good angular resolution

5. Modularity in order to facilitate the adaptation of the detection system to various experimental situations

Suggested solution:
Combine time of flight and the idea of calorimetry
ENERGY RESOLUTION
\[
\leq 2\% \text{ at } 1 \text{ GeV}
\]
if \(\Delta t \approx 180 \text{ ps}\)

PROTOTYPE MODULE TESTED AT
SATURNE \(T_n = 200, 500, 850 \text{ MeV}\)

AHM : DETECTION EFFICIENCIES, \(\beta\) CONVERTER
SHOWER PARAMETER
COMPARISON WITH SIMULATION

Fig. 7: Schematic view of the proposed set-up.
BC: Beam defining counters
VC: 1 cm thick plastic veto counters (about 50 elements)
TC1,TC2: \(\text{BaF}_2\) (and/or NaI) target detector (about 160 elements, 20 thick)
Ge: HPGe detectors
DP: superconducting dipole magnet as proposed in ref. 4.
Focussing quadrupole magnets might be inserted for particular applications (see text).
3D-MUSIC: Multiple Sampling Ionisation Chamber
C: Total reflection Cerenkov Counter
NO: \(\beta\) Neutron detector; \(\text{P(Fe)}\) denotes layers of plastic scintillators (iron converter)
A typical beam trajectory is indicated; the vacuum chamber covering the trajectories of the projectile-like fragments is not shown.

from: Proposal to the SIS TAC
A. Eichten et al.
Position Resolution (from raw data $T_L$ vs. $T_R$)
50-70 mm

After correcting for time jitter
Improvement by 30-50% expected
$T_n = 850 \text{ MeV}$
\[ \overline{\alpha} = \frac{1}{N} \sum_{i=1}^{N} \alpha_i \]

**N:** NUMBER OF CONSECUTIVE PADDLES WHICH FIRED AFTER HIT IN ANY PADDLE

N > 2 REQUIRED

---

**Plot:**

- **Distribution functions** for the mean shower direction angle \( \overline{\alpha} \) for 200 MeV incident neutrons incident on the Fe-NE 102 sandwich (●) and the NE 102 plastic detector (○).

- **Axes:**
  - Y-axis: \( N(\alpha) \) (arbitrary units)
  - X-axis: Mean angle \( \overline{\alpha} \) (°)

- Labels:
  - **E_\text{n} = 200 \text{ MeV}**

---

**Diagram:***

- **FIBERS**
- **GROOVED Pb SHEETS**
8.

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IRE

Remarks on possible time (energy) errors in previous time-of-flight measurements with high-energy neutrons
Remarks on possible time (energy) errors in previous time-of-flight measurements with high-energy neutrons

1. Detector efficiency
   (not included, but has to be discussed!)

2. "Methodical" time uncertainties

3. "Experimental" time errors
   (detector, electronic circuit)
Example:
Proton pulse length: 0.2 μsec
Neutron energies: see below

<table>
<thead>
<tr>
<th></th>
<th>Flight Path</th>
<th>[m]</th>
<th>T</th>
<th>[MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.2</td>
<td>&quot;</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>0</td>
<td>0.2</td>
<td>&quot;</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>0</td>
<td>0.2</td>
<td>&quot;</td>
<td>500</td>
<td>1000</td>
</tr>
<tr>
<td>0</td>
<td>0.2</td>
<td>&quot;</td>
<td>1000</td>
<td>1000</td>
</tr>
</tbody>
</table>

\[
T = \frac{E - m_0 c^2}{-m_0 \left(1 - \frac{v^2}{c^2}\right)^{-\frac{1}{2}} - 1} \\
\Rightarrow \frac{dT}{dt} = \frac{k}{k-1} \frac{dt}{t} \\
\text{assump.: } k = \left(1 - \frac{v^2}{c^2}\right)^{\frac{1}{2}}\text{ and } \frac{dc}{dt} = 0
\]

Energy resolution is dependent of:

a. time uncertainties
b. flight path, i.e. flight path
"Experimental" time errors:

- detectors
- electronic modules
  - dynamic range
  - time walk

Two different approaches:

Cierjades: problems with first CFD due to dynamic range of ~1000:1

Howe: problems with beam pick-up stability
Simplified circuit diagram of the electronics used in the time-of-flight experiments

<table>
<thead>
<tr>
<th>( \Delta T / T ) [%]</th>
<th>16</th>
<th>39</th>
<th>1</th>
<th>2.2</th>
<th>4.4</th>
<th>3</th>
<th>8</th>
<th>16.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta t ) [usec]</td>
<td>0.2</td>
<td>0.5</td>
<td>1.0</td>
<td>0.2</td>
<td>0.5</td>
<td>1.0</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Flight Path [m]</td>
<td>7.3</td>
<td>30</td>
<td>30</td>
<td>1500</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness [mm]</td>
<td>585</td>
<td>800</td>
<td>2500</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Only due to proton pulse width.

Note: Quadrature sum of total time uncertainty (min).

S. Howe, Ph.D. Thesis, Kansas State University, 1980
Importance of high-energy neutrons produced by cosmic radiation in extraterrestrial matter
Importance of high-energy neutrons produced by cosmic radiation in extraterrestrial media

- cosmic rays and cosmogenic nuclides
- thick target modelling
- transcription to space conditions

- needs for experiments with fast neutrons
- measurement of spectra \( f(\text{Chemistry}) \)
- measurement of multiplicities
- activation experiments

SOLAR PROTONS AT 1 A.U.
\( J_o(4\pi, E > 10 \text{ MeV}) = 70 - 140 \text{ cm}^{-2}\text{s}^{-1} \)
\( R_0 = 100 - 150 \text{ MV} \)

GALACTIC PROTONS
a) LOCAL INTERSTELLAR SPECTRUM
b) 1965 (SOLAR MINIMUM) AT 1 A.U.
c) 1969 (SOLAR MAXIMUM) AT 1 A.U.
### Cosmogenic Nuclides in Meteorites

<table>
<thead>
<tr>
<th>Element</th>
<th>Stabilized Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe</td>
<td>STABIL</td>
</tr>
<tr>
<td>Kr</td>
<td>STABIL</td>
</tr>
<tr>
<td>Ar</td>
<td>STABIL</td>
</tr>
<tr>
<td>Ne</td>
<td>STABIL</td>
</tr>
<tr>
<td>He</td>
<td>STABIL</td>
</tr>
<tr>
<td>Te, Ba, La, Ce</td>
<td></td>
</tr>
<tr>
<td>Rb, Sr, Zr</td>
<td></td>
</tr>
<tr>
<td>Fe, Ca, K</td>
<td></td>
</tr>
<tr>
<td>Mg, Al, Si, Fe</td>
<td></td>
</tr>
<tr>
<td>O, Mg, Si, Fe</td>
<td></td>
</tr>
</tbody>
</table>

- **129I**: 1.3 Ga
- **53Mn**: 3.8 Ma
- **10Be**: 1.6 Ma
- **26Al**: 720 ka
- **36Cl**: 300 ka
- **81Kr**: 210 ka
- **41Ca**: 100 ka
- **59Ni**: 76 ka
- **14C**: 5.73 ka
- **39Ar**: 269 a
- **32S**: 101 a
- **44Ti**: 47.3 a
- **3He**: 12.3 a
- **60Co**: 5.26 a
- **22Na**: 2.6 a

---

**Cosmogenic Nuclides in Meteorites**

---

**Kirk, 1977**
PRODUCTION OF COSMOGENIC NUCLIDES

IN EXTRA TERRRESTRIAL MATTER

2 different approaches for the interpretation of observed nuclide abundances:

a) THICK TARGET APPROACH

Simulation of the cosmic ray bombardment as close as possible in lab. experiments.

Measurement of the production rate depth profiles.

b) THIN TARGET APPROACH

\[ P(\vec{d}, R) = P_{\text{sec}}(\vec{d}, R) + P_{\text{GCR, prim}}(\vec{d}, R) + P_{\text{GCR, sec}}(\vec{d}, R) \]

\[ P_x(\vec{d}, R) = \sum_i N_i \int_0^{\Phi_R} (E) \cdot \Phi_x(\vec{d}, R, E) \, dE \]

\( d \) depth
\( R \) radius
\( N \) density of target atoms
\( i \) target element
\( x \) \( \text{GCR, prim} \), \( \text{GCR, sec} \).
DEPTH DEPENDENT PRODUCTION OF COSMOGENIC NUCLIDES IN METEORITES BY GALACTIC PROTONS

"1967"
MOVEMENTS OF THE TARGET:
1. VERTICAL, 50 cm, 3.3 cm/min
2. HORIZONTAL, 48 cm, 11.0 cm/min
3. ROTATION, $2\pi$, 2 rpm
4. ROTATION, $2\pi$, 5 rpm

A Fe-TUBE, INNER DIAMETER 1.9 cm, CONTAINING 9 SAMPLE STACKS

LENGTH OF ARRANGEMENT 126 cm

CERN SC-96
7 irradiations

$R = 5, 15, 25$ cm
$\rho = 3.0$ g cm$^{-3}$

SIMULATION OF AN ISOTROPIC IRRADIATION OF SPHERICAL TARGETS BY COMPLEX MOVEMENTS ($V_x, V_y, \Omega_1, \Omega_2$)
\[ P_{ij}(R, d, E_{\text{prim}}) = \frac{N}{A_i} \sum_{k} \int \sigma_{ijk}(E_k) \cdot J_k(R, d, E_k, E_{\text{prim}}) \, dE_k \]

- Unification of thick target and thin target approach ($E_{\text{prim}} = 600$ MeV, 800, 1200)
- Validation of thin target calculations at different energies
- Calculation of $J_k(R, d, E_k, E_{\text{CER}})$
- Mekoroid model

**MCOE CAR CALCULATIONS OF NUCLEON SPECTRA**

- Size depend.
- Depth depend.
- Chemistry dep.
- LETC, SIMPLE, MORIE

- $E_p \geq 14$ MeV
- $E_n \geq 2.1$ MeV

**THICK TARGET EXPERIMENTS**

- *4* isotropic irradiation
- all cosmogenic nuclides
- all monitor nuclides
- different $p$-energies $600$ MeV, $800$...
- target chemistry

**THIN TARGET CROSS SECTIONS**

- measured
- calculated
- evaluahed
- target element
- product nuclea
- particle type $p, n, \ldots$

**MONTE CARLO EXPERIMENTS**

- $r$ (cm)
- target chemistry

\[ 134 \]
Monte Carlo Modelling and Comparison with Experiment of the Nuclide Production in Thick Stony Targets Isotropically Irradiated with 600 MeV Protons

by


SPECTRUM OF PRI. + SEC. PROTONS IN A STONY SPHERE WITH R=25 CM RADIUS
SECONDARY NEUTRONS
REGION 0.0 - 6.0 CM

A priori calculations of integral cross sections
- Equilibrium- and pre-equilibrium models

equilibrium:
Weisskopf & Ewing, Phys. Rev. 59 (1940) 472

pre-equilibrium:
hybrid model
Alam, Phys. Rev. Lett. 27 (1971) 337
geometry dependent hybrid model
Alam, Phys. Rev. Lett. 28 (1972) 757

Codes:
OVERLAID ALICE UR-NSRL-181 (1973)
ALICE LIVERMORE 82 UCID-19614 (1982)

Rudstam E. Naturskold, 21a (1966) 1027
Silberberg & Taqman, Astrophys. J. Suppl.
25 (1973) 315-335

parameters according to:
Rudstam & Sandberg, Comp. Phys. Com. 23 (1981) 411
- INC mode (HETC)

PRODUCTION RATE OF $^{59}$Fe FROM Co. I A STONY SPHERE WITH RADIUS = 25 cm

$^{59}$Co $(n, p) ^{59}$Fe

$^{56}$Co $(p, xn) ^{56}$Co
PRODUCTION RATES OF $^{21}\text{Ne}$ FROM Mg IN A STONY SPHERE WITH RADIUS -25 cm

![Graph showing production rates of $^{21}\text{Ne}$ from Mg in a stony sphere. The graph includes experimental data and calculated results for total, primary proton (pri. p), secondary proton (sec. p), and secondary neutron (sec. n) production rates.](image)

PRODUCTION RATE OF $^{58}\text{Co}$ FROM Ni I A STONY SPHERE WITH RADIUS -15 cm

![Graph showing production rates of $^{58}\text{Co}$ from Ni. The graph includes experimental data and calculated results for total, primary proton (pri. p), secondary proton (sec. p), and secondary neutron (sec. n) production rates.](image)

$\text{Ni} \ (p, p' n) \ ^{58}\text{Co}$

$\ ^{58}\text{Ni} \ (n, p) \ ^{58}\text{Co}$
PRODUCTION RATES OF $^{26}$Al FROM Si IN A STONY SPHERE WITH RADIUS -15 cm

Experimental: Δ  
Calculated: --- total  
prl. p  
sec. p  
sec. h

P [10^{-4} g^{-1} s^{-1}] (cm^{-2})

Position (cm)

-15  -10  -5  0  5  10  15

PRODUCTION RATES OF $^7$Be FROM Fe I. A STONY SPHERE WITH RADIUS -25 cm

Experimental: Δ  
Calculated: --- total  
prl. p  
sec. p  
sec. h

P [10^{-4} g^{-1} s^{-1}] (cm^{-2})

Position (cm)

-20  -10  0  10  20
Fig. X.1 Neutron yields obtained from the bombardment of thick Be, Sn, Pb and depleted U by intermediate energy protons. Targets of Sn, Pb and U were cylinders, the first dimension shown being the diameter and the second the length; the Be target was rectangular.

\[ A < 1.10: \quad \gamma = 10^{-4} (A + 10) \left( E_{(n,\gamma)} - 120 \right) \]

Production rates of $^{21}$Ne from Jilin in a Stony Sphere with radius 25 cm.

Experimental: ▲ Calculated: Total

\[ P \left[ 10^{10} \text{ B}^2 \text{s}^{-1} \text{ cm}^{-2} \right] = \]

\[ 0.04 \quad 10^{-3} \quad \text{cc} \text{ cm}^{-2} \]

Position (cm)
$\Phi_{\text{prim}, p}(E > 10\text{MeV}) [\text{cm}^{-2}\text{s}^{-1}]$

- $c$ center
- $s$ surface
- $\rho = 3.0\text{gcm}$
- $\overline{A} = 21$

$\Phi_{\text{sec}, p}(E_p > 10\text{MeV}) [\text{cm}^{-2}\text{s}^{-1}]$

- $c$ center
- $s$ surface
- $\rho = 3.0\text{gcm}$
- $\overline{A} = 21$

$\phi_{f, \text{prim}} = 1 \text{ cm}^{-2}\text{s}^{-1}$
**Galactic data**

**CENTER OF H-CHANDRILES**

![Graph](image)

- **$R \ [\text{cm}]$**
- **$J_0 \ [\text{cm}^{-2} \cdot \text{s}^{-1}]$**

- **$E_0 > 3 \text{ GeV}$**
- **$E_0 > 10 \text{ GeV}$**
- **$E_0 > 30 \text{ GeV}$**

- **$S = 0.6 \ (\text{erg} \cdot \text{cm}^{-2} \cdot \text{s}^{-1})$**

- **$J \cdot R \ P$-spectrum**

- **$600 \text{ MeV protons}$**

- **$\bar{A} = 2A$**

- **C center**
- **S surface**

- **$\phi_{\text{prim}} = 1 \text{ cm}^{-2} \cdot \text{s}^{-1}$**

- **$E > 10 \text{ MeV}$**

**Sec'n (E > 10 MeV) $J_0 \ [\text{cm}^{-2} \cdot \text{s}^{-1}]$**
10.

W. Scobel

Universität Hamburg

1. Institut für Experimentalphysik

TOF spectroscopy of neutrons from (p,n) reactions with $E_p \leq 160$ MeV
Continuous Neutron Energy Spectra from $(p, xn)$ Reactions, $E_p \leq 160$ MeV

I. Why $(p, xn)$

- Development of reaction in time, dissipation of energy (precompound vs. compound; precession vs. rotation)
- Simple entrance channel \(1p1n\) in \(^{238}U\), no breakup or cluster phenomena complicating interpretation
- Exit channel + entrance channel

i.e. Physics motivation:

- Effective Nucleon-Nucleon Interaction:
  - a) Single step processes: quasielastic, $\Theta < 20^\circ$
  - b) Multiple step processes: inelasticity, $\Theta > 90^\circ$

- Reaction models based on intranuclear nucleon-nucleon collisions, e.g.
  - i) Extremization to high $E_p$ proton degrees
  - ii) Design of hadronic calorimeters
  - iii) Extension to $HI$ reactions: BME model etc.

Here: Consistent extension $E_p = 20$ MeV $\to$ 200 MeV:

- Experimental neutron TOF - techniques
- Multi step reaction models

---

Experimental Measurements (NIM ASSY (1985) 123)

- Collimator
- Shielding (water)
- Detectors $Di-DK$ (NE213)
- Cyclotron Beam $E_p = 26-30$ MeV $\Delta E = 1.0$ nsec

\( \Theta_{lab} = 3^\circ \)
\( \Theta_{lab} = 177^\circ \)

Time of Flight Spectra:

- $\Theta = 3^\circ$
- $\Theta = 177^\circ$

TIME OF FLIGHT SPECTRA:

1. Target
2. Shadow Bar
EXPERIMENTAL SET UP:

- SAME RATES
- CLEAN BACKGROUND CONDITIONS

**IMPROVED ENERGY RESOLUTION**

\( \Delta E_n = 30 \text{ keV} \) for \( E_n = 5 \text{ MeV} \)
\( 250 \text{ keV} \) for \( E_n = 20 \text{ MeV} \)

PARTIALLY COATED LIGHT PIPE:

Polished light pipe causes \( \frac{I(I) - I(0)}{I(0)} \leq 40\% \)

SAMPLE TOF DATA

- \( \theta_{lab} = 3.9^\circ \)
- \( E_n = 25.5 \text{ MeV} \)
- \( \Gamma : \text{EFFECT} \)
- \( \Gamma : \text{SHADOW BAR} \)

LONG TERM STABILITY

REF: STABILIZED LIGHT SOURCE
INDIVIDUAL PULSE-HEIGHT CALIBRATION OF DETECTORS

\[ E_0 \times F \times i \times \text{PULSEHEIGHT} \]

\[ N \times \text{PE} = 2 \]

DETECTOR #2

\[ \text{COUNTS} \]

\[ \text{COMPTON SCATTERING: SINGLES} \]

\[ \text{COMPTON BACKSCATTERING:} \theta \geq 173^\circ \]

\[ \frac{d^2\sigma}{d\Omega dE} = \sum_{n} \frac{d^2\sigma}{d\Omega dE}_{\text{SMDE}} + \sum_{n} \frac{d^2\sigma}{d\Omega dE}_{\text{SHCE}} + f \text{ stage cont.:} \]

STATISTICAL TREATMENT OF MULTISTEP PROCESSES

\[ \begin{align*}
  P_0 & = P_1 \rightarrow P_2 \rightarrow P_3 \rightarrow P_4 \\
  Q_0 & = Q_1 \rightarrow Q_2 \rightarrow Q_3 \rightarrow Q_4 \\
  \text{SHDE} & \Rightarrow \text{r STAGE} \\
  \text{SHCE} & 
\end{align*} \]

\[ \text{STAGE OF COMPLEXITY n : 1} \quad 2 \quad 3 \]

\[ \rightarrow \text{EVOLUTION IN TIME} \]

\[ \text{SMDE} : \text{Chaining of particle unbound states} \]

\[ \text{SHCE} : \text{Particle bound states are chained} \]

ASSUMPTIONS:

1. CHAINING HYPOTHESIS: Only \[ n \rightarrow n+1 \]
   due to residual interaction
   Implies weak coupling such that \[ P \rightarrow Q \]

2. RANDOM PHASE APPROXIMATION for
   \[ \text{SHCE} : \text{Random relative phases for matrix elements} \]
   \[ \text{Involving different channel quantum numbers} \]
   \[ \Rightarrow \text{SYMMETRY AROUND} \quad \theta_{\text{cm}} = 90^\circ \]
   \[ \text{SHDE} : \text{Constructive interference of matrix elements} \]
   \[ \text{with same momentum change of unbound particle} \]
   \[ \Rightarrow \text{FORWARD PEAKING} \]

3. SELF AVERAGING: \[ T_{n+1} > D_n \]

\[ \text{From the r-th stage on: equal probability for all configurations} \]

\[ \text{not yet below cut off of} \quad \text{CN} = \]
**FKK Model**

- CHAINING HYPOTHESES
- PHASE STATISTICS

\[
\frac{d^2\sigma}{d\Omega_d dE_n} = \frac{d^2\sigma}{d\Omega_d dE_n} \text{SHOE} + \frac{d^2\sigma}{d\Omega_d dE_n} \text{SHCE}
\]

**SHOE** CHAINING PARTICLE UNBOUND STATES
FORWARD PEAKING ANGULAR DISTRIBUTIONS

**SHCE** PARTICLE BOUND STATES
PHASE STATICS \(\approx\) SYMMETRIC AROUND 90°

**CONSISTENT CALCULATION:**
- Yukawa Residual Interaction
- Finite Range \(\approx 1.5\) fm
- \(V_0 \approx 2.6 \pm 1.1\) MeV
- DUSA MATRIX ELEMENTS

**CHANGING**

**Angular Distributions**

\(^{100}\text{Mo}(p,xn)\):
\((E_p = 25.6\text{ MeV})\)

- \(E_n = 9.5\) MeV
- \(16.5\) MeV
- \(17.0\) MeV
- \(21.5\) MeV

For \(E_n < 10\) MeV: SHSC dominates
For \([E_n > 18\) MeV], \([u < 6\) MeV]: 1st step SHSD dominates

\(E_p > 25\) MeV: CONSISTENT VALIDITY OF FKK MODEL PERSISTING?
The page contains a diagram and text related to neutron detection and pulse shape information.

**IJCF NEUTRON TOF FACILITY:**

- **\( E_p \leq 200 \text{ keV} \)**

- **Beam Swinger BS**

**Detector Geometry**

- **\( E_p = 80 \text{ keV} \):**
  - TOF (\( E_p = 80 \text{ keV} \)):
    - 16 m
    - 38 m
    - 26 m
    - 15 m
    - 11 m
  - TOF (\( E_p = 120 \text{ keV} \)):
    - 61 m
    - 48 m
    - 35 m
    - 23 m
    - 18 m

- **Swinger:**
  - 0°
  - 10°
  - 24°

**Pulse Shape Information:**

1. TOF
2. Pulse Height
3. PSD: Zero crossing of integrated anode signal

**Detector:**

- **8" x 12"**
- **\( E_p = 80.5 \text{ keV} \)**
- **\( E_{He} = 12 \text{ keV} \) (software)**
COSMIC - VETO SHIELD: SUPPRESSION OF UNCORRELATED BACKGROUND:

DETECTOR #3: 45°
HIT COSMIC VETO

TOF

PULSES = SIGNAL

DETECTOR #2: 24°
NO COSMIC VETO

TOF

PULSES = SIGNAL

90°(p, xn) \ E_p = 80.5 MeV

\[ \theta = 0° \]
TOF = 47 ns
TARGET

\[ \theta = 45° \]
TOF = 26 ns
TARGET

\[ \theta = 12° \]
TOF = 19 ns
TARGET

DETTECTOR CROSSE: 12" x 8"
SCHATTENSTAB: 6" x 150 cm, WASSERGEL"T
ZEITAUFLÖSUNG: \( \Delta t \) = 2 ns
ENERGIEAUFLÖSUNG: \( \Delta E \) = 700 keV BEI \( E_p = 70 \) MeV (EAR)

TARGET: \( ~70 \) mg (cm² \( \Delta E = 400 \) keV)
$^{208}\text{Pb}(p,xn)$

$E_p = 160.3$ MeV

Flight Path: 48 m

$\Theta_{lab} = 24^\circ$

TARGET RUN
\[ q_0^{2\gamma}(p,xn) \quad E_x = 120 \text{ MeV} \quad \theta = 0^\circ \]

**Differential Cross Section**

**Polarization Transfer Cross Section**

T. Todducci et al.

\[ q_0^{2\gamma}(p,xn) \quad E_x = 160 \text{ MeV} \quad \theta = 0^\circ \]

**Excitation Energy**

TARGET: 212 mg/cm²
TFD: 45 cm
n-DET: 15 × 15 × 100 cm KER 102 (6×)

**Angular Distributions**

\[ \frac{d^2\sigma}{dE_n d\Omega} \ (\text{mb/MeV sr}) \]

**Angular Distributions**

\[ \frac{d^2\sigma}{dE_n d\Omega} \ (\text{mb/MeV sr}) \]

**Angular Distributions**

\[ \frac{d^2\sigma}{dE_n d\Omega} \ (\text{mb/MeV sr}) \]
**Effective Nucleon-Nucleon Interaction**

- Effective NN strength $V_0(E_p)$
- IAR
- GT - Resonance
**SUMMARY**

**PRECOMPOUND EMISSION IN (p,xn) REACTIONS**

Below pion threshold

- **SEMICLASSICAL MODELS**
  Qualitatively correct for 90% of the yield
  At variance for multistep contributions (θ > 90°)

- **QUANTUM STATISTICAL MODELS**
  Principally capable of describing multistep process
  Correct scaling of effective nucleon-nucleon interaction with projectile energy
  => Extrapolation to higher energies feasible
  Inclusion of pionic degrees of freedom?

- **EXPERIMENTAL (LOW ENERGY) TECHNIQUES:**
  - Size of liquid scintillator based detectors
  - ηγ discrimination
  - Background treatment important
  - Efficiency calculations (CECIL code) reliable on a 20% level
  - Time resolution at ≤ 2 ns feasible
  - Implementation into a Cooler Ring experiment e.g. \( \eta - \gamma \) BREMSSTRAHLUNG

**NOTES:**

Due to insufficient treatment of nucleon-nucleon interaction?

(Sequential decay, \( NNN \rightarrow N^* \rightarrow \))
SPECULATION:

**Neutron-Proton-Bremsstrahlung**

\[ E_p = 500 \text{ keV} \]

\[
L = 10^{20} \text{ cm}^2 \text{s}^{-1}
\]

\[
\sigma = 20 \mu \text{b} \implies \nu_c = L \cdot \sigma = 30 \text{ s}^{-1}
\]

\[
\frac{d^2\sigma}{d\Omega dE_p} \approx 50 \mu \text{b cm}^2 \text{ steradian}^{-2} \implies \nu_c = 0.15 \text{ s}^{-1}
\]

\[ \sigma_{\nu} = 6 \cdot 10^{-3} \text{ sr} \]

\[ \sigma_p = 0.18 \text{ sr} \]

\[ p + d \rightarrow p + p + n + \gamma \text{ Beams} \]

- Low background experiment
- Neutron "tagged" by \( p \)

- \( D \approx 3-4 \text{ m} \) \( \implies \) \( n-\gamma \) and \( p-\gamma \) discrimination by TOF for \( E_n \leq 500 \text{ keV} \), i.e. \( \gamma \leq 0.75 \)

- \( p-n \) discrimination: veto paddles
- \( p-d \) discrimination: energy loss in veto paddle
11.

H. Machner

Kernforschungsanlage Jülich

IKP

Energy spectra of secondary particles
produced by high-energy protons
SCOPE:
- Introduction
- Energies 40 MeV to 400 MeV
  - structure effects
  - neutron – proton effects
- Energies 400 MeV to 1 GeV
  - neutron – proton effects
  - reaction mechanisms
- Energies 1 GeV to +00 GeV

Continuous Energy Spectra of Secondary Particles from Nuclear Reactions above 40 MeV

H. Machner
Institut für Kernphysik
KFA Jülich
Postfach 1913
D5170 Jülich
$^{Cu}(\alpha, p)^X$

$E_\alpha = 54.8$ MeV

Demeyer, Chevarier, et al.
Fig. 3. Comparisons of the laboratory proton spectra resulting from 6 MeV protons on $^{54}$Fe, 90 and 198 MeV proton on $^{50}$Ni at various angles.
The energy spectra of particles emitted from energetic nuclear reactions show up a large continuous region.

The spectral shapes depend on the incident and final channels. The less nucleons are transferred, the "harder" is the spectrum and vice versa.

In energetic collisions the spectra show bumps around the beam velocity even in tightly bound projectile particles.

At high bombarding energies a large spike is visible in the inelastic channel at forward angles.
$^{58}\text{Ni}(p,X)$ $E_p = 100\,$MeV

$d^2\sigma/d\epsilon d\Omega$ (mb/MeV sr)

$\epsilon$ (MeV)

$P$

$d \times 10$ shifted by $10\,$MeV

$t \times 100$ shifted by $14\,$MeV

Wu et al. P.R.C. 15, 615 (1977)

$^{197}\text{Au}(p,X)$ $E_p = 200\,$MeV

$d^2\sigma/d\epsilon d\Omega$ (mb/MeV sr)

$\epsilon$ (MeV)

$P$

$d \times 10$ shifted by $1\,$MeV

$t \times 100$ shifted by $6\,$MeV

Julich-Orsay-Collab.
### ISOTOPIC YIELDS

#### $^{27}$Al

<table>
<thead>
<tr>
<th>$E_p$ (MeV)</th>
<th>$G_P$ : $G_{d}$ : $G_{t}$ : $G_{x}$ : $G_{d}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>61</td>
<td>77 : 9.7 : 1 : 1.2 : 18</td>
</tr>
<tr>
<td>80</td>
<td>77 : 11 : 1 : 1 : 3.5</td>
</tr>
<tr>
<td>200</td>
<td>100 : 10 : 1 : 0.2 : 0.2</td>
</tr>
<tr>
<td>800</td>
<td>104 : 14 : 1 : 0.4 : *</td>
</tr>
<tr>
<td>2100</td>
<td>100 : 12 : 1 : 0.4 : *</td>
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</tbody>
</table>

#### $^{208}$Pb

<table>
<thead>
<tr>
<th>$E_p$ (MeV)</th>
<th>$G_P$ : $G_{d}$ : $G_{t}$ : $G_{x}$ : $G_{d}$</th>
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</thead>
<tbody>
<tr>
<td>61</td>
<td>30 : 4 : 1 : 0.08 : 1.5</td>
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<tr>
<td>80</td>
<td>183 : 16 : 1 : 0.5 : 0.5</td>
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<tr>
<td>200</td>
<td>100 : 10 : 1 : 0.2 : 0.2</td>
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<tr>
<td>800</td>
<td>47.8 : 14 : 1 : * : *</td>
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<tr>
<td>2100</td>
<td>34.4 : 8.9 : 1 : 0.6 : *</td>
</tr>
</tbody>
</table>

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The diagram on the right shows the relationship between mass number $A$, $^{27}$Al, and $P$. The $E_p$ axis is labeled with various photon energies, and the $\sigma$ axis is in arbitrary units.
$A(\text{He},t)X$  $\theta_{\text{lab}}=22^\circ$

$E = 90 \text{ MeV}$

$\frac{d\sigma}{d\Omega}$ (mb/sr)

- $1.8 \cdot A^{1/3}$
- $3.1 \cdot A^{1/3}$

- bump
- background

$A$

---

\[
\begin{array}{c}
\text{p} \\
\text{d} \\
\text{A}
\end{array}
\]

\[
\begin{array}{c}
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\[
\begin{array}{c}
\text{p} \\
\text{d} \\
\text{A}
\end{array}
\]
\( \varepsilon = (E - \mathcal{U}) \cos^2 \theta \)

0 \leq \mathcal{U} \leq 78 \text{ MeV}
Chrien et al., P.R.C 2A, 1014 (1980)

$\Sigma W(\phi_{i}P')$

$E_p = 800$ MeV

$\phi_{i} = \phi_{\alpha} \chi_{\alpha}$

$\phi_{f} = \phi_{p} \chi_{p}$

$S_{5}/S_{4} = \frac{\phi_{p} - \phi_{\alpha}}{\phi_{p}}$
Individually adjusted

\[ J_0 = \frac{A}{8\pi v} \left( \frac{2}{f} \right) \]

Composite nuclei:
- $^{28}$Si
- $^{28}$Si
- $^{28}$Si
- $^{30}$P
- $^{30}$S

Structure:
- e-e
- e-e
- e-e
- e-e
- e-e

<table>
<thead>
<tr>
<th>Composite</th>
<th>$d$</th>
<th>$t$</th>
<th>$\gamma$</th>
<th>$\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{28}$Si</td>
<td>263.6</td>
<td>135.6</td>
<td>284.2</td>
<td>406.2</td>
</tr>
<tr>
<td>$^{28}$Si</td>
<td>264.4</td>
<td>135.6</td>
<td>277.1</td>
<td>412.0</td>
</tr>
<tr>
<td>$^{28}$Si</td>
<td>252.3</td>
<td>135.6</td>
<td>175.5</td>
<td>407.2</td>
</tr>
<tr>
<td>$^{30}$P</td>
<td>254.2</td>
<td>135.6</td>
<td>185.0</td>
<td>405.2</td>
</tr>
<tr>
<td>$^{30}$S</td>
<td>254.1</td>
<td>135.6</td>
<td>182.2</td>
<td>407.2</td>
</tr>
</tbody>
</table>

Mean:
- $d$ = 265.2
- $t$ = 135.6
- $\gamma$ = 284.2
- $\tau$ = 406.2
**Quasi-free**

\[
\frac{\sigma(p,p)}{\sigma(p,n)} = \frac{2G_{pp} + N\sigma_{pn}}{N\sigma_{pn}}
\]

\[
\frac{\sigma(n,p)}{\sigma(p,p)} = \frac{2G_{nn} + N\sigma_{np}}{N\sigma_{np}}
\]

for \( G_{pp} \approx 0.5G_{nn} \); \( A \approx 58 \); \( \rho = 0.6 \)
What is the origin of fast particles?

*Backward emission is kinematically forbidden in free nucleon – nucleon scattering.*

They arise from high momentum components of nucleons in the target nucleus. Such components are due to a strong spatial dependence of the nucleon wave function on other nucleons in the nucleus.

(correrlated clusters)

- They are from nucleon - nucleon scattering were the remaining A-1 nucleons recoil coherently (quasi two-body scaling QTBES).
- They are from a series of multiple scattering on two or more uncorrelated nucleons in the target nucleus (cascade, exciton)
$^{181}\text{Ta}(\alpha,p)X$

$E_d = 720\text{ MeV}$

$\sigma(\text{mb})$

$\eta = 8p + 4h$

$E(\text{MeV})$

$\frac{d\sigma}{d\Omega} (\text{mb/ster})$

$E(\text{MeV})$

$\theta = 60^\circ, 30^\circ, 90^\circ, 120^\circ, 15^\circ$
\[ \frac{dE}{d\Omega} = \left( \frac{\pi}{A} \frac{dG_{ee}}{d\Omega} + \frac{N}{A} \frac{dG_{en}}{d\Omega} \right) \cdot \int S(\tau) d\tau e^{-\frac{E_{\text{in}}^{\text{out}}}{E_{\text{out}}}} \]

\( E_{\text{in}}^{\text{out}} \) = point of interaction measured from the nuclear surface.

\( \lambda_{\text{free}} \) = mean free path.

**Direct Knock-out (Boeh, Amado, Holoshyn)**

\[ \frac{d^2E}{dE d\Omega} = \frac{\mu_{ee}}{u(e^+)^2} \cdot \frac{9}{2} \int \frac{d^3p}{E^2 E_k} \left( n(N) |T_{ee}|^2 + n(n) |T_{en}|^2 \right) \]

\[ \times S\left( E_{T_1} T_{ee} - E_{T_2} T_{en} \right) \]

\[ \frac{d^2E}{dE d\Omega} = \frac{C}{|p - p'|} \cdot G(k_{\text{min}}) \]

\[ G(k_{\text{min}}) = \int_{k_{\text{min}}}^{\infty} k n(k) dk \]
After a few nucleon-nucleon collisions the momentum distribution becomes isotropic.

C.M. system of a moving source:
\[ \frac{d^2\sigma}{d\epsilon d\Omega} = \frac{1}{\sqrt{1 - \epsilon/E_0}} \]

Lab. system:
\[ \frac{d^2\hat{\sigma}}{d\epsilon d\hat{\Omega}} = c \sqrt{\epsilon} \frac{1}{\epsilon/E_0} \left[ (1 - \sqrt{2\epsilon v^2 \cos \Theta + \frac{1}{2} v^4}) / E_0 \right] \]

Transformation
\[ \frac{1}{P'} \frac{d^2\hat{\sigma}}{d\epsilon' d\hat{\Omega}'} = \frac{1}{P} \frac{d^2\hat{\sigma}}{d\epsilon d\hat{\Omega}} \]

\[ \frac{1}{P} \frac{d^2\hat{\sigma}}{d\epsilon d\hat{\Omega}} = A \cdot \epsilon / E_0 \]
$\text{Cu}(p,n)X$

$E_p = 4\text{ GeV/c}$

$E_4 = 57.0\text{ MeV}$
$E_2 = 116.9\text{ MeV}$

$E_4 = 52.2\text{ MeV}$
$E_2 = 115.7\text{ MeV}$

$H.\ En'yo\ et\ al.$
*Phys.\ Lett.\ A588, A (1985)*

T. A. Shibata et al
*N. P. A408, S25 (1985)*
12.

S.M. Qaim

Kernforschungsanlage Jülich

ICH1

Complex-particle emission in neutron induced nuclear reactions
Complex Particle Emission in Neutron Induced Reactions

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D-5170 Jülich

Phenomena observed in the interactions of fast neutrons with nuclei

- Elastic and inelastic scattering
- Radiative capture
- Nucleon emission
  - First chance emission
  - Sequential emission
- Emission of complex particles $^2$H, $^3$H, $^3$He, $^4$He
- Nuclear fission (limited to heavy mass nuclei)
Difficulties associated with the study of complex particle emission

- Low cross section (μb–mb)
- Emitted particles of short range (thin targets essential)
- Low neutron flux densities (10^7–10^10 n cm^-2 sec^-1)
- Strong background (high purity target material)
  (high resolution, low level counting)

Role of Radiochemistry

Interdisciplinary techniques are essential
Significance of Studies on Reactions involving Complex Particle Emission

- Test of nuclear models
- Information on cluster formation
- Role of spin and angular momentum in case of isomer distribution ratio
- Development of systematic trends
- Practical applications
  (tritium breeding, radiation damage etc.)

Topics

- Neutron Sources
- Experimental Techniques
- Calculational Methods
- Triton Emission Cross Sections
- $^3$He Emission Cross Sections
- Deuterium Emission Cross Sections
- Conclusions and Outlook
Production of Quasi-Monoenergetic Neutrons at the Compact Cyclotron CV18

Source reaction: \(^3\text{H}(\text{d},\text{n})^3\text{He}\)

Target: D\(_2\) Gas target

Production of d(He)-Breakup Neutrons at the Isochronous Cyclotron JULIC

Target: Be (water cooled)

Irradiations: around 0° direction

Flux density measured via monitor reactions

Irradiations: around C° direction

Flux density measured via monitor reactions

Collection of charge in a Faraday cup and calculation of neutron yield
Characterization of Neutron Spectra

Technique: Multiple Failing Activation (MFA)
(Activation of threshold reaction products, gamma-ray spectrometry, determination of absolute activity, spectrum unfolding using code SAND)

Quasi-monoenergetic neutrons

- Applicability of method limited to ~30 MeV, since knowledge of excitation function of neutron threshold reaction above 30 MeV is scanty.

MFA technique (12 threshold detectors)
Irradiations in 0° direction
Fluxes normalized to \( \sum_{E_n} \phi(E_n) \Delta E = 10^5 \)

- In 0° direction: bell-shaped distribution, \( E_n \approx 0.4 E_B \)
- Low-energy component strong, falling off exponentially with neutron energy (contributing processes: direct inelastic scattering to neutron unbound states, multi-body breakup, etc.)
Experimental Techniques used in the Study of Complex Particle Emission

- **On-line methods**
  - (detection of emitted particles)
  - Counter telescope
  - Quadrupole spectrometers

- **Off-line methods**
  - (detection of reaction products or radioactive emitted particles)
  - Activation
    - (in combination with modern radiochemical preparations)
  - Tritium / He
    - (preparation and low-level counting)
  - Mass spectrometry
    - ($^3\text{He}, ^4\text{He}$)

Energy scheme of $(n.n')$, $(n.2n)$, $(n.p)$, $(n.t)$, $(n.\alpha)$ and $(n.\alpha)$ reactions
Hauser-Feshbach Calculations

The total cross section for the excitation of a state at excitation energy $E_0$ and with spin $I_0$, via the reaction $A(a,b)B$, reads

$$\alpha(E_0, I_0) = \sum_J \alpha_{	ext{conv}}(J) G(E_0, I_0, J) / g(J).$$

The total width $g(J)$ for the decay of the compound nucleus into all open channels (denoted by primes) $b'$ + $B'$ is split into two parts,

$$g(J) = \sum_S \sum_{S_0} \frac{\epsilon_S + J}{\epsilon_{S_0} + I_0} \sum_{T_G} T_G + \sum_{T_G} T_G' \sum_{l_0} \sum_{l_0'} \sum_{S_0} \sum_{S_0'} T_G \rho(E_0; I_0) dE_0;$$

thus replacing the summation over transmission coefficients $T_G$ (of discrete levels by an integration over level densities $\rho(E_0; I_0)$ at the beginning $E_0$ of the "continuum region".

Optical model parameters

<table>
<thead>
<tr>
<th>Particle</th>
<th>Real</th>
<th>Imaginary</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Potential (MeV)</td>
<td>Radius (fm)</td>
</tr>
<tr>
<td>$^3$H</td>
<td>152</td>
<td>1.24 A^{1/3}</td>
</tr>
<tr>
<td>$^3$He</td>
<td>158.1</td>
<td>1.24 A^{1/3}</td>
</tr>
</tbody>
</table>

Said Features
- Discrepancy in ENSDF/β-$\bar{\nu}$ mainly due to combination of neutron and triton emission data.
- Data from threshold to 9.5 MeV in good agreement. Beyond 9.7 MeV the Harwell data appear to be low.
- Data base weak between 10.5 and 13 MeV.
- Data around 19 MeV show some scatter, however, no serious discrepancy.
- New evaluation appears worthwhile.
Tritium Emission Cross Sections

Neutron source: 53 MeV d(Be) (E_n > 31 MeV)

Techniques:
- Activation
- Tritium accumulation, purification, gas counting

Excitation Functions of (n,t) Reactions

Neutron source: ³H(d,n)⁴He in Gel (E_n 13 to 20 MeV)

Samples for irradiation: Thick targets (θ°-90°)

Technique: Tritium preparation, low-level gas phase β counting

---

- Tritium emission cross section for the lightest nuclei high, presumably direct interactions
- For elements with Z > 20 cross section small and practically constant
- Emission of three particles (1p2n) favoured over Emission of a bound trinucleus (³H).

---

- (n,t) Cross section increases slowly with energy
- Statistical model describes the (n,t) cross section of nuclei in the (25,14) shell well. For heavier nuclei non-statistical processes are important.
Isomeric cross-section ratios in (n,t) reactions at 14.6 ± 0.4 MeV on nuclides with Z≥22 as a function of the spin of the isomeric state.

$^{3}$He-Emission Cross Sections

Neutron source: 53 MeV $d(\alpha)$ ($E_\alpha \approx 4$ MeV)

Techniques:
- Activation
- Mass spectrometry

---

- $\sigma_m$, $\sigma_a$ (experiment)
- $\sigma_m$ (experiment), $\sigma_b$ (systematics)
- Trend (eye-guide)

---

Ratios of $^{3}$He/$^4$He emission cross sections obtained using the two techniques agree within 50%.

Hauser-Feshbach calculation can not reproduce the ratio. Calculation using direct reaction means essential.
Excitation Function of $^{93}\text{Nb}(n, ^3\text{He})^{94}\text{Y}$ Reaction

Neutron source: $^3\text{H}(d, n)^4\text{He}$, Ge detector ($E_n = 13$ to $20 \text{ MeV}$)

Sample for irradiation: Nb pellets ($0^\circ$ to $90^\circ$)

Technique: Radiochemical separation, low-level $\beta$-counting of $^{94}\text{Y}$

---

Important considerations:

- $(\gamma, ^3\text{He})$ cross section low ($\mu$b)
- Transition from $^{14}\text{N}$MeV region to higher energies smooth
- Statistical model does not reproduce the integrated cross section; presumably strong component from direct interactions

---

Experimentally determined $^3\text{He}/^3\text{H}$-Emission Ratio as a Function of Incident Neutron Energy

![Graph showing cross-section ratio vs. neutron energy for $(n, ^3\text{He})$ reaction]

$\frac{\sigma^{^3\text{He}}(n, ^3\text{He})}{\sigma^{^3\text{He}}(n, f)}$ vs. Neutron energy (MeV)

Cross-section ratio

1. $10^{-3}$
2. $10^{-2}$
3. $10^{-1}$

Neutron energy (MeV)

15. $\sigma^{^3\text{He}}(n, ^3\text{He})$ vs. $\sigma^{^3\text{He}}(n, f)$

- $\sigma^{^3\text{He}}(n, f)$ is relatively high at $\approx 0.1$
- $\sigma^{^3\text{He}}(n, ^3\text{He})$ is relatively low

---

$^3\text{He}$-emission is intrinsically weaker than $^3\text{H}$-emission

<table>
<thead>
<tr>
<th>$(\gamma, ^3\text{He})$</th>
<th>$(n, f)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q-value (MeV)</td>
<td>$-7.7$</td>
</tr>
<tr>
<td>Coulomb barrier (MeV)</td>
<td>$\approx 9.5$</td>
</tr>
<tr>
<td>Activation product</td>
<td>$^9\text{Y}$</td>
</tr>
<tr>
<td>No. of levels x product</td>
<td>small</td>
</tr>
<tr>
<td>Selectivity</td>
<td>$\Delta T = 1$</td>
</tr>
</tbody>
</table>
Excitation Function of $^{58}Ni(\gamma,d)^{57}Co$ Reaction

Neutron source: $^2H(\alpha,n)^3$He ($E_\alpha = 4$ to 10 MeV)

Samples for irradiation: $Ni_2$O$_3$, 0° direction

Technique: Radiochemical preparation of $^{57}$Co, thin source, X-ray spectroscopy

Conclusions

- Studies of reactions with complex particle emission are of fundamental significance; data find practical applications
- Available information on such reactions is still small
- Interdisciplinary experimental techniques, especially radiochemical methods, are of considerable importance

Outlook

- Radiochemical studies of excitation functions of $(\gamma,d)$ and $(\gamma,He)$ reactions near their thresholds
- Mass spectrometric study of deuterium emission in reactions induced by breakup neutrons
- Investigation of emission of heavier complex particles like $^7Re$ and $^7C$
- Development of newer calculational methods (in collaboration with theorists)

---

Statistical model reproduces the excitation function well in the energy region of 8 to 10 MeV

Precompound model describes the excitation function within a factor of 2

In the energy region of 6 to 8 MeV disagreement between experiment and model calculations—presumably tunneling effect
13.

J. Krug

Ruhr-Universität Bochum

Institut für Experimentalphysik

Few-nucleon reactions with neutrons
NEUTRONS AT COSY

Few-nucleon reactions with neutrons

---

**Two Nucleons**

\[ NN \rightarrow NN \]
\[ \text{Nuclear Force} \]
\[ \text{NN} = \text{pp, up, un} \]

**Loss Energy**

only elastic \( NN \rightarrow NN \)

zero-energy limit: shape-independent effective-range expansion of s-wave phase shifts:

\[ \Delta E = \frac{1}{2} a_0 + \frac{3}{2} k^2 r - P k^4 r^2 + \ldots \]

<table>
<thead>
<tr>
<th>( nn )</th>
<th>( up )</th>
<th>( pp )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a^2 / fm^2 )</td>
<td>( 1.150 \pm 0.005 )</td>
<td>( -22.72 \pm 0.01 )</td>
</tr>
<tr>
<td>( r^2 / fm )</td>
<td>( 2.3k )</td>
<td>( 2.14 \pm 0.05 )</td>
</tr>
<tr>
<td>( a^4 / fm^4 )</td>
<td>( 0.44 \pm 0.05 )</td>
<td>( 0.44 \pm 0.05 )</td>
</tr>
<tr>
<td>( r^4 / fm )</td>
<td>( 1.150 \pm 0.005 )</td>
<td>( 1.150 \pm 0.005 )</td>
</tr>
</tbody>
</table>

---

2) S. Lowen, K. Wilson, PR C91, 1529 (1979)

a) uncorrected; b) with e.m. corrections + off-shell smart;
c) with e.m. corrections
d) from \( 3^2 \)
e) average, all available \( a_{un}\) \( \text{(no 3NF)} \)

\( a_{nm} \) \( = 16.9 \pm 0.6 \) \( r_{nm}^2 = 2.65 \pm 0.18 \) \( \text{fm} \)

f) final state \( \rightarrow \) 3NF

2) A. Gabriud et al., NP A420, 446 (1973)

---

keywords: neutron, nucleon, few-nucleon, few-body, forces between nucleons, particular symmetries
free scattering, FS1; \( a_{pp} \) very accurate
model dependent, \( A_{pp} \neq 1 \text{ fm} \)

M. Calmaan, G. A. Miller, PR C82, 912 (1982)

up: free scattering, FS1; parameters best determined in neutron beam
we find \( a_{up} = -23.5 \pm 1.0 \text{ fm} \)
I was pointed to study the weak part of strong force

up: cannot be measured in free scattering
+ target neutron bound, e.g. in \( ^2\text{H} \)
-complex analysis, FS1 \( \rightarrow \) \( a_{up} \) ; FS1 \( \rightarrow \) \( a_{uu} \)

Comparison \( a_{uu}(ap) - a_{up} \): clear CIB

exp.: \( a_{uu} - a_{up} = 5.3 \pm 0.5 \text{ fm} \)
then.: \( 5.6 \pm 1.0 \text{ fm} \) \( \Rightarrow \) (mass diff. \( E^2 \text{ in } TPE \))
K-shell change, \( \Delta \text{NN} \) (completing)
- subtract out all other effects

5) T. E. Osborne, G. A. Miller, FL 1126, 42 (1973)

Evidence of CIB: exp.: \( \Delta a_{u} = a_{up} - a_{uu} = 9.2 \pm 1.0 \text{ fm} \),
agreement with calculation (3, R, R', K)
but model dependent

less model dependent: \( \Delta E_{g} = E_{g}(u) - E_{g}(p) = 100 \pm 20 \text{ MeV} \)
(after corrections)

8) D. F. Buch et al., PR C82, 1403 (1982)
We also: L. A. Conn, H. D. Sackorn, FL C16, 3202 (1982)

Classification of NN force
1) (originating from isospin formalism; simplified)
   Class I: \( C_1 \)
   Class II: \( C_1 \), but \( C_5 \)
   Class III: \( C_5 \), symmetric in b.o. particles, no effect on \( \text{up} \)
   Class IV: \( C_5 \), not symmetric \( \rightarrow \) Foppwin indistinguishability
   no effect on \( \text{uu} \), \( \text{pp} \)
   \( \text{p.e.} \) \( \Delta E_{g} \) measures Class IV forces
   \( \Delta E_{g} \) Class III \( \mu \) force can be attractive, \( \text{up} \) is not

Medium Energy

pp: elastic - large amount of data; \( s_f \), \( d_f / d_0 \), \( p_i \), Wolfenstein parameter \( (3, R, R', K) \)
spin transfer coeff. \( K_{ps}, K_{ps} \)
spin correlation coeff. \( A_{ps}, A_{ps} \)

Spin observables: indispensable for studying distinct parts of the force
complete set of observables (amplitude)

High precision needed; measure necessary; still underway from MeV to GeV
\( \text{C(q) / MeV, normalization (high inelasticity):} \)
\( T=1: \) \( E_{s} \) (2.13 GeV)
\( E_{p} \) (2.22 GeV)
\( E_{t} \) (500-800 MeV)

\( \text{pp} \) scattering particularly suited for studying parity violation (PNC) in NN force
\( A_2 \) for long. p, \( \propto 10^{-2} \) agreement with pnc prediction: PNC well established \( \rightarrow \) nature of PNC components (simple system favored)
inelastic - $pp \to d^+ n$, $np^+ n$ (coupled)

then-body final state, to be described by two-body approach

300 GeV
down
same
$A_{DD}$ decreasing with E
500 GeV
50%
$70^\circ$ increasing but remains
800 GeV
(20%)
$80^\circ$
important

proton production in NN collisions is the dominant
inelastic channel at intermediate energies (300-800 GeV)

$pp \to d^+ n$

$A_{DD}$ inter, $B=2$ resonances

almost complete set of spin observables in
the $A$-resonance region

model calculations: relative approach

coupled channels calc.

leading pion rescattering diagram:
relativistically

2-body formulation: measurements much
easier than for $pp \to np^+ n$ ($NN \to NNN$)

10) W.B. Frippe et al., PR C14, 1973 (1973)

one very recent note: no direct evidence for either
of the two dibaryon resonances existing

10) W.B. Frippe et al., PR C14, 1973 (1973)

$pp \to np^+ n$: lessons from analysis started only recently

$\eta$ models: ($A$-inter, $P_{33}$ in $P_{33}$ ($A_3$) and
$P_{31}$ ($N\pi$ pole)); no crossing

again: dibaryons, no existence

11) T.S. Bulkin et al., PR C29, 207a (1973)

up:
generally sparse data (diff. obtaining

good angular beam, determining flux)

some observable like $pp \to d^+ n$

but: $T=0, 1$

(low energy: recent p.d. data from Duke,

Karenke, Davis, TAMU)

elastic - measured $d^+ d$, $A_1$, spin transfer

and corr. parameters

CEX peak

also CSB (below)

inelastic - $np \to d^0$

$d^0(1059) \to A + 2g^0 + B \pi^0 g$

$A_1^+$ agrees with $pp \to d^+ n$

good for ab. normalization ($T=0$

$- np \to np^+ n$, mainly $T=1$

diff. phases $P_{33}$ - spectra - evidence $T=0$

indication for non-resonant (non-

Isol.) pion production

Description of NN data

- phase shift $\delta_0$ (8)

11) R.B. Arndt et al., PR C6, 1972 (1972)

R.A. Arndt et al., PR C67, 95 (1973)

- also: Yale phase shift $\delta_0$; R.R.closest $\delta_0$ BC 155, 1525 (1969)


- Reid left-core potential (phenomenological) (11)


- Paris potential (11) Standard formula since 10y

$P_{33} - (P_{33})_{33} - \text{exchange,}

\text{short-range, phenomenological}$

13) M. Lacombe et al., PR C31, 491 (1970)
- Some potential work on $\alpha_5$, $\Delta_5$, EWSR (Princeton) [11]
  - Many more potentials (the above ones being used in SN - calculations)

CSB from elastic up at medium energies
- indirect evidence: $\Delta_{5S}, \Delta_{5P}$
- up elastic scattering provides a fit for
  $T$ - mixing forces $\rightarrow$ CSB, Class IV [15]

10. L. Choo et al., NP A126, 342 (1974)
    A. Gurtler, PR C24, 2174 (1960)

Wolfenstein pointed out that for up scattering
spin conservation dictates the equivalence of
$\Delta_{5S}(A)$ and $\Delta_{5P}(E-1)$, i.e. $\Delta_{5S}(A) = \Delta_{5P}(E-1)$ [18]
- Class IV CSB breaks this equality


- Expected difference (c.m. effect, $S$- $E$ mixing)
  $\approx 3 \times 10^{-3}$ diff. to measure

- Alternatively: $A(\uparrow p) \approx A(\uparrow p)$
  same energy, angle

Experiments at LANL, energy dependence [17]
TRIUMF: $\Delta_{5S} = A_{\alpha} - A_{\alpha}$
  $\approx 0.8 \pm 0.01 \pm 0.006$ [18]

Significant!

12. T.S. Bethke et al., PR C24, 796 (1981)

Theor. analysis: $\Delta_{5S}$ mainly due to up mass diff.
but also QCD effects [20]

20. G.H. Fuller et al., PRL 54, 2977 (1985)
    A.H. Williams et al., PR C26, 1526 (1982)

Three Nucleons

NNN; ND $\rightarrow$ NNN

(resonance)

considerately less data than for NN because of much
more complicated dynamics (and - inelastic kinematics)
exp. harder because of long breakup counting
times (kin. comp. exp.)

Low Energy ND $\rightarrow$ NNN breakup

G. B. Faddeev (early 60's) proved a certain
system of coupled integral equations
to provide a complete set of unique solutions
to the quark - nucleon three-body problem.
Input: Full on - and off - shell behavior of the NN force.
Only short range force $\rightarrow$ no Coulomb! -
So, in principle, only ND - system relevant.

However, difficult to solve $\rightarrow$ first practical
codes only ten years later, but still crude
for more than 10 y, not possible to strictly
correlate physics and numerics, only
slow progress
$\rightarrow$ yet good qualitative agreement with the
exp. data already with simple sep. pot.
$\rightarrow$ also pot data calculated (Coulomb effects $\approx$ small in most cases)
Very recently, calculations possible with "realistic" (nuclear-theoretical) NN potentials also for elastic scattering and breakup:
→ PEST pt. (same sep. exp. to Paris pt.)
→ Paris pt.
→ Born pt. (OBEPK)

Numerical accuracy \( \leq 1\% \) large CMS bins vectorized comp.

next iteration: now effect of 10% or less to consideration
→ Coulomb effect discarded - only used in beam hard to measure

Current aims:
→ as many and as precise real-data as possible, incl. spin obs.
→ test of "realistic" calc.
→ try to base differences to 3NF

Measurements by groups at
→ JALKE
→ Helsinki
→ Bochum
→ PSI (1st)

Measurements of hot elastic (\( < 100\text{MeV} \)) not coupled:

26.0: 40.6 6\( ^3\)He/\( ^{12}\)C, \( \delta = 15-70^\circ, \text{c.m.} \)
35 6\( ^3\)He/\( ^{12}\)C, \( \delta = 445^\circ, 160^\circ, \text{c.m.} \)
20: 30.8 6\( ^3\)He/\( ^{12}\)C, \( \delta = 90^\circ, \text{c.m.} \)
12.0 6\( ^3\)He/\( ^{12}\)C, \( \delta = 50-120^\circ, \text{lab.} \)
50 6\( ^3\)He/\( ^{12}\)C, \( \delta = 90-150^\circ, \text{c.m.} \)
50 6\( ^3\)He/\( ^{12}\)C, \( \delta = 170^\circ, \text{lab.} \)
10-14 6\( ^3\)He/\( ^{12}\)C, \( \delta = 60-160^\circ, \text{c.m.} \); high accuracy

22) J.L. Romero et al., PR C29, 2834 (1970)
25) W. Tornow et al., NP A396, 28 (1974)
26) E. Li Watson, et al., PR C25, 2219 (1982)
27) J.L. Romero et al., PR C32, 2219 (1982)
28) P. Schwartz et al., NP A332, 7 (1983)

Breakup possible in many kin. configurations among 36 \( ^3\)He p.t.

- quasi-two-particle reactions
  FS1 sensitive to \( \omega_{\pi} \) short-range force
  NN interaction 3\( ^3\)He pole in \( \Sigma \)

- FS2 sensitive to on-shell force dominate over almost entire phase space
  (with phase exch.) pole in \( E \) (Prilezhaev-Yang test)

- Reactions with special kinematics
  SST fully symmetric in c.m.s., non-coplanar \( \text{in lab.} \)
  insensitive to NN off-shell behavior
  sensitive to 3NF (attractive)
  \( \text{Col} \) peak? (close to 3NF in principle)
  sensitive to 3NF (repulsive)

We have measured the diffusion of \( ^{12}\)C + \( ^{15}\)O p
(bias, c.m. exp.) in an SST configuration with \( \text{in-}
\) projectile, unpolarized, \( E_p = 10\text{MeV} \)
3NF: possibly expected to become more important at higher energies (extremely short range)

- Ambiguity: 3NF ↔ off-shell NNF
- Scaling with Eq. (6)
Medium Energy

\[ pd : \text{ elastic } + \text{ inelastic (} pd \rightarrow pp n \text{)} \]

Measured, Vector + tensor spin by, \( \Delta s/dw \text{ } \)
calc. Relativistic multiple scattering theory IA, RPPF, l. scattering, FS, Snee. model problem w/\text{ONEX} backward peak in \( \Delta s/dw \text{ }

Inelastic here: \( n \) emission at \( 0^\circ \) by \( pd \), 200-800 \text{ MeV, } up-\text{ QFS } + \text{ pp-FS, narrow l.-line \( 0^\circ \) (10-15 \text{ MeV} \text{ Full})} \]

\[ \text{inelastic } (pd \rightarrow \text{ } ^3\text{He } \text{ } K^+ \text{)} \]

Measured \( \Delta s/dw \text{ }, \text{ } T_{20} \text{ } \text{ for } \text{ } pd \rightarrow ^3\text{He } K^+ \text{, } \text{ for- and back-}
ward angles, 15 \text{ to } 50 \text{ MeV, } \text{ } 2.0 \text{ } GeV \text{ [33]}. \]

33) L. Korbul et al., PL 1128, 28 (1970)

\[ \text{measured } \Delta s/dw \text{, } A_g(\lambda) \text{ for } \text{pd } \rightarrow ^3\text{He } \text{K}^+, \text{ Ep } = 350, \text{ 450, 500 MeV [32]} \text{, } \text{other models: } \Delta s/dw \text{ oK}^+, \text{ } A_g 50 \%

34) J.H. Cameron et al., IP 4422, 718 (1977)

\[ \text{np } \rightarrow ^3\text{He } K^+ \text{)} \]

Measured \( A_g(\lambda) \text{; Ep } = 800, 1000, 1100 \text{ MeV [35]} \)

_\text{rapo variations of } \Delta s/dw \text{ yield at very backward angles, related to baryonic excitations, but not explained yet (cay} \text{.}

35) B. Mayer et al., PL 1148, 25 (1976)

For some kind of completeness:

CSJ also discussed for \( K^- \text{ scatting of } ^3\text{He, } ^3\text{He} \text{ with some positive indication} \)


Summary and Outlook

- Intermediate energies

NN:
- Lack of good 
  up data
  (phase-shift, models of potential)
- Recommended at present:
  up CSB-experiment at COSY
  (TRB-experiment?)
- Special experiments

NNN:
- No longer domain of (non-understood)
  scaling:
  off-shell behaviour of NN forces?
  NNN forces?
- Reaction mechanism:
  Relativistic NNS (Temminck graphs)
  open: D-Isobars, dibaryon resonances
- Particularly unknown: can the Coulomb
  problem be solved from the medium energy
  side with (only) simple graphs?

Still widely unknown: (strange) physics -

Not only pions, but also strange mesons
  (kaons)