Nuclear data for production of the therapeutic radionuclides ^{32}P, ^{64}Cu, ^{67}Cu, ^{89}Sr, ^{90}Y and ^{153}Sm via the (n,p) reaction : Evaluation of excitation function and its validation via integral cross section measurement using a 14 MeV d(Be) neutron source

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Abstract

Nuclear data for production of the therapeutic radionuclides ^{32}P, ^{64}Cu, ^{67}Cu, ^{89}Sr, ^{90}Y and ^{153}Sm via (n,p) reactions on the target nuclei ^{32}S, ^{64}Zn, ^{67}Zn, ^{89}Y, ^{90}Zr and ^{153}Eu, respectively, are discussed. The available information on each excitation function was analysed. From the recommended data set for each reaction the average integrated cross section for a standard 14 MeV d(Be) neutron field was deduced. The spectrum-averaged cross section was also measured experimentally. A comparison of the integrated value with the integral measurement served to validate the excitation function within about 15%. A fast neutron source appears to be much more effective than a fission reactor for production of the above mentioned radionuclides in a no-carrier-added form via the (n,p) process. In particular, the possibility of production of high specific activity ^{153}Sm is discussed.

Keywords: Therapeutic radionuclide; (n,p) reaction; Excitation function; Integral test; 14 MeV d(Be) neutron source; Nuclear model calculation

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1. Introduction

Radionuclides emitting low-range highly ionising radiation (β^- and α-particles, Auger and conversion electrons) are of increasing significance in internal radiotherapy (cf. Hoefnagel, 1991; Stöcklin et al., 1995; Qaim, 2001). Most of them are produced at nuclear reactors (Stöcklin et al., 1995; IAEA-TECDOC-1340, 2003; Mirzadeh et al., 2003), although in recent years the use of cyclotrons has also been enhancing (Qaim, 2001, 2002, 2003). In reactor production, very commonly the (n,γ) process is utilized which, however, leads to a product of low specific activity, unless the activated product decays to a daughter radionuclide which could be chemically separated and used in medical work. Another important production process is the fission of ^{235}U which gives rise to "no-carrier-added" (nca) products. The radiochemical work involved in the separation of fission products, however, is rather cumbersome. In a few cases the (n,p) reaction is also utilized to obtain a product of high specific activity, although its cross section with fission neutrons is rather low. Four such radionuclides are ^{32}P ($T_{½}$ = 14.3 d), ^{64}Cu ($T_{½}$ = 12.7 h), ^{67}Cu ($T_{½}$ = 61.9 h) and ^{89}Sr ($T_{½}$ = 50.5 d); they are produced via the (n,p) reaction on the target nuclei ^{32}S, ^{64}Zn, ^{67}Zn and ^{89}Y, respectively. In recent years the production of ^{64}Cu and ^{67}Cu has shifted over mainly to cyclotrons (cf. Qaim, 2003); but ^{32}P and ^{89}Sr are still produced via the (n,p) reaction at nuclear reactors. Two other therapeutic radionuclides, namely ^{90}Y($T_{½}$ = 64.8 h) and ^{153}Sm ($T_{½}$ = 46.75 h) are presently available via the fission-produced $^{90}Sr/^{90}Y$ generator system and the $^{152}Sm(n,\gamma)$-reaction, respectively, the latter, however, with low specific activity. They could possibly also be generated via the (n,p) reaction on ^{90}Zr and ^{153}Eu, respectively.

In a recent publication Spahn et al. (2004) described cross section measurements on the reactions $^{64}Zn(n,p)^{64}Cu$, $^{67}Zn(n,p)^{67}Cu$ and $^{89}Y(n,p)^{89}Sr$

with 14 MeV d(Be) break-up neutrons. The values were found to be 3-5 times higher than with fission neutrons, suggesting that the yield of the therapeutic radionuclide with fast neutrons (e.g. from a spallation source) would be appreciably higher than that from the present day fission reactors. In the present work the nuclear data relevant to the production of all the above mentioned six therapeutic radionuclides via the (n,p) reaction were considered in some detail. The aim was to compare the experimental cross section data and evaluations available in the literature with the results of nuclear model calculations, to consider the systematics, and finally, to develop the best fitted excitation function (evaluated curve) for each reaction. A comparison of the integrated cross section deduced from the evaluated excitation function and the spectral distribution of a 14 MeV d(Be) neutron source with the integral cross section measured using the same neutron source should then establish the reliability of the database for the production of each of the above mentioned therapeutic radionuclides. This data validation has been requested by the IAEA (cf. Sublet and Capote Noy, 2004) and is considered to be an integral part of the database standardisation for production of therapeutic radionuclides via (n,p) reactions at present day fission reactors as well as at future fusion or spallation neutron sources.

2. Evaluation of excitation functions

For each (n,p) reaction under consideration the available experimental cross section data were plotted as a function of the neutron energy. All the data were taken from the EXFOR (2003) file. As far as we could check, the compilation was found to be complete. The resulting experimental excitation function was scrutinized regarding the consistency of data (cf. IAEA-TECDOC-1211, 2001), and some very discrepant data were ignored. The best fit to the data was then obtained via one of the following methods:

a) reliance on the Dosimetry and/or Activation file of the IAEA

b) nuclear model calculation

c) eye guide curve

The Dosimetry file (IRDF-2002) and the Activation library (IAEA-TECDOC-1285, 2002), give recommended data for the (n,p) reactions on ^{32}S and ^{64}Zn studied in this work. The nuclear model calculation was done using the code STAPRE (Uhl and Strohmaier, 1976), which is a combination of the Hauser-Feshbach and precompound formalisms. Such calculations have been done by us previously for nuclear reactions induced on ^{90}Zr, ^{89}Y and ^{67}Zn (Qaim et al.,1990; Klopries et al.,1997; Nesaraja, 1999; Nesaraja et al.,1999); similar calculations were done now for the other target nuclei. In addition we performed calculations on all the target nuclei using the code EMPIRE 2.19 (Herman et al., 2005); the details are given elsewhere (Sudár and Qaim, 2005; Al-Abyad et al., 2005). If a satisfactory reproduction of the available experimental data was not achieved, then an eye guide curve was drawn through all the selected experimental data points. We discuss below the various reactions studied individually.

2.1. $^{32}S(n,p)^{32}P$

The excitation function is shown in Fig.1. The references to all experimental data are to be found in the EXFOR file (2003). Nuclear model calculations using the codes STAPRE and EMPIRE 2.19 describe the trend of the excitation function globally; they, however, do not reproduce the fine structures. The best fit is given by IRDF-2002, and it is recommended that this curve be adopted as the standard excitation function of this reaction.

2.2. $^{64}Zn(n,p)^{64}Cu$

This reaction has been extensively studied and all the data are available in EXFOR. The results are shown in Fig. 2. Since in most of the cases simply the annihilation radiation was counted, there are considerable discrepancies in the data. It is not possible to comment on each cross section value since the exact experimental conditions are not known. Nonetheless, it appears that one data set between 5 and 10 MeV (Smith and Meadows, 1975) gives too low values, a few other sets around 15 MeV (Paul and Clarke, 1953; Preiss and Fink, 1962; Dresler et al., 1973) and one set between 15 and 20 MeV Bormann et al., 1963) give too high values. The later values by Bormann and Lammers (1969) are more consistent. The STAPRE calculation describes the excitation function fairly well up to 12 MeV, but gives higher values than the experimental data at higher energies. The EMIPRE 2.19 calculation grossly overestimates the excitation function. Among the two recommended curves, the one from the Activation file gives a good fit to most of the data whereas the IRDF curve is too low between 5 and 12 MeV. We therefore adopted the curve from the Activation file as the standard excitation function of this reaction.

2.3. $^{67}Zn(n,p)^{67}Cu$

The experimental cross section data for this reaction are shown in Fig. 3 as a function of neutron energy. All the data were taken from the EXFOR file. At a first glance there appear to be large discrepancies in the data. A careful analysis, however, clarifies the picture to some extent. The data can be divided into three groups:

a) the low energy region up to 12.1 MeV where a systematic study has been done.
b) the energy region around 14 MeV where several measurements were performed using a neutron generator, and
c) the energy region above 15 MeV where most of the discrepancies exist.

The nuclear model calculation done using the code STAPRE (Nesaraja, 1999; Nesaraja et al., 1999) is in excellent agreement with the cross section data in the low energy region and also in fair agreement with the lower set of values around 14 MeV, but not in the energy range between 15 and 20 MeV. The EMPIRE 2.19 calculation, on the other hand, gives higher values. We interpret the very high experimental values in the energy region above 15 MeV to be due to significant contributions of the (n,pn) and (n,np) processes on ^{68}Zn. It has been shown by Qaim (1982) that this contribution amounts to 15-20 % of the (n,p) cross section at 14.5 MeV and increases rapidly with the increasing incident neutron energy. Since in ^{nat}Zn the abundance of ^{67}Zn is only 4.1 % as compared to 18.8 % of ^{68}Zn, the amount of ^{67}Cu formed via the ^{68}Zn(n,np+pn)-process at about 19 MeV, for example, may be much more than that via the ^{67}Zn(n,p)-reaction. In other words the formation cross section of ^{67}Cu at neutron energies > 15 MeV obtained using ^{nat}Zn as target material does not describe the ^{67}Zn(n,p)^{67}Cu reaction cross section alone; it gives rather a sum of all the contributing processes. Since the d(Be) break-up neutron spectrum involved in the present work (see below) does not extend beyond 16 MeV, we adopted the STAPRE calculation as the standard excitation function of this reaction.

2.4. $^{89}Y(n,p)^{89}Sr$

The experimental cross section data for this reaction (all from EXFOR) are plotted in Fig. 4 as a function of neutron energy. The results of Tewes et

al (1960) are rather low. It is not possible to check them since no details are available. The results of STAPRE calculations reported earlier (Klopries et al., 1997) and of EMPIRE 2.19 done in this work are reproduced in Fig. 4. There is good agreement between the experiment and the two model calculations up to 13 MeV; at higher energies, however, the STAPRE results are in better agreement than the EMPIRE 2.19 values. We therefore adopted the STAPRE curve as the standard excitation function of this reaction.

2.5. $^{90}Zr(n,p)^{90}Y$

The experimental cross sections for this reaction given in the EXFOR file are reproduced in Fig. 5 with the results of STAPRE (Qaim et al., 1990) and EMPIRE 2.19 calculations (this work). Some of the data near the threshold are either shifted in energy or are too high. The model calculations show agreement with some of the experimental data but not with all the data over the whole energy range. We therefore drew the eye guide curve through all the data points in the high energy region but only through the Jülich data (Qaim et al., 1990) in the lower energy region, and adopted that curve as the standard excitation function of this reaction.

2.6. $^{153}Eu(n,p)^{153}Sm$

For this reaction only a few data points around 14 MeV have been reported. In Fig. 6 the experimental data together with the results of STAPRE and EMPIRE 2.19 calculations are shown as a function of neutron energy. The calculational results were normalised to the average values around 14 MeV. The curve given by the STAPRE calculation was adopted as the standard excitation function of this reaction.

3. Measurement of integral cross section

The spectrum-averaged cross section of each of the above mentioned (n,p) reactions induced by 14 MeV d(Be) break-up neutrons was measured integrally via the activation technique. The results for the $^{64}Zn(n,p)^{64}Cu$, $^{67}Zn(n,p)^{67}Cu$ and $^{89}Y(n,p)^{89}Sr$ reactions have already been reported and discussed in the terms of production of the three radionuclides involved (Spahn et al., 2004). Now we describe the characterization of the neutron field in some detail and report on the spectrum-averaged cross section measurements on $^{32}S(n,p)^{32}P$, $^{90}Zr(n,p)^{90}Y$ and $^{153}Eu(n,p)^{153}Sm$ reactions.

3.1. Characterization of neutron field

The fast neutron field used in this work was generated via break-up of 14 MeV deuterons on a thick beryllium target. The neutron energy spectra and yields from d(Be) sources have been measured and discussed by several groups (cf. Qaim, 1987; Oláh et al., 1998; Ibn Majah et al., 2001). The beryllium target installed at the compact cyclotron CV 28 in Jülich consists of a disk shaped metallic Be (19.7 mm diam, 1.9 mm thick, 98% purity) embedded into a 2 mm thick copper holder cooled with water (for more details cf. Oláh et al., 1998).

The neutron spectrum characterization was accomplished by multiple-foil activation and unfolding using an iterative method. The basic data for the calculation were achieved by irradiation of different metal foils with neutrons, whereby 11 different threshold reactions were induced (Table 1). The radioactivity of each product nuclide was determined via conventional high-resolution γ-ray spectrometry. For unfolding the neutron field, the code SULSA (Sudár, 1989) was used. It is an iterative code based on the

generalized least squares method and does not require any input spectrum. The deduced neutron spectrum at 0° for a primary deuteron energy of 14 MeV on Be is given in Fig. 7. It is similar to that reported earlier (Oláh et al., 1998) for 13.6 MeV deuterons on Be. A flux of about 10^{10} $n \cdot cm^{-2} \cdot s^{-1}$ is generated. The maximum flux density occurs at 2.5 to 3.5 MeV neutron energy. This spectrum was adopted as the standard field for integral measurements.

3.2. Integral cross section measurements

For spectrum-averaged cross section measurements, pellets of high-purity materials (^{nat}S, $^{nat}ZrO_2$ and $^{nat}Eu_2O_3$) were prepared (0.05 to 0.3 mm thick). Each pellet was irradiated simultaneously with a set of Al and Fe monitor foils attached on both sides of the pellet. Irradiation was done in each case with neutrons for about 2 h at a distance of 1 cm from the beam stop. The deuteron beam current was 5 μA. The neutron flux densities in front and at the back of each sample were determined via the monitor reactions $^{27}Al(n,\alpha)^{24}Na$ and $^{56}Fe(n,p)^{56}Mn$. The excitation functions of those monitor reactions were taken from the International Radiation Dosimetry File (IRDF-2002) and averaged for the standard neutron spectrum, described above.

The radioactivity of the studied therapeutic nuclide was determined in two different ways. The radionuclides ^{32}P ($T_{1/2}$ = 14.3 d) and ^{90}Y ($T_{1/2}$ = 64.8 h) are pure β^- emitters having relatively high β^- end-point energies of 1.7 and 2.3 MeV, respectively. They were characterized by β^- counting in a well calibrated gas flow proportional counter (Klopries et al., 1997) and decay curve analysis. In the case of ^{153}Sm ($T_{1/2}$ = 46.3 h), the activity was determined via high-resolution HPGe detector γ-ray spectrometry using the low energy γ-ray at 103.18 keV (28.3 %). The results are given in Table 2.

As in the previous work (Spahn et al., 2004), we estimate the uncertainty in the cross section values as approximately 17%.

4. Integral test of differential data(validation of excitation function)

The experimentally determined spectrum-averaged cross section $\langle\sigma\rangle$ can be used to check the differential data of a particular reaction under investigation, the $\langle\sigma\rangle$ being given by:

$$\langle\sigma\rangle = \int_{E_{thr}}^{E_{max}} \sigma\langle E\rangle\, \Phi(E)dE \Big/ \int_{E_{thr}}^{E_{max}} \Phi(E)dE$$

The calculated $\langle\sigma\rangle$ values were obtained using the neutron spectrum described above (Fig. 7) and the energy dependent cross section values from the recommended curves for the chosen six reactions (Figs. 1 to 6). A comparison of the measured and calculated data is given in Table 3. The uncertainties in the experimental data are given. It should be mentioned that the calculated $\langle\sigma\rangle$ values have also inherent uncertainties. Since the neutron spectral distribution has an uncertainty of about 8 %, and the recommended excitation function curves have estimated uncertainties of about 4 % in the case of the well-investigated reactions like those for the formation of ^{32}P and ^{64}Cu, and about 8% for the other reactions, the total uncertainty in the calculated $\langle\sigma\rangle$ may amount between 9 and 11 % (cf. Ibn Majah et al., 2001). Keeping the uncertainties of both the experimental and calculated data in mind, the measured and calculated $\langle\sigma\rangle$ values show good agreement (Table 3). We therefore conclude that the recommended cross section data of all the

above mentioned six reactions are validated via the integral tests done in this work, within 10 % in the case of well-investigated reactions and within 15 % for the others.

5. Applications of the data and conclusions

An analysis of the available information on the excitation functions of the $^{32}S(n,p)^{32}P$, $^{64}Zn(n,p)^{64}Cu$, $^{67}Zn(n,p)^{67}Cu$, $^{89}Y(n,p)^{89}Sr$, $^{90}Zr(n,p)^{90}Y$ and $^{153}Eu(n,p)^{153}Sm$ reactions allowed to suggest recommended data for those reactions. Those data could now be used as standards for calculating the averaged cross sections for a given neutron spectrum, e.g. fission or d(Be) break-up neutrons. There has been a lack of such evaluated data and a running co-ordinated research project (CRP) of the IAEA has actually requested such evaluations and their validations (cf. Sublet and Capote Noy, 2004). In this work, the recommended excitation function curves were also validated within about 15% by integral tests using a 14 MeV d(Be) neutron field, thus meeting both the requests of the IAEA.

Besides data development in general, it is interesting to consider the significance of the measured integral cross sections in the actual production of the above mentioned therapeutic radionuclides with high specific activity. The four most important radionuclides are ^{32}P, ^{64}Cu, ^{67}Cu and ^{89}Sr. As mentioned above, in the case of ^{64}Cu and ^{67}Cu the emphasis has shifted over to cyclotron production. For the other two radionuclides, the only way of achieving high specific activity is presently the production via the (n,p) reaction. Our earlier study (Spahn et al., 2004) showed that the $^{89}Y(n,p)^{89}Sr$ reaction with 14 MeV d(Be) neutrons has three times higher cross section than with fission neutrons, and the present work gives approximately the same result for the reaction $^{32}S(n,p)^{32}P$ as well [$\langle\sigma\rangle$ 14 MeV d(Be) = 152 ±

27 mb; $\langle\sigma\rangle_{FS} = 69 \pm 4$ mb]. Thus the production of both ^{32}P and ^{89}Sr can be done more effectively with high-intensity fast neutron spectral sources (e.g. a fusion or a spallation source) than with the present day research reactors.

As far as the production of ^{90}Y is concerned, the $^{90}Zr(n,p)^{90}Y$ reaction does not have high enough cross section and so it cannot compete with the commonly used $^{90}Sr/^{90}Y$ generator system, since ^{90}Sr is available in large quantities via the fission process.

The case of ^{153}Sm is very interesting. It is presently produced via the $^{153}Sm(n,\gamma)$-process in large quantities but with low specific activity. The increasing importance of this radionuclide in radiotherapy demands a search for alternative production routes which could lead to higher specific activity ^{153}Sm. In this regard, the $^{153}Eu(n,p)^{153}Sm$ reaction investigated in this work may be worth considering. The estimated cross section of this reaction with fission neutrons is only 0.015 mb (cf. Calamand, 1974), and thus too low for production purposes. The measured value with 14 MeV d(Be) neutrons is considerably higher (0.26 ± 0.04 mb). Thus, if a 5g sample of Eu_2O_3 is irradiated at our facility (with about 10^{10} n·cm^{-2}·s^{-1}) for 100 h, about 18 kBq of no-carrier-added ^{153}Sm would be produced at the end of the bombardment (EOB). Use of an enriched ^{153}Eu target would increase the yield to about 35 kBq but the total ^{153}Sm activity would still be rather low for practical applications. Newer concepts of spallation neutron sources aim at flux densities of $> 10^{14}$ n·cm^{-2}·s^{-1}. If production is done at such a facility, the total ^{153}Sm yield could be > 350 MBq and its specific activity quite high. The product would then be sufficient and more suitable for therapeutic applications.

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Table 1. Nuclear reactions, threshold energies and decay data of the radioactive products induced in a set of foils used for neutron spectrum unfolding

Nuclear reaction	Decay data of activation product			Threshold energy (MeV)
	$T_{1/2}$	E_γ (keV)	I_γ (%)	
$^{58}Ni(n,p)^{58m+g}Co$	70.91 d	810.7	99.44	0.4
$^{115}In(n,n')^{115m}In$	4.48 h	336.0	45.90	0.4
$^{47}Ti(n,p)^{47}Sc$	3.34 d	159.0	67.90	1.0
$^{54}Fe(n,p)^{54}Mn$	312.2 d	834.5	99.97	1.5
$^{46}Ti(n,p)^{46m+g}Sc$	83.83 d	889.0	99.97	1.8
$^{56}Fe(n,p)^{56}Mn$	2.57 h	846.0	100	2.8
$^{27}Al(n,\alpha)^{24}Na$	15.03 h	1369.0	100	3.2
$^{48}Ti(n,p)^{48}Sc$	1.82 d	983.0	100	3.2
$^{197}Au(n,2n)^{196}Au$	6.18 d	355.6	87.0	8.0
$^{93}Nb(n,2n)^{92m}Nb$	10.15 d	934.0	100	8.8
$^{58}Ni(n,2n)^{57}Ni$	1.50 d	127.2	16.6	12.4

Table 2. Integral cross sections* measured in this work

Nuclear reaction	Cross section $\langle\sigma\rangle$ (mb)
$^{32}S(n,p)^{32}P$	152 ± 27
$^{90}Zr(n,p)^{90g}Y$	2.7 ± 0.50
$^{153}Eu(n,p)^{153}Sm$	0.26 ± 0.04

* averaged for a 14 MeV d(Be) break-up neutron spectrum

Table 3 Comparison of integral† and integrated data*

Nuclear reaction	$\langle\sigma\rangle$ (mb)		
	Integral	Integrated	σ (Integral)/ σ (Integrated)
$^{32}S(n,p)^{32}P$	152 ± 27	167	0.91
$^{64}Zn(n,p)^{64}Cu$	132 ± 25	140	0.94
$^{67}Zn(n,p)^{67}Cu$	5.13 ± 0.87	5.0	1.03
$^{89}Y(n,p)^{89}Sr$	0.91 ± 0.20	1.05	0.87
$^{90}Zr(n,p)^{90g}Y$	2.7 ± 0.50	3.20	0.85
$^{153}Eu(n,p)^{153}Sm$	0.26 ± 0.04	0.30	0.87

† experimental measurement using the 14 MeV d(Be) breakup neutron field

* deduced from the recommended excitation function and the 14 MeV d(Be) breakup neutron field

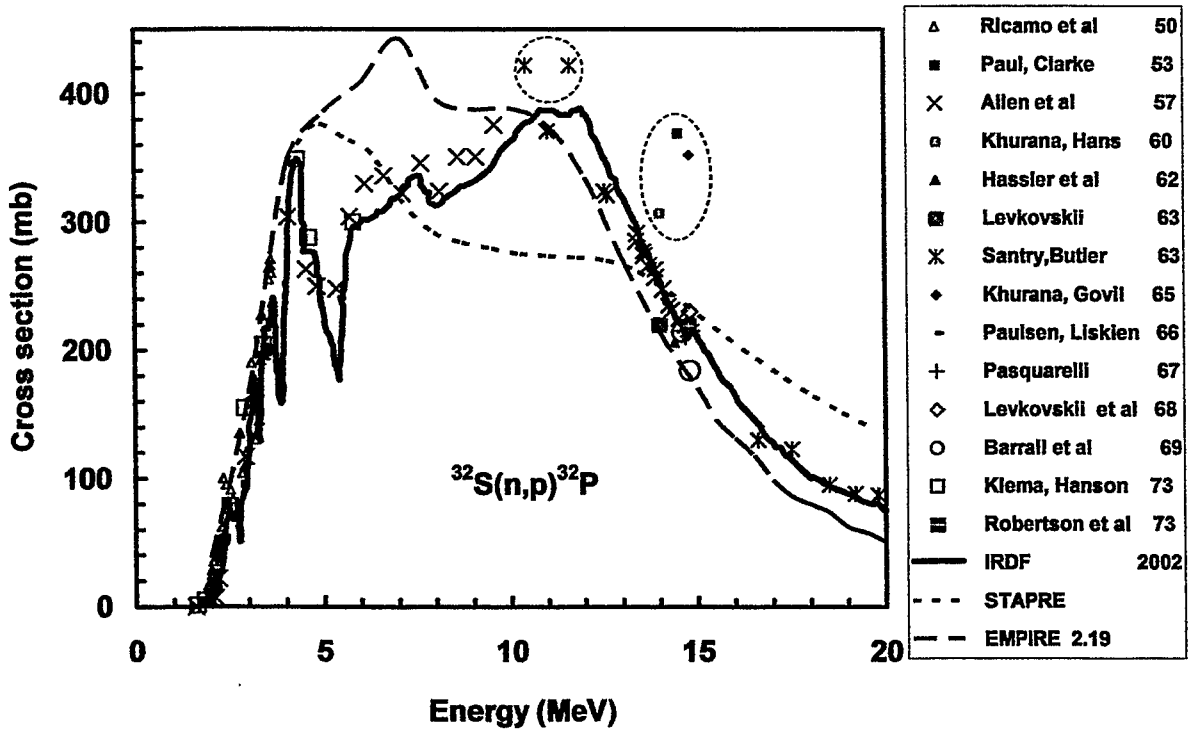

Fig. 1. Excitation function of the $^{32}S(n,p)^{32}P$ reaction. For references to experimental data cf. EXFOR. The data by Paul and Clarke (1953), Khurana and Hans (1960) and Khurana and Govil (1965) are discrepant and should be neglected. Out of the three data points measured by Santry and Butler (1963) using the d-d neutrons, the ones at 10.4 and 11.6 MeV also appear to be discrepant but their other data up to 20 MeV obtained using the d-t neutrons are consistent. The discrepant data are encircled. The results of nuclear model calculations (STAPRE and EMPIRE 2.19) and the curve given in the Dosimetry file (IRDF-2002) are also shown. The IRDF-2002 curve is recommended.

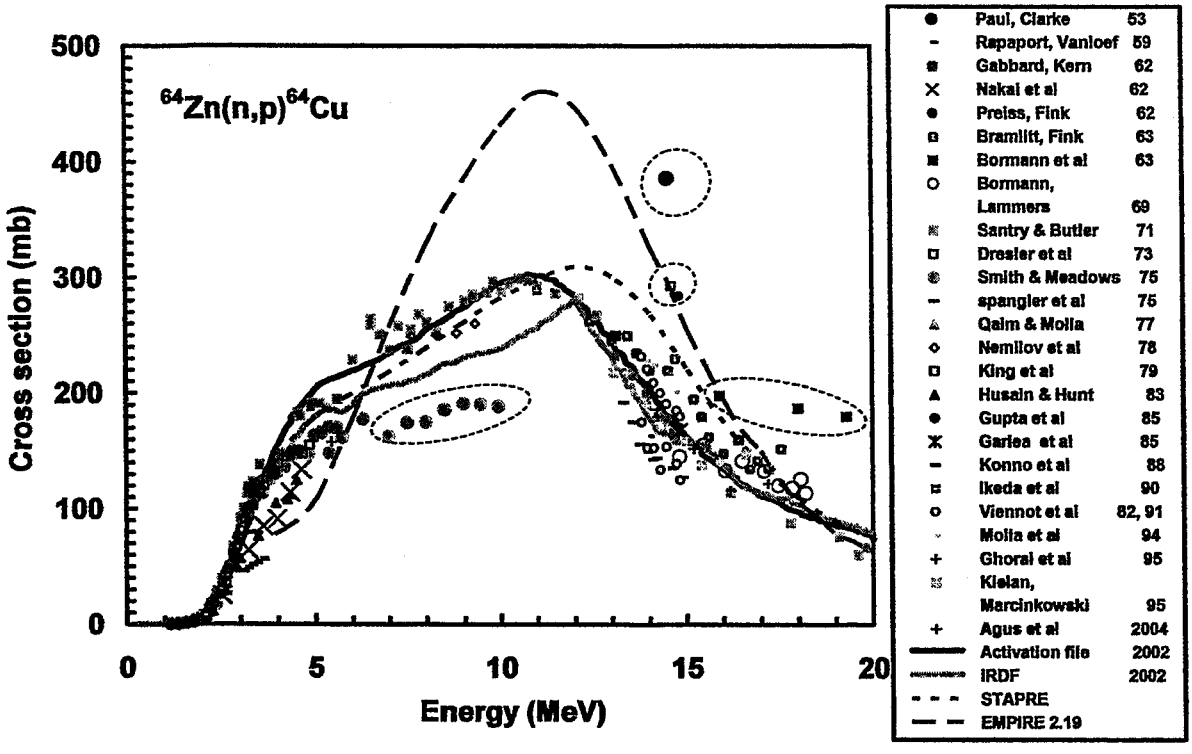

Fig. 2. Excitation function of the ^{64}Zn(n,p)^{64}Cu reaction. For references to experimental data cf. EXFOR. Some data sets between 5 and 10 MeV (Smith and Meadows, 1975), around 15 MeV (Paul and Clarke, 1953; Preiss and Fink, 1962; Dresler et al., 1973), and between 16 and 20 MeV (Bormann et al., 1963) are rather discrepant and are encircled. They should be neglected. The results of nuclear model calculations (STAPRE and EMPIRE 2.19) and the curves given in the Dosimetry and Activation files are also shown. The Activation library curve is recommended.

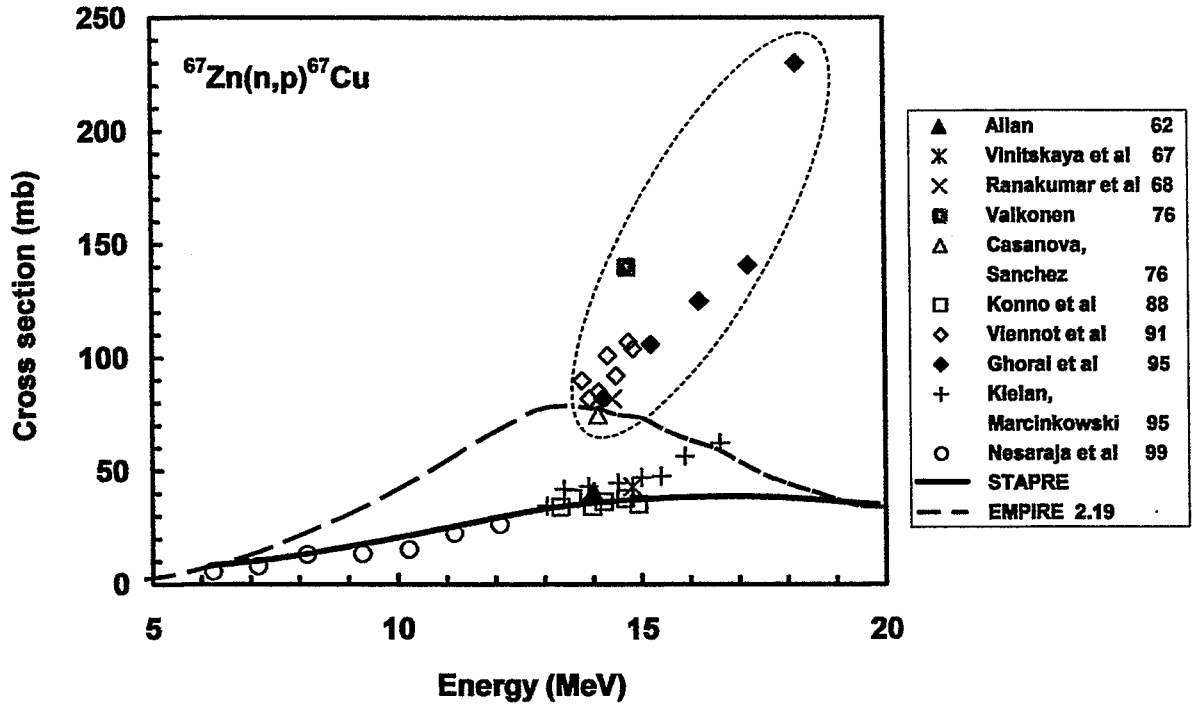

Fig. 3. Excitation function of the ^{67}Zn(n,p)^{67}Cu reaction. For references to experimental data cf. EXFOR. The low energy data (Nesaraja et al., 1999) and some of the data at higher energies(Allan, 1962, Konno et al., 1988; Kielan and Marcinkowski, 1995) appear to be more consistent. The data reported in the higher energy region by some other authors (Ranakumar et al., 1968; Casanova and Sanchez, 1976; Viennot et al., 1991; Ghorai et al., 1995) appear to be rather high and should be ignored. The discrepant data are encircled. In particular the two data sets above 15 MeV (Ghorai et al., 1995; Kielan and Marcinkowski, 1995) differ considerably from each others. The results of nuclear model calculations (STAPRE and EMPIRE 2.19) are also shown. The STAPRE curve is recommended.

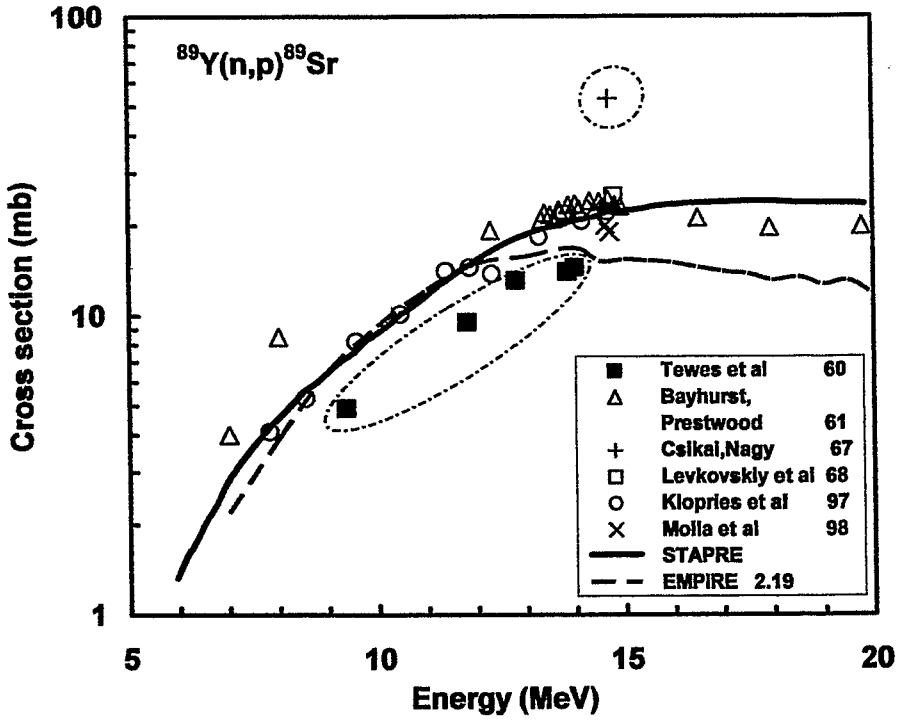

Fig. 4. Excitation function of the ^{89}Y(n,p)^{89}Sr reaction. For references to experimental data cf. EXFOR. The results of Tewes et al. (1960) are rather low and of Csikai and Nagy (1967) rather high. They are encircled. The results of nuclear model calculations (STAPRE and EMPIRE 2.19) are also shown. The STAPRE curve is recommended.

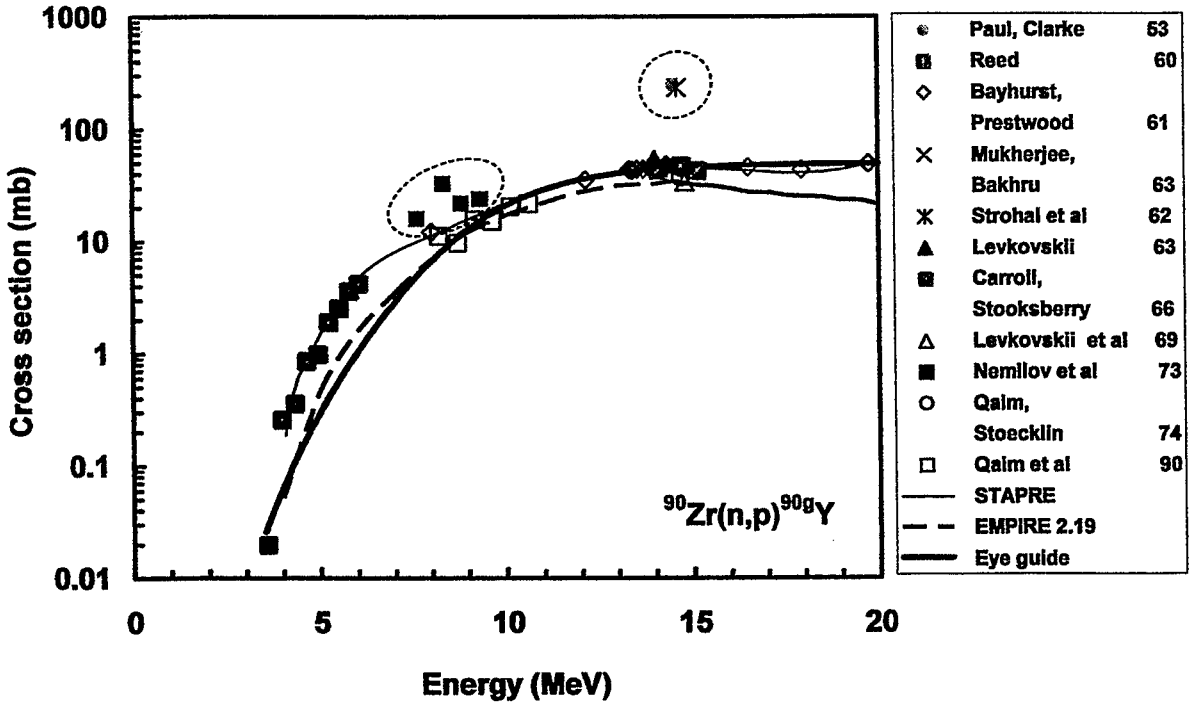

Fig. 5. Excitation function of the ^{90}Zr(n,p)^{90}Y reaction. For references to experimental data cf. EXFOR. Some of the data near the threshold(Carroll and Stooksberry, 1966) were shown (cf. Qaim et al., 1990) to be shifted to lower energies by about 1 MeV and the others (Nemilov et al., 1973) to be too high. Similarly the data by Paul and Clarke (1953) and Strohal et al., (1962) are also too high. They are encircled. The results of nuclear model calculations (STAPRE and EMPIRE 2.19) are also shown. The eye guide curve was drawn through all the data points in the high energy region but only through the Jülich data (Qaim et al., 1990) in the lower energy region. The eye guide curve is recommended.

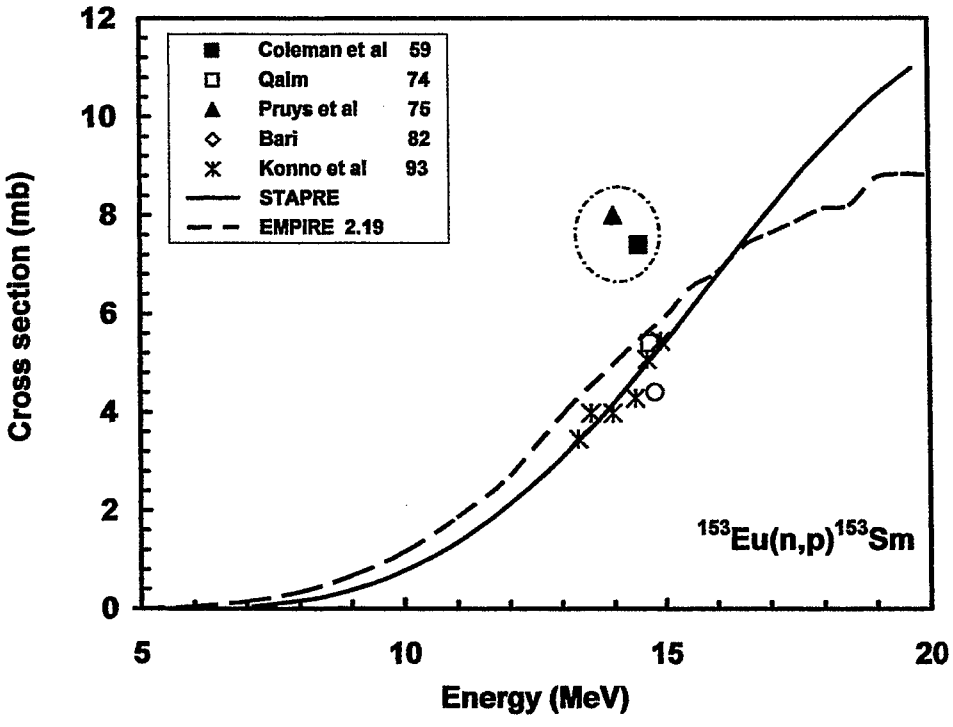

Fig. 6. Excitation function of the $^{153}Eu(n,p)^{153}Sm$ reaction. For references to experimental data cf. EXFOR. The data by Coleman et al (1959) and Pruys et al (1975) appear to be rather high and are encircled. They were ignored. The results of nuclear model calculations (STAPRE and EMPIRE 2.19) are also shown. The STAPRE curve is recommended.

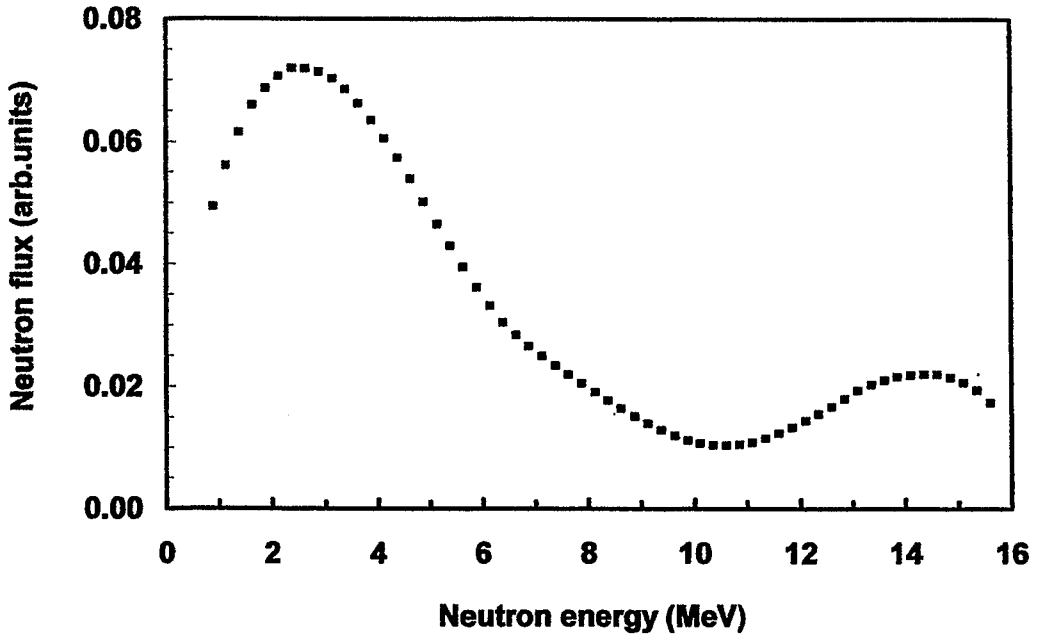

Fig. 7. Energy spectrum of 14 MeV d(Be) neutrons determined via multiple foil activation and the iterative computer code SULSA.