

A large acceptance scintillator detector with wavelength shifting fibre read-out for search of eta-nucleus bound states

The GEM Collaboration: M.G.Betigeri^a, P.K.Biswas^b,
A. Budzanowski^c, A. Chatterjee^a, R. Jahn^d, S.Guha^b,
P.Hawranek^e, B.K.Jainⁿ, S.B.Jawale^b, V. Jha^{a,*}, K. Kilian^f,
S. Kliczewski^c, Da. Kirillov^f, Di. Kirillov^g, D. Kolev^h,
M. Kravcikovaⁱ, T. Kutsarova^j, M. Lesiak^f, J. Lieb^k,
H. Machner^{f,o}, A. Magiera^e, R. Maier^f, G. Martinska^l,
S. Nedev^m, N. Piskunov^g, D. Prasuhn^f, D. Protić^f,
J. Ritman^f, P. von Rossen^f, B. J. Roy^a, P. Shukla^a, I. Sitnik^g,
R. Siudak^{c,f}, R. Tsenov^h, M. Ulicny^l, J. Urban^l, G. Vankova^{f,h}

^a*Nuclear Physics Division, BARC, Mumbai-400 085, India*

^b*Centre for Design and Manufacture, BARC, Mumbai-400 085, India*

^c*Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland*

^d*Helmholtz-Institut für Strahlen- und Kernphysik der Universität Bonn, Bonn,
Germany*

^e*Institute of Physics, Jagellonian University, Krakow, Poland*

^f*Institut für Kernphysik, Forschungszentrum Jülich, Jülich, Germany*

^g*Laboratory for High Energies, JINR Dubna, Russia*

^h*Physics Faculty, University of Sofia, Sofia, Bulgaria*

ⁱ*Technical University Kosice, Kosice, Slovakia*

^j*Institute of Nuclear Physics and Nuclear Energy, Sofia, Bulgaria*

^k*Physics Department, George Mason University, Fairfax, Virginia, USA*

^l*P. J. Safarik University, Kosice, Slovakia*

^m*University of Chemical Technology and Metallurgy, Sofia, Bulgaria*

ⁿ*Physics Department, Mumbai University, Vidyanagari, Mumbai*

^o*Fachbereich Physik, Universität Duisburg-Essen, Duisburg, Germany*

Abstract

A large acceptance scintillator detector with wavelength shifting optical fibre readout has been designed and built to detect the decay particles of η -nucleus bound system (the so-called η -mesic nuclei), namely, protons and pions. The detector, named as ENSTAR detector, consists of 122 pieces of plastic scintillator of various shapes and sizes, which are arranged in a cylindrical geometry to provide particle identification, energy loss and coarse position information for these particles. A solid angle coverage of $\sim 95\%$ of total 4π is obtained in the present design of the detector. Monte Carlo phase space calculations performed to simulate the formation and decay of η -mesic nuclei suggest that its decay particles, the protons and pions are emitted with an opening angle of $150^\circ \pm 20^\circ$, and with energies in the range of 25 to 300 MeV and 225 to 450 MeV respectively. The detailed GEANT simulations show that $\sim 80\%$ of the decay particles (protons and pions) can be detected within ENSTAR. Several test measurements using alpha source, cosmic-ray muons etc. have been carried out to study the response of ENSTAR scintillator pieces. The in-beam tests of fully assembled detector with proton beam of momentum 870 MeV/c from the Cooler synchrotron COSY have been performed. The test results show that

the scintillator fiber design chosen for the detector has performed satisfactorily well. The present article describes the detector design, simulation studies, construction details and test results.

Key words: Scintillator detector; WLS optical fibre read-out; Eta-nucleus bound states

1 Introduction

A large acceptance plastic scintillator detector ENSTAR has been designed and built for studies of η -mesic nuclei - a bound system of η -meson and a nucleus. The finding of strong and attractive nature of the η -nucleon(η -N) scattering length and the presence of a resonance near the η -N threshold, provide an interesting possibility of the formation of η -nucleus bound states [1,2]. The experimental confirmation of the existence of such bound systems would open up new avenues for elucidation of the η -nucleus dynamics at intermediate energies. Such experiments [3] are being performed at the intermediate energy accelerator facility COSY Jülich, using GeV energy proton beam. The experiments use recoil-free transfer reactions $p+({}^Z X_A) \rightarrow {}^3\text{He} + ({}^{Z-1} X_{A-2})_\eta$ on several target nuclei $X = \text{Li, C, Al, etc.}$ The expected cross section for events corresponding to formation of η -mesic nuclei is rather low, hence, a dedicated detection system is needed to enhance the sensitivity of the measurement. ENSTAR is the part of detection system which has been developed in order to obtain an unambiguous signal for the formation and decay of the η -nucleus

* Corresponding author. Nuclear Physics Division, BARC, Trombay, Mumbai-400085, India. Tel:++91-22-25593457; Fax: ++91-22-25505151.

Email address: vjha@barc.gov.in (V. Jha).

17 bound state. The outgoing ${}^3\text{He}$ particles are detected in the Big Karl detec-
18 tion system [4,5], which includes a magnetic spectrograph and its focal plane
19 detectors consisting of drift chambers and scintillator hodoscopes. The corre-
20 sponding proton and pion from the decay of η -mesic nucleus are registered in
21 ENSTAR. In addition to the η -bound states search, the ENSTAR detector can
22 also be used in many other experiments where the missing mass determination
23 of the reaction product needs to be done in coincidence with its decay prod-
24 ucts e.g., for the study of Δ interaction in nuclear matter, where the decay
25 products of Δ states, protons and pions can be detected by ENSTAR [6]. The
26 details of the Big Karl spectrometer have been reported elsewhere [4,5]. In this
27 paper, the description of the newly built ENSTAR detector is reported. The
28 geometric design, simulation studies and fabrication procedure are described.
29 Test measurements done at various stages during the construction of ENSTAR
30 as well as the in-beam tests performed at the COSY accelerator are presented.

31 **2 Physics background and ENSTAR design considerations**

32 Phase space calculations to simulate eta-mesic nucleus decay events were per-
33 formed using the N-body Monte-Carlo event generator program “Genbod” [7].
34 The program generates multi-particle weighted events according to Lorentz in-
35 variant Fermi phase space. The reaction $p+{}^{16}\text{O} \rightarrow {}^3\text{He}+{}^{14}\text{N}_\eta$ was studied at
36 a momentum close to the magic momentum. The magic momentum is defined
37 as the beam momentum at which recoil-less η can be produced in the ele-
38 mentary process. For the reaction considered, the elementary reaction is pd
39 $\rightarrow {}^3\text{He}\eta$, for which the magic momentum was calculated to be 1.745 GeV/c,
40 corresponding to a proton kinetic energy of $T_p=1.05$ GeV. The η -nuclei for-

41 mation proceeds through the excitation of N^* (1535 MeV) resonance and one
 42 of its decay channels is through proton and pion. The simulations were per-
 43 formed in two steps. In the first step, Monte Carlo events were generated for
 44 the $p+^{16}\text{O} \rightarrow {}^3\text{He}+^{14}\text{N}_{ex}$ reaction where an excitation energy of 547 MeV,
 45 equal to the mass of eta meson, is given to ^{14}N nucleus. Only those ^{14}N events
 46 were considered for which the corresponding ${}^3\text{He}$ particle is within the Big
 47 Karl acceptance ($\theta_{lab}({}^3\text{He}) \leq 6^\circ$). In the next step, the decay of N^* to $p-\pi$
 48 pair was simulated. The mass of N^* was taken equal to the mass of a nucleon
 49 plus the mass of an eta meson, while its velocity was assumed to be the same
 50 as that of the recoil ^{14}N modified by the Fermi momentum distribution. The
 51 $p-\pi$ opening angle distribution shows a peak at around $\approx 150^\circ$ with a width of
 52 40° (Fig. 1). The energy spectrum for the proton peaks at $T_p \approx 100$ MeV with
 53 a width (FWHM) of 120 MeV (Fig. 2), while the pion spectrum has a peak
 54 at ≈ 320 MeV and a similar width (Fig. 3) as that of proton peak. The sim-
 55 ulations were also carried out for other eta-mesic nuclei formation reactions
 56 on different target nuclei. The energy spectra and opening angle distributions
 57 were found to be similar as that in the previous case.

58

59 A detector employing plastic scintillators in the $\Delta E - E$ configuration, which
 60 provides the particle identification and energy information of the measured
 61 particles, has been chosen for the present design. The thickness of the detector
 62 elements has been designed to stop the decay protons and obtain a good
 63 signal for pions, keeping in mind the space constraints around the detector
 64 in the experimental area. The detector has been segmented in both θ and ϕ
 65 direction for obtaining position information with the desired granularity. Large
 66 solid angle coverage has been achieved by minimising any unwanted material

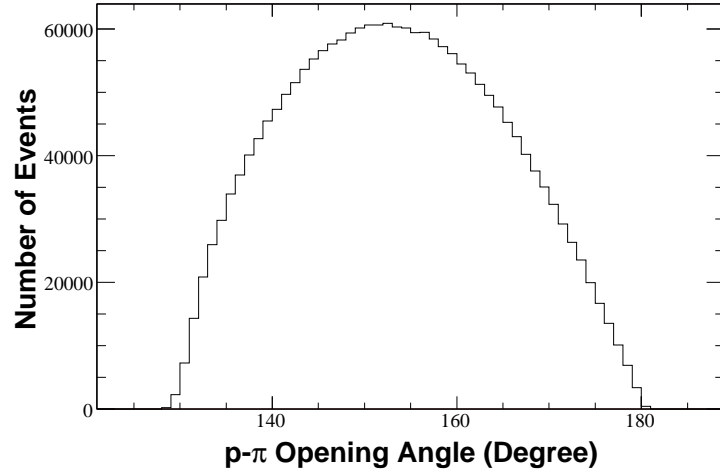


Fig. 1. The p- π opening angle distribution for η -mesic nucleus decay particles obtained from Monte-Carlo phase space calculations as detailed in the text.

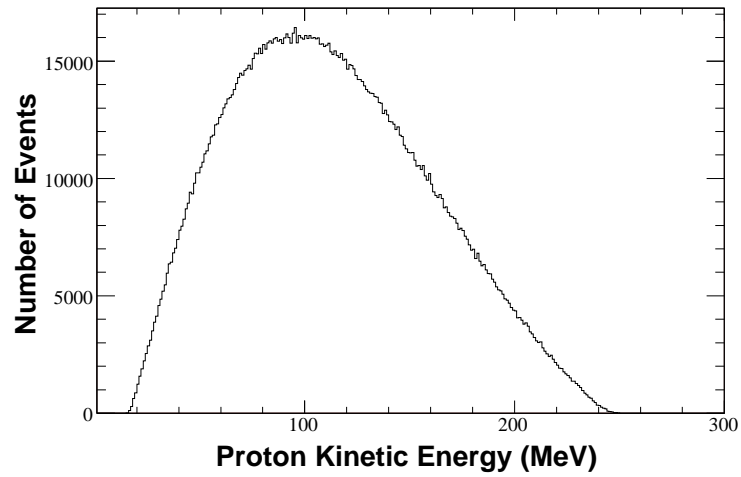


Fig. 2. Kinetic energy distribution of protons from η -mesic nucleus decay obtained from Monte-Carlo phase space calculations.

67 within the detector.

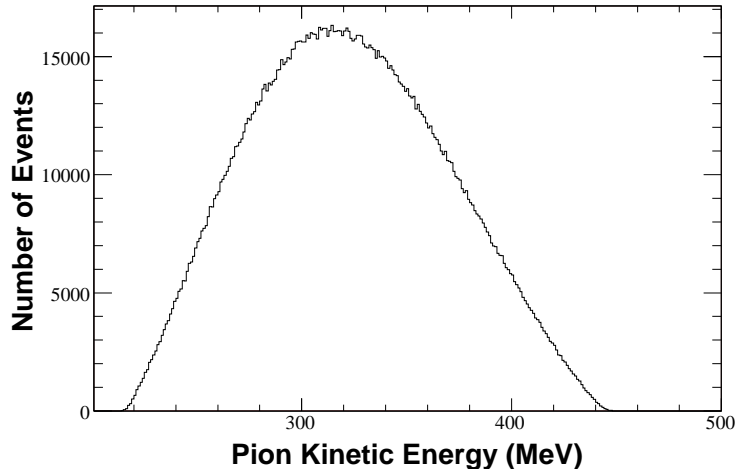


Fig. 3. Kinetic energy distribution of pions from η -mesic nucleus decay obtained from Monte-Carlo phase space calculations.

68 3 Design details and fabrication

69 3.1 Detector geometry

70 Based on the design and geometric criteria, ENSTAR is cylindrically shaped
 71 with three layers of plastic scintillators. These layers are used to generate
 72 $\Delta E - E$ spectrum for particle identification and to obtain total energy infor-
 73 mation for the stopped particles. Each layer is divided into a number of pieces
 74 to obtain θ and ϕ information. The detector, which is made up of two identi-
 75 cal half cylinders, is assembled around a scattering chamber of 1.5 mm thick
 76 carbon compound fibre material. The scattering chamber as shown in Fig. 4 is
 77 designed in a "T" shape with a thin target pipe projecting out from the middle
 78 of beam pipe. The two half cylinders of the detector are placed on either side
 79 of the target pipe. The target pipe has sufficient space from inside to enable
 80 mounting of solid targets. A Liquid target chamber, similar to the one existing
 81 at COSY laboratory can also be used after some modifications. The angular

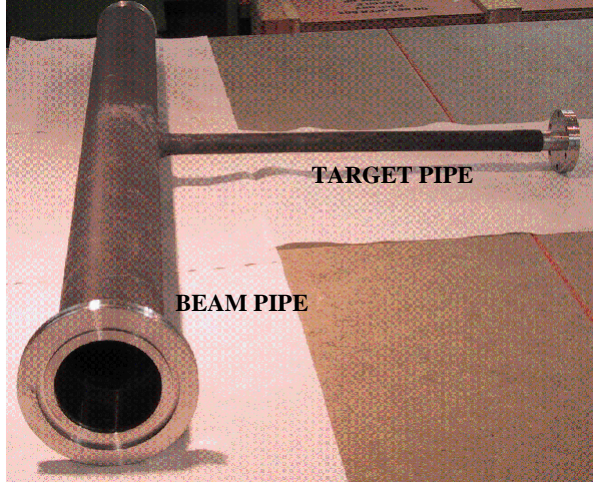


Fig. 4. Photograph of the scattering chamber made from the carbon fibre material. It consists of a beam pipe and a thin target pipe for inserting a target ladder.

82 coverage of the detector is $\theta_{lab} = 15^\circ - 165^\circ$ in the θ -direction, while its cylin-
 83 drical geometry ensures an azimuthal angle coverage of $\phi = 0^\circ - 360^\circ$. With
 84 the present design, the detector provides a solid angle coverage of $\sim 95\%$ of
 85 4π . An assembly drawing of ENSTAR together with its sectional view through
 86 the target is shown in Fig. 5. A total of 122 pieces of scintillators of different
 87 shapes and dimensions are used to give three concentric cylindrical layers on
 88 assembly.

89

90 The inner layer is used to provide the energy loss and ϕ information of the
 91 particles passing through it and is designed as two hollow plastic scintillator
 92 cylinders with the following dimensions; Inner diameter(ID) = 84 mm, Outer
 93 diameter(OD)=96 mm and a length of 390 mm. Both the cylinders are split
 94 into eight equal sectors with a sector angle equal to 45° . Thus the inner layer
 95 consists of a total of 16 segmented annuli each of which is read out separately.
 96 A ϕ resolution of 45° is satisfactory for the studies on η -mesic nuclei, as the
 97 decay particles are emitted with a very large opening angle between them.

108 Signals from the middle layer are used to obtain energy and θ information.
109 This layer consists of seven identical scintillator bars in both the halves, each
110 in the form of an isosceles triangle with base = 243.1 mm and height = 152.4
111 mm arranged to form an annular cylinder of ID=100 mm, OD= 449.4 mm and
112 length = 390 mm in each half. Each of triangular bars (390 mm long) is further
113 split lengthwise into six pieces of length 13 mm, 16 mm, 21 mm, 37 mm, 213
114 mm, and 90 mm so that each piece covers an angle interval of $\Delta\theta_{lab}$ equal to
115 15° . A total of 84 pieces of scintillators are used for the middle layer cylinder.
116 The geometrical granularity allows an angular resolution of $\Delta\theta_{lab}$ equal to 15° .
117 In conjunction with signals from middle layer, signals from the outer layer are
118 expected to provide an unambiguous signal for pions. The outer layer consists
119 of a total of 22 identical bars, each 390 mm long and a cross section of an
120 isosceles triangle with base = 328.3 mm and height = 105.5 mm. These outer
121 layer pieces form an annular cylinder of ID = 453.5 mm, OD = 692.5 mm.
122 Thus, with two identical cylinders on either side of the target for all the three
123 layers, the detector provides an angular coverage of $15 \leq \theta_{lab} \leq 165^\circ$ in the
124 θ -direction and almost full coverage in the ϕ -direction.

115

116 3.2 GEANT simulation

117 GEANT [8] calculations have been carried out by simulating the conditions
118 of the real experiment to simulate the ENSTAR detector's response to eta-
119 nucleus decay particles, namely, protons and pions. The detector geometry has
120 all its 122 pieces arranged around the scattering chamber. The target has been
121 positioned at the centre of the detector, inside the scattering chamber which

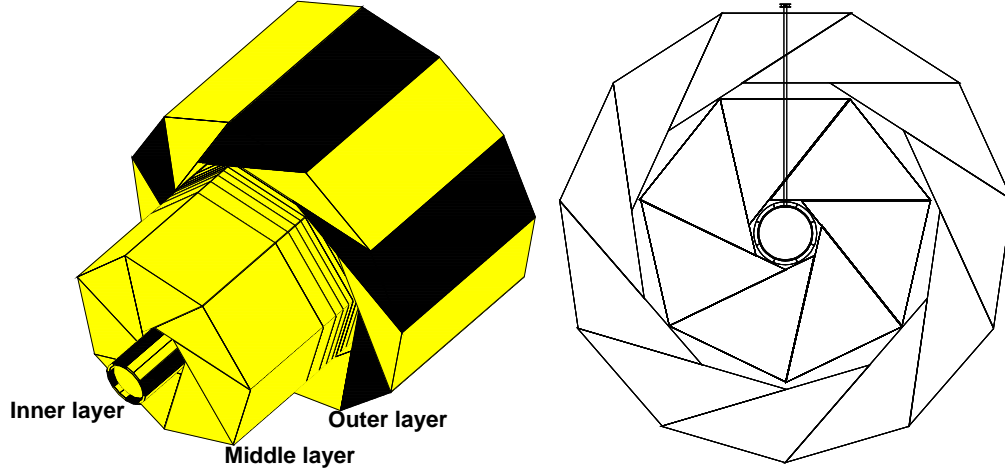


Fig. 5. Left part : An assembly drawing of ENSTAR detector is shown. Some pieces of the middle and outer layers are moved out for an inside view. Detailed dimensions are given in the text. Right part : A Sectional view of the detector through the target is shown. Beam pipe along with the target pipe attached to it, is also drawn.

122 is in vacuum. The existing gap between the various layers of ENSTAR is filled
 123 with air. The η -mesic nucleus decay events are produced in a collision of 1.05
 124 GeV proton beam with a target. A Monte Carlo event generator as detailed
 125 in section 2 is used to simulate such events. The protons are stopped in the
 126 detector while pions, as expected, pass through it giving only partial energy
 127 loss in the detector. Fig. 6 shows a two dimensional plot of energy loss in the
 128 first layer versus total energy loss in the detector. The response of various
 129 layers of ENSTAR for protons and pions from such events have been inves-
 130 tigated. The present design does not plan to obtain full energy information
 131 of pions, however, as desired a mass separation of pions from protons can be
 132 achieved. From the particle selection in the ΔE -E two-dimensional spectrum
 133 of Fig. 6, the decay events detected within the detector can be estimated. It
 134 is found that the 80 % of total protons and pions generated can be identified
 135 from the ΔE -E spectrum. It is further clear from the figure that the energy
 136 loss for most of pions is in the 50-100 MeV range , where a clear separation

137 between protons and pions can be achieved. The separation of pions from the
 138 protons could be difficult in the higher energy loss region of pions. However
 139 the fraction of the pion events in the energy range of 100-250 MeV is less
 140 compared to number of events in the low energy range.

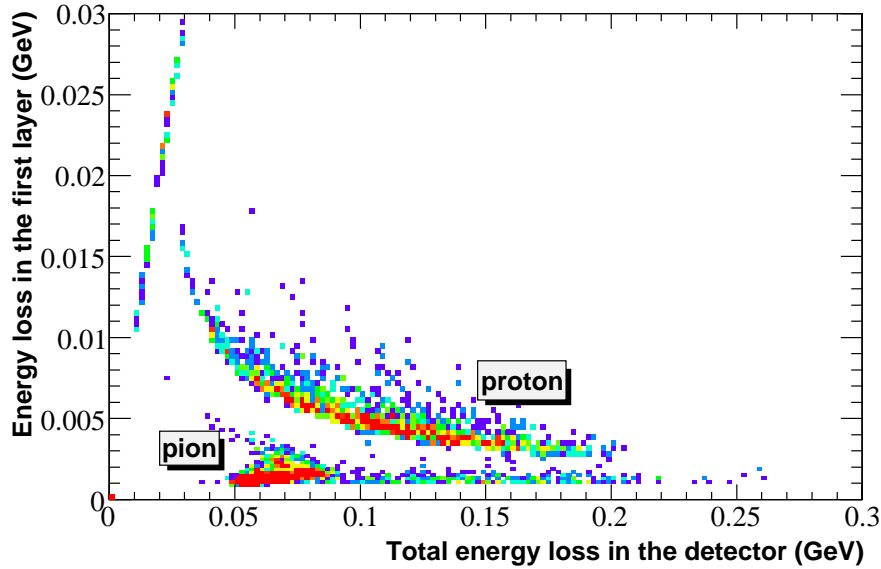


Fig. 6. A two dimensional plot of ΔE (energy loss in the inner layer) vs $E + \Delta E$ (energy loss in all the layers) showing the particle separation in ENSTAR. The results are obtained from GEANT simulations for the events from the η -mesic nucleus decay.

141

142 3.3 Scintillator grooving and fibre coupling

143 Plastic scintillators, having the properties equivalent to Bicron BC-408 series,
 144 were procured from Scionix Ltd, Netherlands [9], for the fabrication of detector
 145 elements. The use of light guides for scintillator read out was not practicable
 146 due to the complicated geometry of the detector. The idea of using wave-

147 length shifting (WLS) optical fibres for scintillator read out was invoked for
148 the present detector. Earlier studies[10,11] have shown that the double-clad fi-
149 bres give better light yield (70% more light) than comparable single clad ones,
150 due to an increase in the fraction of light that undergoes total internal re-
151 flection. The double-clad WLS optical fibres having 1mm diameter were used
152 for light transport. A number of grooves for fixing fibres to the scintillators
153 were made on the surface of scintillators . The middle and outer layer pieces
154 were machined for 19 grooves each having 4 mm width and 1.5 mm depth.
155 The grooves cover roughly 40 % of the area of one face of scintillator. For
156 the inner layer pieces, 15 grooves of 1.0 mm width and 1.5 mm depth were
157 machined with a spacing of 1.5 mm. The machining was done at the Central
158 Workshop, BARC using a computer controlled 4 mm (1mm for the grooves on
159 inner layer pieces) carbide cutter (End-Mill). A suitable cooling arrangement
160 with chilled air was used in order to avoid any local heating. Each piece of
161 middle and outer layer has 76 fibres placed in 19 grooves (4 fibres in each
162 groove), while each inner layer piece has 15 fibres (1 fibre in each groove. The
163 scheme of fibre scintillator coupling is illustrated in Fig. 7 for a typical middle
164 layer scintillator piece.

165

166 The total amount of fibre used was 7.8 km in length. The fibre length for
167 each scintillator pieces was decided on the basis of availability of space in the
168 experimental area. While the length of fibre should not be very long in order
169 to minimise attenuation losses, its bending radius should also be kept high.
170 The conventional minimum bending radius of these fibres is ten times the fi-
171 bre diameter. Bending fibres below this radius may result in significant light
172 loss due to damage in mechanical as well as optical properties. The length

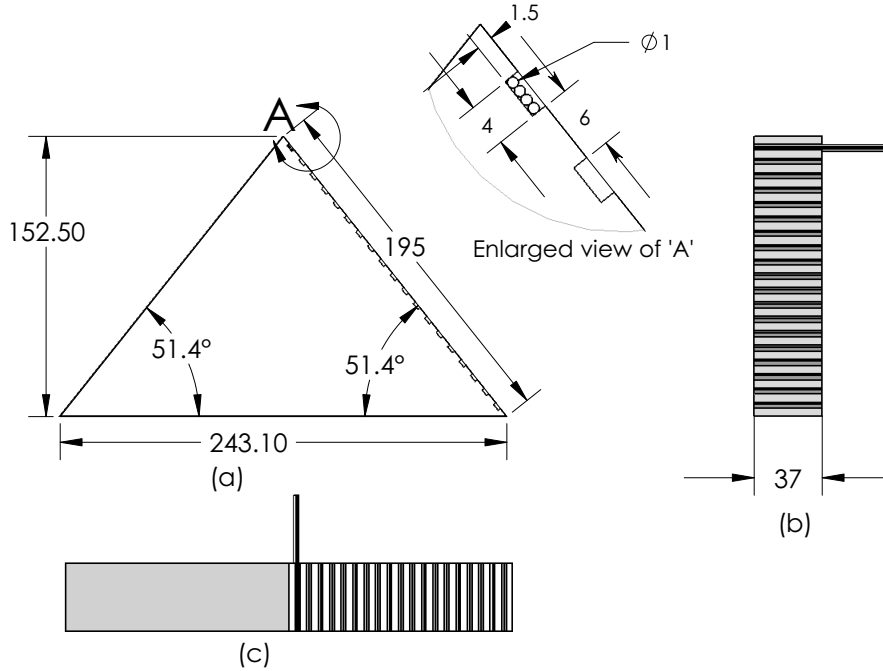


Fig. 7. The sketch diagram of a typical middle layer scintillator piece showing the grooves and fibre alignment details. There are 19 grooves on one face of this triangular bar with four fibers placed inside each groove. The alignment of fibres with the scintillator is shown in (b) and (c). For illustration purposes fibres in only one groove are drawn.

173 of fibres for each scintillator piece was optimized accordingly. Since the light
 174 readout is from one end of the fibres only, the light traversing to the other end
 175 must be reflected back. Therefore, before fixing the fibres, a highly reflective
 176 anodized aluminum sheet (known as EverBrite [12]) was placed on one face
 177 of the scintillator and held in place with aluminized mylar tape. A good sur-
 178 face finish and polished fibre ends are essential to prevent light losses at both
 179 the reflecting as well as at the readout interface . This has been achieved by
 180 different techniques. The cutting and polishing of fibres for the middle and
 181 outer layer pieces were done before fixing them to the scintillators. For polish-
 182 ing, many fibres were grouped together in bundles inside a perspex tube. The
 183 fibre face was cut along with the perspex by a diamond tipped cutting tool

184 giving a surface finish of $0.7 \mu\text{m}$. The final polishing of these fibres was done
185 with $0.3 \mu\text{m}$ size alumina powder on velvet cloth. The polished fibres were
186 fixed in the scintillator grooves with the Bicon 600 optical cement at few
187 locations along the grooves. However, to give an additional holding strength,
188 five-minute epoxy was used wherever necessary. It is preferable to use the
189 Bicon cement as it has the same refractive index as that of the scintillator
190 and its light transmission above 400 nm wavelength is more than 98% . In
191 addition, aluminized mylar tape was also used at few places for holding the
192 fibres. For the inner layer pieces, a different method was followed. First, the
193 fibres were fixed in the grooves using Bicon cement with a small amount of
194 five-minute epoxy glue at the ends of the fibre-scintillator joint. This end of
195 the scintillator along with the fibres were then polished for all 16 inner-layer
196 pieces. This was done at the optics workshop of the Spectroscopy Division,
197 BARC by the lapping technique. Fine alumina powder of $20 \mu\text{m}$, $12 \mu\text{m}$ and
198 $6 \mu\text{m}$ were used in successive stages of lapping. The final finishing was then
199 achieved by polishing with diamond paste and alumina of $1 \mu\text{m}$ and $0.3 \mu\text{m}$
200 sizes giving a surface finish of $0.3 \mu\text{m}$. Fig. 8 (left part) shows the polished end
201 of one of the scintillator pieces. Finally the highly reflective EverBrite sheet
202 was placed at this polished end (not shown in the figure) for light reflection.
203 The other open end of all the fibres of individual scintillator pieces were bun-
204 dled together and then glued to the inside of a 2.54 mm diameter perspex tube
205 - known as “cookie” [11] (a cylindrical piece of acrylic, matching the photo
206 multiplier tube in diameter). This end of fibres were polished along with the
207 cookie. The fibres along with the cookies were diamond polished by diamond
208 paste and alumina powder. Fig. 8 (middle picture) shows some of the finished
209 (except for its covering by black foil) inner layer pieces with fibres and cookie
210 attached. One of the middle layer piece is also shown in Fig. 8(right picture).

211 The cookie end was coupled to the photo-multiplier tube for conversion of the
212 light signal into photo-electrons which were then processed electronically. In
213 order to reduce light losses from scintillators, the scintillator elements were
214 wrapped with tyvek, a paper-white reflecting foil made of polyethylene[13].
215 The wrapping by tyvek, apart from light reflection, also helps in minimising
216 the cross-talk. All the detector pieces were finally covered by black tedlar foil
217 for light tightness and reducing the cross-talk among various detector elements.

218

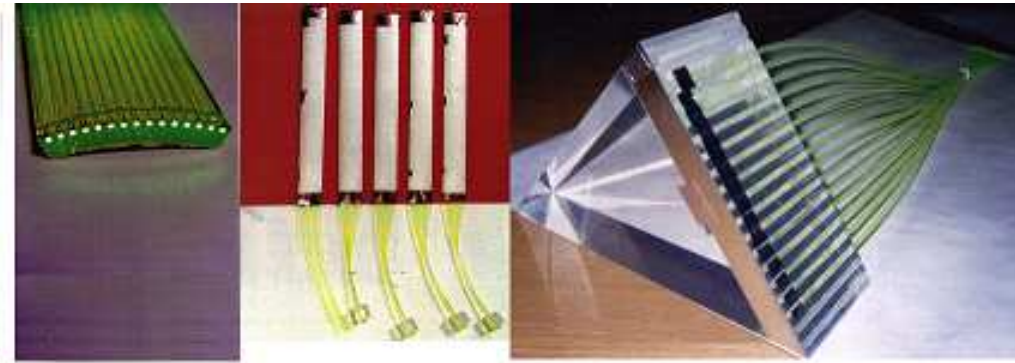


Fig. 8. Photograph of some inner and middle layer pieces of ENSTAR while being fabricated. Left part shows inner layer pieces with fibres inside scintillator grooves while the middle part shows the some of the similar pieces after it has been covered with the Tyvek paper. At the other end fibres from each piece are bundled together and coupled to a “cookie”. In the right part of the figure one of the middle layer pieces with fibres placed inside the grooves is shown.

219 3.4 Scintillator readout details

220 The Bicon optical fibre BCF-91A, used in the present detector for collect-
221 ing light produced in the scintillator volume has an emission spectrum in the
222 visible green region. In order to have an efficient readout of this light, the
223 photomultiplier tubes (PMTs) that have a spectral response extending into

224 the green region and which match the light emission characteristic of the wave
225 length shifting fibres were selected. The PMTs are of the 9112B series manu-
226 factured by Electron Tubes Ltd (ETL), United Kingdom [14]. The PMTs are
227 of 25 mm diameter with Rubidium bialkali photocathode having an enhanced
228 green sensitivity. A total of 122 photomultiplier tubes are used for the readout
229 of ENSTAR. The PMTs have a current amplification of 10^6 and a dark cur-
230 rent of less than 10 nA. The tubes are fast and have a rise time of less than 3
231 ns. The PMTs, during the experiment, were covered by μ -metal sheets which
232 have also been procured from ETL, UK. The base of the PMTs i.e., voltage
233 dividers are also made by the same manufacturer. Special aluminum holders
234 were fabricated for holding the PMTs and cookies together.

235 *3.5 Detector assembly*

236 The pieces of the inner layer of the detector are the lightest ones and were
237 easy to mount. They were simply held around the beam pipe/target chamber
238 with tape. The other pieces of ENSTAR i.e., middle and outer layer pieces
239 are relatively heavier and special support structures were designed and built
240 for holding these pieces in place. The basic supporting structure, which is
241 mostly an exoskeleton, was made from hylam (low Z material) plates. Due to
242 the compact geometry of the detector no support structure was needed inside
243 the sensitive volume of the detector, except only at few places in the space
244 between the middle and the outer layer where three support strips made of
245 hylam have been put in each half of the detector. These support strips were
246 joined by aluminum rings on both ends for the middle layer. The simulations
247 were repeated with and without the hylam strips (acting as inactive material

248 inside the detector). An acceptance loss of less than $\sim 1\%$ for the particles
249 to be detected is predicted. For the outer layer, the hylam plates were joined
250 by aluminum brackets at both ends. The detector after assembly was placed
251 on a stainless steel stand which was fixed on a movable trolley made from
252 angle-iron. A stand to hold PMTs was also constructed and integrated in the
253 same support structure. Fig. 9 shows a photograph of ENSTAR detector along
254 with its support structure mounted at the COSY beam line.

255



Fig. 9. A photograph of the ENSTAR detector mounted at the COSY beam line along with its support structure and the stand which has been used to transport the detector to the beam line.

256 4 Test Measurements

257 A number of test measurements were performed during the construction and
258 commissioning of the detector. A light-tight black box was constructed for the
259 preliminary tests of the phototubes and the scintillator pieces. The PMTs and
260 its bases were tested to check for their proper functioning and to determine
261 their optimum operating voltage. The variation of signal pulse height from a

262 scintillator tile was studied as a function of number of fibres. The pulse height,
 263 which depends on the amount of light collected by the fibres, is observed to
 264 increase with the increase in the number of fibres and saturates when fibre
 265 covers about 30 - 40% of the scintillator tile surface. The number of fibres
 266 for each scintillator tile has been optimized accordingly. The light output of
 267 different pieces of ENSTAR was also tested with an alpha source for which a
 268 simple test setup was constructed.

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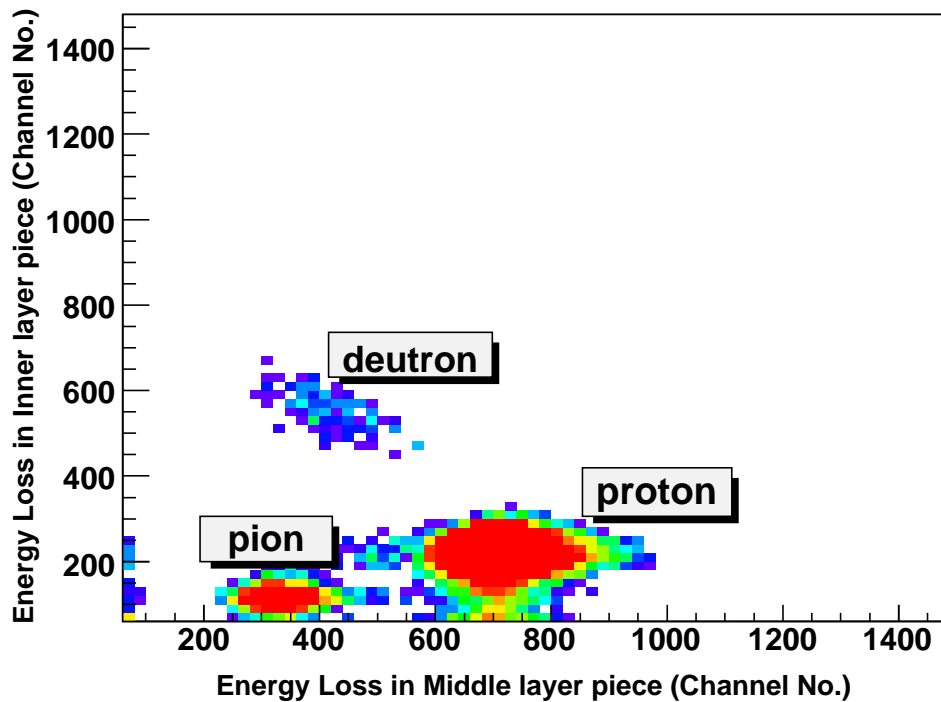


Fig. 10. A two dimensional spectrum of the energy losses in inner and middle layer pieces of ENSTAR mounted at the focal plane exit of Big Karl magnetic spectrograph in $\Delta E1 - \Delta E2$ configuration. The spectrum shows the pions, protons and deuterons of energies ~ 430 MeV, ~ 150 MeV and ~ 80 MeV respectively, which are selected by a BigKarl momentum setting of 550 MeV/c.

270 The first in-beam test at COSY was performed by mounting a few pieces of
271 ENSTAR from the inner and middle layers arranged in a $\Delta E1 - \Delta E2$ configu-
272 ration at the exit of the focal plane of the magnetic spectrograph BigKarl. A
273 proton beam of momentum 1.54 GeV/c, corresponding to kinetic energy of 865
274 MeV, was bombarded on a thick Alumina target. The spectrograph BigKarl
275 was set for different momenta to select various energies of protons from 35 to
276 225 MeV and pions in the range of 150 to 560 MeV. Fig. 10 shows the $\Delta E1$ -
277 $\Delta E2$ energy spectrum of various particles detected in scintillator pieces for a
278 typical BigKarl momentum setting of $p/q=550$ MeV/c. A Good separation
279 among all particle groups (e.g. pions, protons, deuterons etc.) was obtained.
280 The particle identification was confirmed from the time of flight information,
281 which was measured simultaneously between two hodoscopes layers placed at
282 a distance 4m apart at the focal plane of BigKarl.

283

284 The final test measurement of ENSTAR in fully assembled condition was per-
285 formed using a proton beam of momentum 0.870 GeV/c at COSY. In addition
286 to light-output test of all scintillator pieces, a study of the relative gain of vari-
287 ous elements and absolute calibration was performed. Several nuclear reactions
288 (pp elastic scattering, $pp \rightarrow d\pi^+$, proton impinging on a heavy target etc.)
289 were used for this purpose. Coincidence data i.e. a 2-fold coincidence between
290 different elements of ENSTAR were collected. In addition, cosmic-ray data
291 were also recorded with good statistics.

292

293 In the pp elastic scattering measurement scattered protons having energies
294 from 25 to 340 MeV are detected in the forward half of the detector. In this
295 case, the trigger was made from the events which have a double hit in the

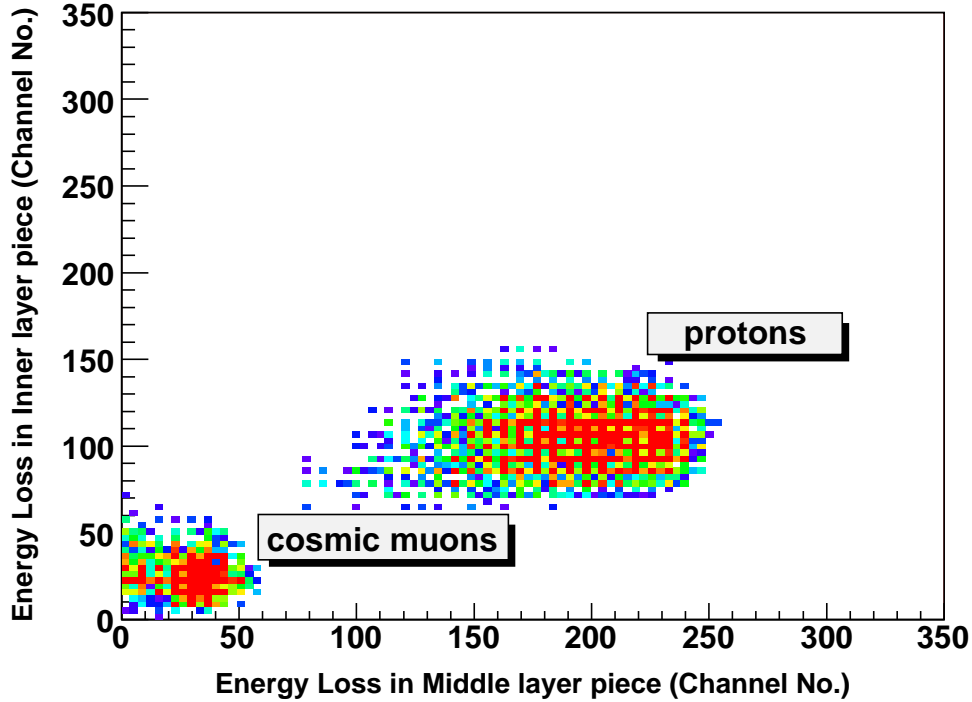


Fig. 11. A two dimensional spectrum of one of the inner layer piece vs the corresponding middle layer piece of ENSTAR for protons in the energy range of 225-330 MeV obtained from pp elastic scattering data. Cosmic ray data from a different run are also shown in the same figure.

296 inner layer and at least a single hit in the middle layer. In addition, the condi-
 297 tion of co-planarity of the elastically scattered proton pair was ensured. Light
 298 output of one of the inner-layer scintillator piece versus the corresponding
 299 middle-layer scintillator piece is plotted in Fig. 11. The proton band shown
 300 in the figure corresponds to an energy range of 225 – 330 MeV. A band cor-
 301 responding to cosmic muons is also shown in the figure which was obtained
 302 from cosmic-ray data collected separately in a different run, as described later
 303 in the text.

304

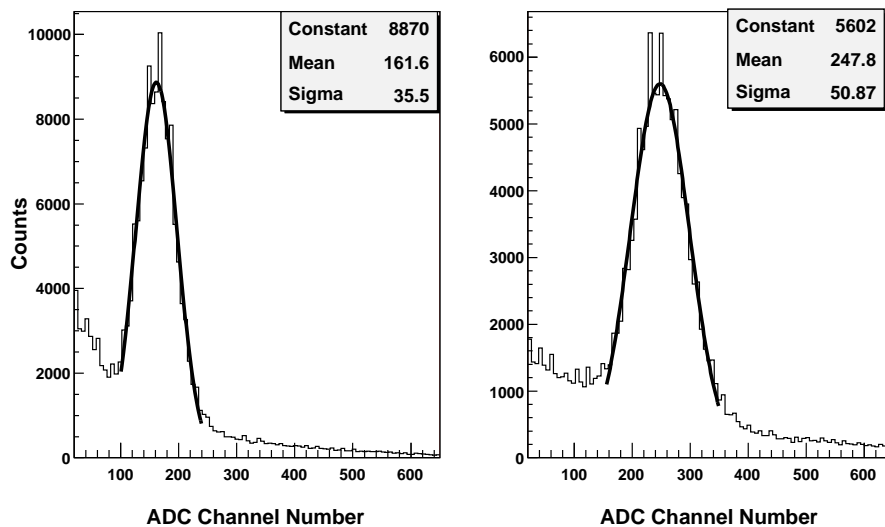


Fig. 12. ADC spectra of two adjacent middle layer scintillators uniformly illuminated in ϕ - direction by scattered particles from beam impinging on a thick target kept in front of detector. Peak positions are used to get the relative gains of various pieces in ϕ -direction.

305 The relative gain calibration among different scintillator pieces covering the
306 same θ - but different ϕ -ranges is achieved using reactions in which protons
307 are incident on a thick heavy target. In this case the target, instead of its
308 conventional location which is at the centre of ENSTAR, was placed at a po-
309 sition where the beam enters the detector, Scintillators of the same shape and
310 dimensions form an annular cylindrical ring and therefore, are uniformly illu-
311 minated by the scattered particles. The relative gain for the different elements
312 of the ring is obtained from the peak positions of the spectra shown in Fig. 12.
313 For measurements with the cosmic-rays, two additional scintillator hodoscope
314 paddles were placed just above and below the ENSTAR scintillator element
315 being tested. Signals from these paddles formed the cosmic-ray trigger. ADC
316 spectra from two adjacent scintillators of the middle layer for the cosmic data
317 are shown in Fig. 13 (left and middle part). The extreme right part of the

318 figure is a pedestal subtracted ADC spectrum generated from combination
 319 of these two spectra using the relative gain between the corresponding two
 320 pieces as determined above. The triangular shape of middle layer(as well as
 321 outer layer) scintillators and the present detector geometry allow a selection of
 322 an overlap portion between two adjacent scintillators such that muons travel
 323 a constant thickness of 150 mm. The centre of the peak corresponds to an
 324 average energy loss of ~ 27 MeV since a minimum ionizing particle typically
 325 loses ~ 1.8 MeV per cm of plastic scintillator [15]. This method was used to
 326 extract the absolute gain calibration of all the middle and outer layer scintil-
 327 lator pieces.

328

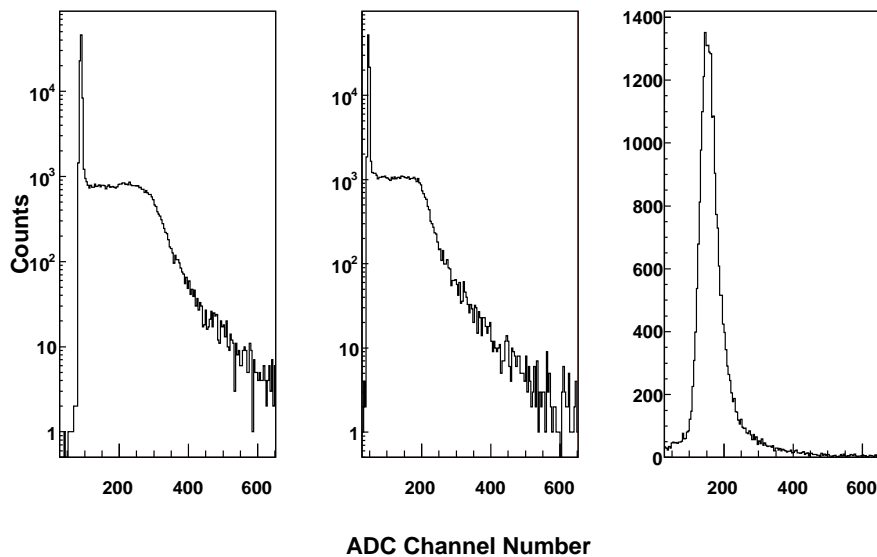


Fig. 13. ADC spectra from two adjacent middle layer scintillators for cosmic ray
 data. The extreme right part of the figure is generated by demanding an overlapping
 geometry condition such that cosmic muons travel a constant thickness. See text
 for details.

329 5 Conclusions

330 We have presented a detailed description of a large acceptance scintillator
331 detector ENSTAR, which has been designed and constructed for studying
332 the production and decay of η -nucleus bound systems, the η -mesic nuclei at
333 the multi-GeV hadron facility COSY. Monte Carlo phase space calculations
334 to simulate the formation and decay of eta-mesic nucleus predict an energy
335 range of 25 to 250 MeV for the decay protons and energies from 250 to 500
336 MeV for the decay pions. The detector is cylindrically shaped in three layers
337 and is segmented into a number of pieces for the detection of η -mesic de-
338 cay events. GEANT simulations predict a clear mass separation between the
339 protons and pions based on the energy loss information in different layers. A
340 number of test measurements have been performed to test the performance of
341 the individual components of the detector. Some of the scintillator pieces have
342 been tested at COSY by placing them in $\Delta E1 - E2$ configuration at the exit
343 of focal plane detection system of the magnetic spectrometer BigKarl. These
344 scintillator pieces have been tested with protons in the energy range of 35-
345 200 MeV and pions in 150-500 MeV energy range selected from the Big Karl.
346 The detector has been further tested in fully assembled condition, using 870
347 MeV/c proton beam from COSY, Jülich. In addition, the measurements using
348 the cosmic muons have been also performed. For the test measurement with
349 870 MeV/c proton beam, the elastically scattered protons having energy in
350 25-340 MeV range, were detected in ENSTAR. A satisfactorily good detector
351 response is obtained with the elastic protons as well as the cosmic muons.

352

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