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ENSTAR detector for η-mesic studies

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Abstract. We have initiated a search for a new type of nuclear matter, the η-mesic nucleus, using beams from the multi-GeV hadron facility, COSY at Juelich, Germany. A large acceptance scintillator detector, ENSTAR has been designed and built at BARC, Mumbai and fully assembled and tested at COSY. A test run for calibration and evaluation has been completed. In this contribution we present the design and technical details of the ENSTAR detector and how it will be used to detect protons and pions (the decay products of η-mesic bound state). The detector is made of plastic scintillators arranged in three concentric cylindrical layers. The readout of the detectors is by means of optical fibres. The layers are used to generate $\Delta E - E$ spectra for particle identification and total energy information of stopped particles. The granularity of the detector allows for position (θ and ϕ) determination making the event reconstruction kinematically complete.

Keywords. η-Meson; bound state; scintillation detector; optical fibre.

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1. Introduction

The possibility of the η-meson forming a bound state with nuclei thereby producing a new state of nuclear matter, $({}_{\eta}A)$ has long fascinated physicists [1–4]. In another contribution to this workshop [5] the interest in a search for such a bound state and the status of previous searches is given. Here we give some details about a detector ENSTAR which has been constructed to make such a search [5].

The elementary reaction, $p + d \rightarrow {}^{3}\mathrm{He} + \eta$, can be used to produce η particles which could bind with the residual nucleus to produce the desired bound state. Recent theoretical predictions [5] indicate that the optimum region in a search to look for ${}_{\eta}A$ is in the region of $A \approx 24$. Accordingly, we consider ${}^{27}\mathrm{Al}$ as a suitable target in the first search. The reaction then would be

$$p + {}^{27}\mathrm{Al} \rightarrow {}^{3}\mathrm{He} + {}^{25}_{\eta}\mathrm{Mg}\ .$$

The preferred beam momentum for this reaction is that for which the η meson is produced at zero momentum relative to the host nucleus. From kinematics, this works out to be $p_{\mathrm{beam}} = 1.74$ GeV/c. This momentum is called the magic momentum of the reaction. The corresponding beam energy is 1.05 GeV.

2. Detection

The proposed scheme for the experiment envisages the detection of ^{3}He in the Big Karl magnetic spectrometer and η-mesic nuclei decay particles in ENSTAR detector. The decay of $_\eta A$ is related to the $N^*(S_{11})$ decay resulting in one of the following branches,

$$\begin{aligned} \eta + N \to N^*(S_{11}) &\to \pi^- + p, \\ &\to \pi^0 + n, \\ &\to \pi^0 + p, \\ &\to \pi^+ + n. \end{aligned}$$

There would be a triple coincidence which is necessary to detect $_\eta A$ in the presence of a large background from other reactions. The signature for the production of $_\eta A$ would be a peak in the ^{3}He spectrum when gated with the kinematically correlated proton and pion detected in ENSTAR.

3. Requirements for ENSTAR

Since we are looking for very low cross-section events, the first requirement for ENSTAR is that it should cover as large a fraction of the 4π solid angle as practical. In order to obtain the requirements on the detected energies of the proton and pion, Monte Carlo phase space simulation using the code GEANT3 was performed. Calculations made for a ^{12}C target are presented in figure 1. Fermi motion is taken into account.

Calculations were also done for ^{16}O and ^{27}Al targets and similar results were obtained.

Accordingly, the detector was designed for obtaining full energy information for protons and reasonably good signal for pions. The opening angle between the proton and pion has a distribution that peaks near 160°.

4. Geometry of ENSTAR detector

ENSTAR [6,7] is constructed from 122 pieces of BC-408 plastic scintillator (Bicron Corporation, Ohio, USA) [8]. It consists of three layers arranged in a cylindrical geometry as shown in the perspecive view of figure 2.

The individual pieces of the inner layer are cylindrical in shape while those of the middle and outer layer are of triangular cross-section. One surface of each piece has grooves cut on it and optical fibres are fixed in the grooves. A sectional view is shown in figure 3.

The scintillator pieces comprising the detector are arranged around a carbon fibre beam pipe. The use of carbon fibre for the beam pipe material results in a reduction of the background caused by beam halo. The outer diameter of the beam pipe is 84 mm. The envelope of corners of each layer forms a cylinder, the dimensions of which are given in table 1.

In this geometry approximately 80% of the 4π solid angle is covered. The full range 0 to 180° in ϕ is covered and in θ the angles 15 to 165 is covered. The energy range for proton and pions are as per the requirements. Protons can be

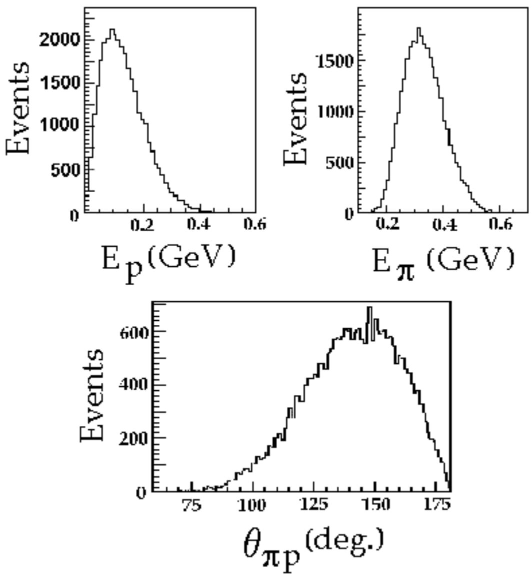

Figure 1. Simulation results for proton and pion emission following $p + {}^{12}C \rightarrow {}^{3}He + {}^{10}_{\eta}B$.

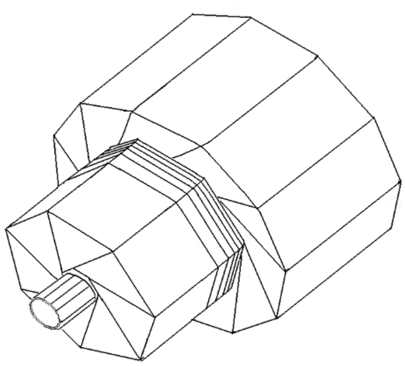

Figure 2. Perspective of one half of ENSTAR detector. Parts of the outer and middle layers are cut away to show the inner layers.

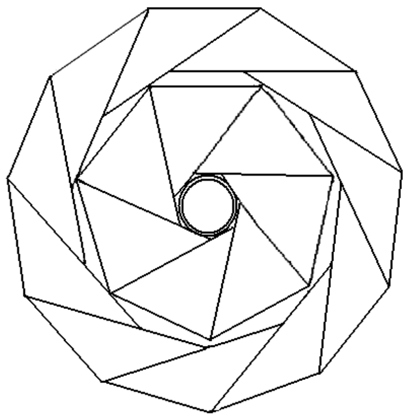

Figure 3. Cross-sectional view of ENSTAR detector.

Table 1. Dimensions for ENSTAR detector.

Component	Inner diameter (mm)	Outer diameter (mm)
Beam pipe	82.5	84
Inner layer	84	96
Middle layer	96	453.5
Outer layer	453.5	692.5

Table 2. Details of detector material.

Characteristic	Value
Light output	64%
Decay constant main component	2.1 ns
Wavelength of maximum emission	425 nm
Bulk light attenuation length	380 cm
Density	1.03 g/cm^{-3}
Refractive index	1.58

identified by $\Delta E - E$ signals in the inner and middle layers. Higher energy protons corresponding to foldback in the $\Delta - E$ spectrum would be identified by the signal in the outer layer. Pions being minimum ionising particles are difficult to stop in a practical size detector. The detector thickness is chosen so as to have a sizeable signal for pions.

The scintillator material is similar to BC-408 (Bicron, USA) obtained from Scionix Ltd, The Netherlands [9]. The properties of the scintillator are set out in table 2.

5. Detector readout

In a complex geometry such as for the present detector, it is difficult to provide light guides for the readout. For the middle layer where each of the seven triangular sections is divided into six pieces for each half of the detector, there is no space to provide light guides. We have used wavelength shifting (WLS) optical fibres for the readout of all the 122 pieces. Optical fibres are fixed in grooves on the surface of each scintillator [9]. These fibres are taken out and bundled into a perspex 'cookie' (annular cylinder) and coupled to photo-multiplier tubes.

Each scintillator piece is prepared by the following steps.

5.1 *Cutting and polishing*

The scintillator elements were procured cut to the required shape and polished. The properties of the scintillator material are as in table 2.

Table 3. Properties of BCF-91A (Bicron) fibre.

Core	Polystyrene
Refractive index (core)	1.6
Cladding	Acrylic
Refractive index (cladding)	1.49
Absorption wavelength	Blue (420 nm)
Emission wavelength	Green (494 nm)
Attenuation length	1.6 m
Diameter	1 mm
Cladding thickness	30 μm
Critical angle	68°

Table 4. Fibres used.

Layer	Length (cm)	Number
Inner	63	240
Middle	59–99	6384
Outer	89	1672
Total		8296

5.2 *Grooves*

For the middle and outer layers, rectangular grooves 4 mm wide and 1 mm deep with a spacing of 6 mm were cut on one surface of each element. The width of each groove was made in such a way as to accommodate four optical fibres of 1 mm diameter. Grooves for the inner layer were 1 × 1 mm with one fibre in each groove. The grooves were machined with a high degree of precision and the surface polish was preserved.

5.3 *Fibres*

Optical fibres of 1 mm diameter were placed in the grooves and fixed at a few points along the length using Bicron optical cement. For the thin inner layer pieces, the fibres were cut at one end to be flush with the end face and diamond polishing was done on this face so as to acheive a surface finish of the order of 0.6 μm. For the other pieces, the fibres were cut and diamond-polished in bundles prior to fixing in the grooves. Surface finish is an important aspect for the cut ends of the fibres. An optical microscope was used to examine the cut ends of the fibres and to verify that the surface finish was better than 0.6 μm.

The properties of the WLS fibre are given in table 3.

In all 7.8 kms of optical fibres were used. The number of fibres used and their lengths are given in table 4.

5.4 *Mirror*

Everbrite (Mercury Lighting Products Inc., NJ, USA) mirrors were fixed to the surface of the scintillator where the fibres terminate. The fixing was done by using only a few spots of optical cement. For the thin inner layer pieces the mirror covered the entire surface while for the other pieces the mirrors were in the form of a strip covering the region where the fibres terminate.

5.5 *Wrapping*

The pieces were wrapped in one layer of Tyvek paper followed by black plastic (Tedlar) (DuPont de Nemours Int. SA, Switzerland). The white Tyvek paper diffusely reflects the emerging light back into the scintillator. The layer of black plastic sheet is to reduce the cross-talk between the elements. The black plastic wrapping is also used to cover the emerging fibres for light tightness.

When light from the scintillators reaches the surface where fibres are fixed there is a probability of its absorption in the fibre. The absorbed light (in the blue region) is re-emitted in the fibre as green light. This process gives rise to a substantial amount of light gathered into the favourable cone (inside the critical angle for total internal reflection). This light travels along the optical fibres to the photo-multiplier tubes. Light in other directions that does not reach the fibre or is not within the favourable cone, has a chance to get collected again after multiple scattering by the Tyvek paper. The use of Tyvek paper which scatters rather than reflects light improves the collection efficiency as compared to other methods (reflecting paint, aluminised mylar wrapping).

6. Assembly

A rigid stand of aluminium material was fabricated to hold the assembled detector. Hylam plates with aluminium brackets were used to hold the detector elements in place. The assembly was a complex process because of the large number of optical fibres which needed careful handling. The scinillator pieces comprising the lower part of the outer layer were placed in position, followed by the middle layer elements of the lower part. The inner layer pieces were fixed to the carbon beam pipe using paper tape at a few points. The beam pipe along with the inner layer pieces was now put in position and then the remaining pieces for the middle and outer layers were placed. Finally the complete construction of hylam plates and aluminium brackets which hold the detector from outside was completed. During this process the free ends of the WLS fibres were supported on a temporary structure of stryofoam.

The fixing of cookies (perpex annular cylinders) and the diamond end polishing was done beforehand for the inner layer pieces. After completion of the entire structure, the cookies for the outer and middle layers were connected to the free ends of each of the fibre bundles. These were then polished in five steps. At first, rough sanding was done using a sanding attachment on a drilling machine. This was followed by emery polishing by hand and eventually three stages of diamond polishing achieving a final finish of 0.6 μm.

Plastic frames of annular shape with holes were fixed to the detector stand at both ends and photomultiplier tubes with their bases were fixed in these holes. The cookies were connected to the photomultiplier tubes employing a little Bicron optical grease. The cookies were held to the photomultiplier tubes by means of aluminium cylinders.

7. Testing

Tests were made to assess the performance of the individual elements as well as of the assembled structure.

7.1 *Testing with α source*

During assembly, a few pieces of each type were tested for light output using a ^{241}Am α source. For this purpose a small hole was cut in the wrapping to allow the alpha particles to penetrate. These tests were made inside a light tight wooden box.

7.2 *In-beam test with ΔE–E configuration*

A proton beam (1.54 GeV/c) from the COSY accelerator was bombarded on a silica target. The reaction products π, p, d, ^{3}He were detected in the Big Karl magnetic spectrometer at different settings. Two elements of the ENSTAR detector from the inner layer and the middle layer were placed in a ΔE–E configuration at the exit focal plane of the spectrometer. A good separation of the particles could be seen. Particle identification was confirmed by time-of-flight measurement.

7.3 *Calibration with cosmic rays*

Cosmic ray muons are minimum ionizing particles which lose about 1.8 MeV/cm in the scintillator material. Detection of cosmic rays prior to the beam runs were used to determine the absolute calibration.

7.4 *In-beam test of ENSTAR*

In-beam tests were made using 870 MeV/c proton beam from the COSY accelerator. Employing a thick alumina target, the spectra for each detector element was recorded. The amplifier gains and small adjustments to the high voltages on the photomultiplier tubes were made so as to have similar spectra in each element composing of a ring in the ϕ direction. In this way, the gain-matching of these elements could be acheived. Gain-matching of the elements differing in θ was done off-beam by matching the spectra from cosmic ray muons.

A two-dimensional spectrum of signals from the inner and middle layers is shown in figure 4. This is a spectrum combined from in-beam elastically scattered protons and cosmic ray muons. The figure demonstrates the separation of protons and muons in the detector.

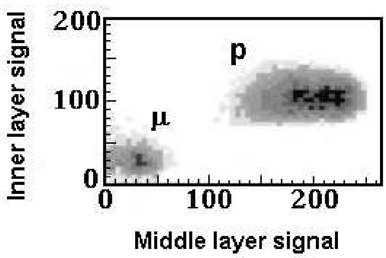

Figure 4. Two-dimensional spectrum of signals from middle and inner layers.

8. Summary

The scintillator array ENSTAR has been constructed for use in the search for η-mesic nuclei. The detector has used cylindrically-shaped pieces for the inner layer and triangular cross-sectional pieces for the middle and outer layers. Wavelength shifting optical fibres are employed for readout. The detector has been successfully tested in-beam both using the individual pieces in a ΔE–E configuration and for the fully assembled detector. The procedure for detector calibration has been worked out.

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