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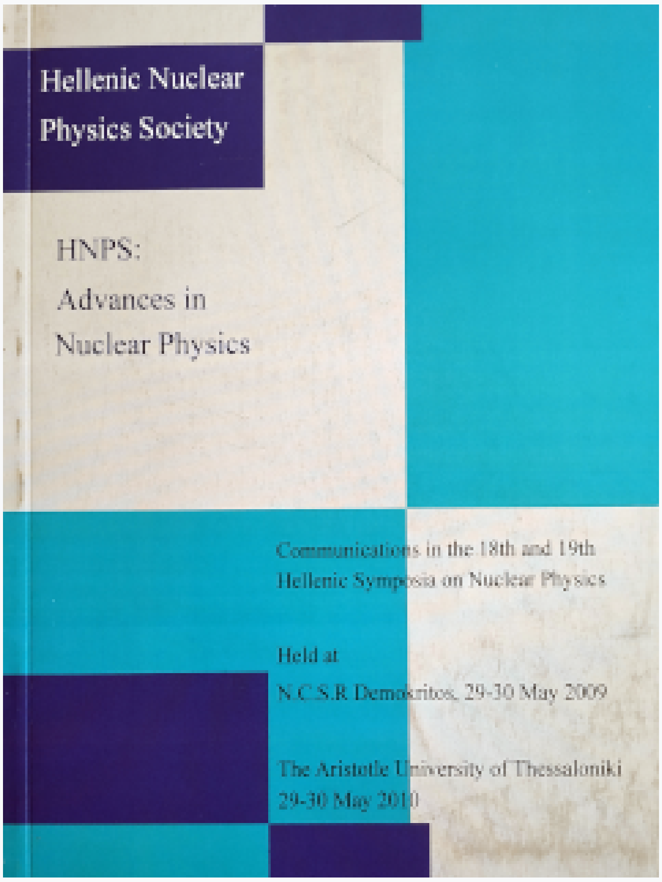

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Abstract

The inelastic cross section of relativistic protons in Lead was determined indirectly by measuring the neutron distribution along a Lead spallation neutron source. The spallation neutron source was irradiated by 1, 1.5 and 2 GeV protons. The experimental results were taken using passive methods. A fitting procedure has been applied to the experimental data and the results have been compared with analytical calculation of the produced hadrons' spatial distribution based on High Energy Physics concepts. Using the beam attenuation coefficient the inelastic cross section of protons in Pb was estimated.

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1. Introduction

The spallation neutron sources are sub-critical neutron systems, driven by an accelerator (ADS). The accelerator bombards a target with high-energy particles mainly protons. Spallation reactions have been thoroughly investigated using energetic proton beams [1-4]. Spallation experiments have been performed also in Dubna using a large cylindrical Pb target surrounded by a paraffin moderator. In order to use slow neutrons for transmutation purposes the moderator has been used to shift the hard spallation neutron spectrum to lower neutron energies [5-7]. In order to perform transmutation experiments using a spallation neutron source, calculation and measurements of produced neutron spectra by the spallation source are necessary. For the calculation of the produced neutrons the inelastic cross section of the projectile particles with the target material is needed to be known. Lead is one of the most common materials used in spallation sources. Several measurements have been made to estimate the inelastic cross section of protons with energy from few hundreds MeVs up to few GeVs in Pb [4, 8-15]. In the current work a measurement of the inelastic cross sections of 1.0, 1.5 and

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2.0 GeV protons in Pb targets was performed. Neutron and proton distributions along the spallation source were performed using Solid State Nuclear Track Detectors (SSNTDs) and activation methods. The inelastic cross sections were determined from neutron and proton spatial distributions along the target applying a fitting procedure based on High energy Physics concept.

2. Experimental

The inelastic cross section of protons in Pb was determined by irradiation of a thick spallation target. The experimental set-up, “Gamma-2”, consists of a cylindrical Pb target, with 40 cm length and 8 cm in diameter covered with a paraffin moderator 6 cm in thickness. The target irradiated by 1, 1.5 and 2 GeV proton beams, produce a fast neutron spectrum with a significant thermal-epithermal neutron component [5]. The experiments have been performed at the Nuclotron accelerator, at High Energy Laboratory, JINR Dubna, Russia. The neutron distribution was studied along the paraffin moderator by using Solid State Nuclear Track Detectors (SSNTDs). Fast neutrons were also measured by proton recoil tracks on the detector CR-39 itself (neutron elastic scattering on H of the detector). The neutron energy region detected by proton recoils is between 0.3-3 MeV due to limitations in the proton registration efficiency [16 - 17]. Neutron distribution along the target at the paraffin surface was determined also by using activation detectors. Natural Cd foils (mass ~ 2 g, purity 99.9%, thickness1mm) were also used as activation detector. The ^{nat}Cd effectively captures neutrons below 1 eV because of the high capture cross section of ^{113}Cd while it can be used for neutron detection above 1 eV via the ^{114}Cd(n,γ)^{115}Cd reaction. Moreover, ^{nat}Cd has a significant cross section to ^{nat}Cd(p,x)^{111}In reaction in the energy range of few MeV up to practically 400 MeV, responded well to the emitted proton spectrum [18-19].

3. Results and Discussion

Typical spatial distributions of fast neutrons and protons, as it was measured by SSNTDs and activation detectors at the same positions for proton beam energy of 1.0 GeV, is presented in figure 1. The neutron spatial distribution has the same behavior for all studied proton beam energies peaked at 10 cm upstream the target. Then a decrease is observed due to the beam attenuation. Protons generated by the target have energies high enough to pass through the moderator. Some of them are products of neutron interactions in moderator. Their energies ranged between 10 to 100 MeV presented a peak around 50 MeV, as it was calculated by Monte Carlo code DCM-DEM [18].

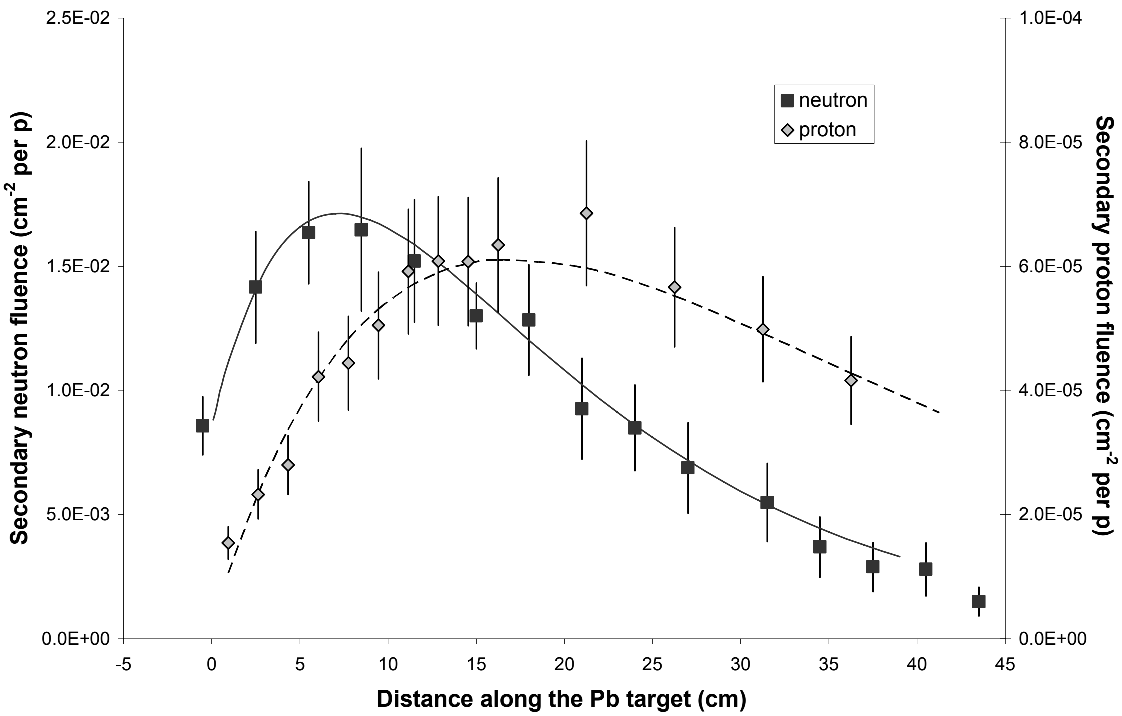

Fig.1. Spatial neutron and proton distributions along the target for incoming proton beam energy of 1 GeV. The lines referred to the fitting process using equation (1).

The hadron fluencies per incident proton (ρ, cm^{-2} per incoming proton) were fitted based on the consideration that two competitive effects take place inside the Pb target. An exponential increase of the secondary particle production at the head of the target, due to internuclear cascade (build up effect) and the exponential decrease of the proton beam intensity along the target (attenuation effect). The following equation was used [19]:

$$\rho = C\,(1-ae^{-bx})\,e^{-dx} \qquad (1)$$

where C is a parameter in units neutrons $cm^{-2}.proton^{-1}$. The first part of the equation was setting to describe the build up effect with the build up parameter a and the build up coefficient b. The second part represents the beam attenuation along the target as it was observed over the moderator surface with the attenuation coefficient d (cm^{-1}). The attenuation coefficient d is related to interaction length of primary protons in Pb. In fact secondary particle production continues along the target but the energy of the particles is low reducing so further particle production. In a heavy target protons and neutrons of low energies can induce fission reactions which in case of a Pb target have very low cross section and can be neglected. So the fall along the target can be attributed basically to the beam attenuation. Such considerations are valid for target dimensions relatively large comparing to the range of protons hitting the heavy target, as in case of Pb target used for the present study. It have to be taken into account that the results of this work correspond to inelastic cross sections as they have taken from measurements at large angles relative to the beam and so the elastic component is not included.

Using the determined interaction length λ, the inelastic cross section of protons in Pb can be estimated by the relation between the interaction length and the inelastic cross section, $\sigma = A/N\lambda\rho$. A is the Pb atomic number, N is the Avogadro's number and ρ is the Pb target density ($gr.cm^{-3}$) [20]. The values of the inelastic cross sections are presented in Table 1, for beam energies applied to those experiments.

Table 1. Inelastic cross section estimations for various incoming proton beam energies.

Proton energy (GeV)	Fast neutron (SSNTDs)	Proton (Cd-activation)	Mean Value
1.0	2.09 ± 0.33	1.67 ± 0.21	1.79 ± 0.18
1.5	1.61 ± 0.18	1.61 ± 0.15	1.61 ± 0.12
2.0	1.70 ± 0.12	1.55 ± 0.18	1.65 ± 0.10

It is interesting to focus the attention on the point that inelastic cross sections can equally be determined by measuring the beam attenuation via neutrons or via protons at the paraffin surface. Independently of the particle-tracker used for the calculation of beam attenuation along the target the inelastic cross sections are in good agreement with the inelastic cross sections of protons in Pb at the same energy region, as it is presented in the literature [4, 8-15,19].

Conclusion

The use of protons in cross section experiments has the advantage of the possibility to have monoenergetic beams of well known energy and energy spread. Moreover it is in theory possible to determine the inelastic cross section accurately by absorbing out the low energy secondary. For relativistic proton at energy range between 1 to 2 GeV the inelastic-total cross section in Pb presented to be quite constant within the measurement uncertainty with value 1.68 ± 0.09 b. The method can be applied also in other heavy targets under the restriction that target dimensions are small relative to the range of proton incident beam in the target.

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