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Fission studies of gold induced by (1665 MeV) π^- using a CR-39 detector

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Abstract: The fission cross section and fission probability of ^{197}Au, induced by (1665 MeV) π^-, have been studied using CR-39 track detectors. A 4π-geometry was used to count track statistics. A beam of negative pions of 1665 MeV was produced at AGS of Brookhaven National Laboratory, USA, and allowed to fall normally on the stack. Two detectors from the stack were scanned for fission fragment tracks after etching in 6N NaOH at 70 ℃. The statistics of fission fragment tracks in both detectors were obtained. It was found that there was a marked asymmetry of registered tracks with respect to the forward and backward hemispheres. This asymmetry could be partly accounted for on the basis of momentum transfer to the struck nucleus. On the basis of counting statistics fission cross section was measured, and fission probability was determined by dividing the fission cross section with the reaction cross section. The fission cross-section and fission probability were compared with the computed values using the cascade-exciton model code CEM95.

Key words: CR-39, fission cross section, CEM95

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1 Introduction

Fission cross sections and fission probabilities have been measured for a wide range of nuclei using negative and positive pions of energies below 500 MeV [1–8]. At higher energies, the pion induced fission cross section data is severely lacking. In order to remedy this situation, earlier we had performed experiments with negative pions of energies of 500, 672, 1068 and 1665 MeV incident on light as well as heavy targets. The preliminary results based on the statistics of observed fission events for the reactions, (1068 MeV) Cu, Sn, Au, Bi, were reported previously [9]. The fission cross sections induced by negative pions on Au and Bi targets using CR-39 material, and their comparison with the cross sections obtained using cascade-exciton model code CEM95 have been reported recently [10]. The object of studying high energy pion-nucleus interactions is to understand the mechanism of nuclear decay under the conditions of high excitation energies and low angular momenta [11].

Some of the characteristics of these reactions are well-studied at the energies below the region of (3, 3) resonance. For example the fission probabilities increase with increasing mass due to the decreasing values of fission barrier heights [4]. With pion energies beyond the region of pion-nucleon resonances, there are indications that the fission probabilities tend to saturate [6]. This is to be expected due to the opening up of more reaction channels and the increasing dominance of direct reactions. Also for gold and bismuth it has been observed that fission cross sections increase with beam momentum and then saturation is observed at higher beam energies [12]. For light mass nuclei, it is interesting to see how much nuclear excitation can be produced by an incident pion of energy well in excess of the fission barrier.

Assuming two-nucleon absorption of pions, the maximum energy that can be deposited in a nucleus by a pion of kinetic energy k_π is

$$E^*_{\max} = m_\pi c^2 + k_\pi - V_c, \tag{1}$$

where V_c is the pion-nucleus Coulomb potential.

In this paper it is shown that the measurement of σ_f at high energies using Solid-State-Nuclear-Track-Detectors is strongly influenced by the backward-forward asymmetry of fission fragments due to high

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momentum transfer to the struck nucleus. If the pion flux is non-uniform or the target has a variation in thickness, then additional constraints arise for extracting the fission cross section from the data on track statistics. The usual counting efficiency problems related to critical angle of etching, angle of track with normal to the detector surface, etc. can be handled reasonably well. We have performed an analytical treatment of fission fragment kinematics to explain the observed asymmetries and derived fission cross section based on the statistics of fission events. Fission probability was calculated by the ratio of the measured fission cross section to the computed reaction cross section using the cascade-exciton model. Fission cross section and fission probability are compared with the computed values using the code CEM95.

2 Experimental details

Circular detectors, each of diameter 5 cm, were prepared by cutting CR-39, made of Parma, Italy, and mica sheets. A set of two identical detectors, one containing the target coating and the other without it, was joined so that the target material was sandwiched between the two detector sheets. A stack consisting of thirty six detectors of mica and CR-39 was prepared at PINSTECH, Pakistan. This stack was exposed at normal incidence to a beam of negative pions of energy 1665 MeV. The exposures were carried out at Brookhaven National Laboratory (USA), using a D6 beam of the AGS accelerator in parasitic mode. The total number of pions produced in a run of 5 h was 1.104×10^{10}. The pions falling on the target were monitored with an array of wire chambers.

The exposed detectors were unmounted and one sandwich was selected for the counting of tracks. To remove the target layer, the detector with target material was treated with aqua regia (HNO_3+HCl). This detector was weighed before and after the removal of the target material to determine the target thickness deposited on the detector surface. To reveal the fission tracks, both of the detectors making up a sandwich were simultaneously etched in 6 N NaOH at 70 ℃ for various intervals of time. The track statistics has been given in Table 1.

The fission tracks were counted manually using an optical microscope at a total magnification of 400X. Random rechecking of the fission counts was done by different observers to confirm that event identification is unambiguous. Track statistics and other parameters are given in Table 1.

Table 1. Number of fission fragment tracks, observed in the forward and backward detectors after etching in 6 N NaOH at 70 ℃, and other parameters used to compute the fission cross section.

energy/MeV	total number of pions	target	target thickness/(mg/cm^2)	No. of tracks in detector	
				forward	backward
1665	1.104×10^{10}	^{197}Au	0.138	1345	831

3 Results and discussions

The fission tracks are fairly well identified by their thick dark appearance having a projected length of a few microns. However, in order to quantify the criterion for including a track in the fission track statistics, we adopted a method based on the total track length. For this purpose, about 200 tracks were randomly chosen and their full lengths were calculated by measuring the projected length and depth of the end point of each track. After applying the usual correction for the bulk etch rate of the detector and the effect of change in refractive index, the final length distribution was obtained. It was observed that the track length distribution for fission fragments in gold is very similar to that for fragments from the spontaneous fission of ^{242}Pu [4, 5, 7]. We have also checked whether the observed fission fragment track lengths are consistent with the theoretical fission systematics. For this purpose, the average values of kinetic energies corresponding to the assumed fission fragments were calculated using the Q-value relation [13],

$$Q=[0.1071Z^2/A^{1/3}+22.2]\mathrm{MeV}, \qquad (2)$$

where Z and A are the charge and mass number of the pre-fission nucleus. We further assumed that the fission Q-value is distributed between fission fragments as their kinetic energies in such a proportion that the momentum is conserved in the center-of-mass frame. The corresponding track lengths can then be calculated from the standard range-energy relationship [14] in CR-39. The range of theoretical values of fission fragment track lengths in CR-39 was calculated to be 6–17 μm which is consistent with the observed lengths.

For pion absorption at rest, the nucleus is excited only to the extent of pion rest mass energy. The resulting compound nucleus is stationary and the emission of fission fragments is isotopic in the laboratory frame-of-reference. On the other hand a pion of high kinetic energy deposits its rest mass as well as kinetic energy in the nucleus, which recoils under the impact of the pion, giving rise to forward bending of fission fragments. The best way to treat the angular distribution of fission fragments in this situation is to use the centre-of-mass coordinate system. The conversion to laboratory-frame can then be performed by a proper Lorentz transformation.

For a pion of total energy E_o and kinetic energy k_π, the momentum is given by,

$$p_\pi = \sqrt{E_\mathrm{o}^2 - m_\pi^2},\ E_\mathrm{o} = m_\pi + k_\pi, \tag{3}$$

where we have used the natural units (c=1). After absorbing a pion, the target nucleus of mass M_A acquires a mass and velocity given by [15],

$$M = \sqrt{m_\pi^2 + M_\mathrm{A}^2 + 2E_\mathrm{o}M_\mathrm{A}}, \tag{4}$$

$$V = p_\pi/(E_\mathrm{o} + M_\mathrm{A}). \tag{5}$$

If this excited compound system undergoes binary fission emitting two masses, m_1 and m_2 with kinetic energies k_1 and k_2, then the resultant fragments have momenta, p_1, p_2 and energies E_1 and E_2 given by,

$$p_i = \sqrt{E_i^2 - m_i^2},\ i = 1,\ 2, \tag{6}$$

and

$$E_i = m_i + Q\left(\frac{m_j}{m_i + m_j}\right),\ i \neq j = 1,2. \tag{7}$$

In obtaining Eqs. (6, 7), we have assumed that the fission Q-value 'Q' is given by

$$Q = k_1 + k_2, \tag{8}$$

and kinetic energies, k_1, k_2 are shared by masses m_1 and m_2 in the proportion

$$\frac{k_1}{k_2} = \frac{m_2}{m_1}. \tag{9}$$

The momenta p_i given in Eq. (6) are valid for the centre-of-mass frame. However, these can be converted to a laboratory frame by noting that the center-of-mass is moving with velocity V in the laboratory-frame. We, therefore apply Lorentz transformations to obtain laboratory momenta of masses m_1 and m_2 (assuming that the center-of-mass is moving along the Z-axis).

$$p_{ix}^\mathrm{L} = 0, \tag{10}$$

$$p_{iy}^\mathrm{L} = p_i \sin\theta_i^\mathrm{C}, \tag{11}$$

$$p_{iz}^\mathrm{L} = \gamma\left(p_i \cos\theta_i^\mathrm{C} + \beta\frac{E_i}{c}\right), \tag{12}$$

here

$$\gamma = (1 - V^2/c^2)^{-\frac{1}{2}}, \tag{13}$$

$\beta = V/c$, c=velocity of light.

Suffixes x, y, z are used for the x-, y-, z- components of the laboratory momenta while L and C are used to denote laboratory and centre-of-mass frames respectively. The geometrical relationship of the angles in two frames of reference is shown in Fig. 1.

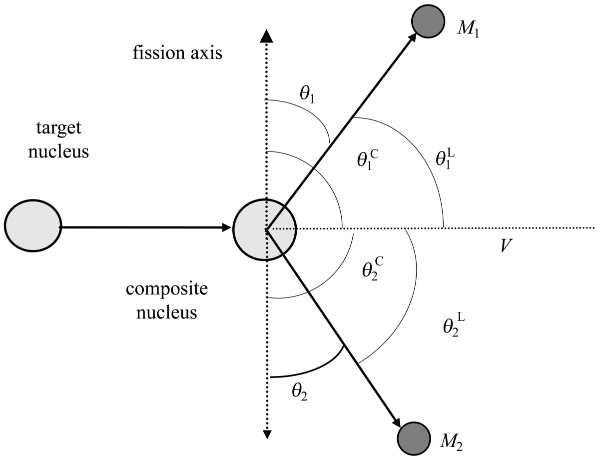

Fig. 1. Schematic representation of fission plane and angles, in center-of-mass and laboratory frames of reference, for the special case of $\theta_1^\mathrm{C} = \theta_2^\mathrm{C} = 90°$.

For the special case of $\theta_i^\mathrm{C} = 90°$ (see Fig. 1), we have

$$\cot\theta_i^\mathrm{L} = \frac{p_{iz}^\mathrm{L}}{p_{iy}^\mathrm{L}} = \frac{\gamma\beta E_i}{p_i}, \tag{14}$$

the observed fission fragment angles in the laboratory frame are then given by

$$\theta_i = 90° - \theta_i^\mathrm{L}, \tag{15}$$

these angles measured with respect to the fission axis represent the folding of fission fragment angular distribution. For the assumed mass split of Au, the values of forward folding angles due to momentum transfer are given in Table 2.

Table 2. Momenta p_i of the fission fragments and their angles θ_i with respect to the fission axis, for (1665 MeV) pion induced fission in Au.

target	fission fragment pair (assumed)	p_i/(MeV/c)	θ_i/(°)
${}_{79}\mathrm{Au}^{197}$	Ag^{108}	977.7	28.5
	Y^{89}	805.7	24.1
	Ru^{101}	914.2	26.9
	Mo^{96}	869.1	25.8

Therefore, an average of 26.3° forward sweeping of fission fragments due to a 1800 MeV momentum of negative pion is expected. Due to this transfer of momentum, the fission fragments emitted in the angular interval of 63.7° to 90° w.r.t. beam direction in the backward hemisphere are not detected in the backward detector. The relative number R of events not observed in the backward hemisphere is

$$R=\frac{\int_{63.7}^{90}\sin\theta\,\mathrm{d}\theta\int_{0}^{2\pi}\mathrm{d}\phi}{2\pi}=0.445, \tag{16}$$

where θ and ϕ are the polar and azimuthal angles. Therefore, for N fission events the asymmetry A of the forward to backward hemisphere is given by

$$A=\frac{N'+RN'}{N''-RN''}=2.6, \tag{17}$$

where $N'=\eta' N$, η' is the detector efficiency based on the non-registering of tracks due to critical angle ($\theta_c \approx 3°$ with respect to the detector plane) and undetected particle within $\sim 15°$ with respect to the beam direction; $N''=\eta'' N$ with η'' as the efficiency factor related to θ_c. The two efficiencies are different because the backward detector is not likely to have any fragments along the line of projectile motion; practically all of them would appear at angles greater than 26°. The experimental asymmetry comes out to be 1.62 which is less than the predicted value.

The number of fission related tracks observed in the well-defined areas of the detector along with other parameters, given in Table 1, can be used to calculate the cross section with the help of the equation,

$$\sigma_f = N_f/N_T\phi, \tag{18}$$

where N_f is the number of binary fission events per unit area of the detector, N_T is the number of target nuclei in a unit target area falling in the path of the beam and ϕ is the fluence. The number N_T depends on the specific thickness of the target material, which is determined experimentally by weighing the detector before and after removing the target material. The fission cross section determined in this case has been compared with the computed fission cross section using the cascade-exciton model CEM95. The fission probability was calculated by dividing the measured fission cross section with the computed cross section.

4 Conclusion and discussions

It is shown in this work that the pion of energy 1665 MeV produces fission in a thin Au target, with strongly asymmetric fission fragment angular distribution in the laboratory frame of reference. This asymmetry is only partly understood in terms of momentum transfer to the struck nucleus. The fission cross section has been calculated by using an average fluence over the total area scanned for fission events and comes out as 230 mb. The computed fission cross section using the code CEM95 is 119 mb. So, the measured value of the fission cross section is approximately double that of the theoretical value. The measured fission probability 0.1397 is also almost twice that of the computed value 0.0719. The uncertainty in the experimental value of the fission cross section is due to the uncertainty in the measurements of the pion beam, in the target thickness measurement, uncertainty in the counting of fission events, the detection threshold of the detector, and in distinguishing fission events from other background scratches.

Around 1665 MeV, the fission cross section of protons is about 100 mb and the fission cross sections of neutrons and photons should be less than that of negative pions [8] and higher for antiprotons. No value of fission cross section is available above 500 MeV for positive poins.

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