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Emission of Fragment Masses Between 4 Amu and 30 Amu in the Heavy Ion Interaction of (14.0 MeV/u) Pb + Pb

Tabassum Nasir[a]*, Ehsan Ullah Khan[b], Saeed Rahman[b] and Matiullah[c]
[a]Department of Physics, Gomal University, Dera Ismail Khan, Pakistan
[b]Department of Physics, CIIT, Islamabad, Pakistan
[c]Physics Division, PINSTECH, P.O. Nilore, Islamabad, Pakistan

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Abstract. Using two threshold solid state nuclear detectors, mica and CN-85, the reaction of (14.0 MeV/u) Pb + Pb was studied. Reaction cross-section was determined experimentally as well as theoretically. Both elastic and inelastic data were used to calculate the experimental reaction cross-section. Theoretical reaction cross-section for 14.0 MeV/u Pb +Pb is 3809 ± 428 mb. Reaction cross-sections from elastic data were 3830 ± 500 mb and 3875 ± 500 mb for mica and CN-85, respectively, While reaction cross-sections calculated from inelastic data for mica and CN-85 were 4081 ± 500 mb and 4092 ± 500 mb, respectively. The partial reaction cross-sections for mica and CN-85 detectors were also determined. It was observed that partial cross- section of inelastic binary events in mica was higher than that in CN-85, whereas, cross section of 4 and 5-pronged events in mica were lower than those in CN-85. However, the number of three pronged events was identical in the two detectors. Using the difference in mass registration threshold of the two detectors, for fragment masses between 4 amu (registration threshold of CN-85) and 30 u (registration threshold of mica) were searched, which were registered in CN-85 but not in mica.

Keywords: heavy ion interaction, solid state nuclear track detectors, total and partial reaction cross-sections, theoretical reaction cross-section, light particle emission.

Introduction

Understanding the properties of nuclear matter is the most important challenge in nuclear physics. To achieve this goal, first the nuclei have to be prepared in extreme conditions of excitation energy, temperature, pressure, spin and isospin. The tool used to obtain such extreme conditions is heavy ion induced reaction. Emission of light particles in heavy-ion-induced reactions contains important information about the reaction mechanism.

Solid state nuclear track detectors (SSNTD) yield useful results in the study of heavy ion interactions. Due to registration of all the heavy reaction products, moving in the forward hemisphere, the use of SSNTDs become unbiased and more versatile in giving information regarding the heavy ion interactions. Solid state nuclear track detectors have been extensively used to investigate the heavy ion (A>4) interactions (Nasir *et al.*, 2009; 2008; Khan *et al.*, 2001; 1998; Brandt, 1980). Each SSNTD has its own mass registration threshold and registers only that particle whose mass is greater than this threshold value (Khan *et al.*, 1984). In the present research work, CN-85 and mica track detectors were used to study 14.0 MeV/u ^{208}Pb + ^{208}Pb reactions. CN-85 (cellulose nitrate) with chemical formula $C_6H_8O_9N_2$ is a sensitive plastic while mica with chemical formula K $Al_3Si_3O_{10}(OH)_2$ is a mineral crystal. Both are etchable solid state nuclear track detectors.

The data presented in this paper consists of 2-, 3-, 4-, and 5-pronged events studies with two detectors, mica and CN-85, having different mass registration thresholds. They registered the fragment masses greater than their mass registration thresholds. Using the inelastic binary and multi-pronged events, the partial and total experimental reaction cross-sections were determined. The experimental reaction cross-section was determined from the elastic binary events and theoretical reaction cross-section for the reaction was also calculated. Analysis of the observed partial cross-sections of various multiplicities and the indirect events have been reported as the signal for the emission of mass fragments having masses between 4 amu and 30 amu, registered by CN-85 (having low registration threshold) and not by mica (having high registration threshold = 30 u), along with the heavy fragment masses in the present reaction.

Materials and Methods

A thin layer of Pb was vacuum deposited on each of the three mica and the two CN-85 detector pieces. These target-detector assemblies were exposed, to a beam of (14.0 MeV/u) Pb

*Author for correspondence; E-mail: tabassum642003@yahoo.com

Table1. Statistics of direct (D) and indirect (ID) multi-pronged events

Detector	Three pronged		Four pronged		Five pronged	
	D	ID	D	ID	D	ID
Mica	320	163 (34%)	74	81 (52%)	1	3 (75%)
CN-85	95	86 (48%)	45	41 (48%)	4	3 (43%)

ions, having the fluence of ~1.5×10^6/cm^2 at the UNILAC of GSI, Darmstadt, Germany. After the exposure the target material was removed from the detectors with HNO_3. Mica detectors were then etched in 48% HF at 23 °C and CN-85 in 10% NaOH at 60 °C. The etching was made in successive time steps at the intervals of a few minutes. After 80 minutes of etching, majority of the latent 'tracks' in mica were etched to their full lengths. In CN-85, however, the etching lasted for 120 minutes.

Events of different multiplicities, direct (D) and indirect (ID), registered in a detector are given in Table-1.

From the total normal binary events '1091' observed in mica and '251' observed in CN-85, a set of elastic binary events was bifurcated using angular and energy correlation for Rutherford elastic scattering (Baluch *et al.*, 1996). The bifurcated elastic binary events were 973 and 221 in case of mica and CN-85, respectively. The number of inelastic binary events was obtained by subtracting the elastic binary events from the total observed binary events. The number of inelastic binary and total multi-pronged events is given in Table-2. Also the number of target nuclei, average fluence, average target thickness and total scanned area is given in Table-3.

Table 2. Events of various multiplicities (2-pronged inelastic (IE) events and 3-, 4- and 5-pronged total events)

Detector	Number of events of different multiplicities			
	2-pronged	3-pronged	4-pronged	5-pronged
Mica	118	483	155	4
CN-85	30	181	86	7

Table 3. Number of target nuclei (N), average fluence (Ö), average target thickness (t) and total scanned area (a) Detector

Detector	(N) $\times10^{19}$	(Ö) $\times10^{6}$ (cm^{-2})	(t) (mg/cm^2)	(a) (cm^2)
Mica	10.9	1.70	1.00	37.68
CN-85	8.3	0.90	1.30	25.12

Results and Discussion

Reaction cross-section. Reaction cross-section was determined experimentally as well as theoretically. The experimental reaction cross-section was determined both from elastic and inelastic data.

The values of reaction cross-sections σ_R^{exp} (el.) from elastic data were 3830 ± 500 mb and 3875 ± 500 mb in case of mica and CN-85, respectively.

The partial reaction cross-sections for mica and CN-85 detectors were also determined. The determined values of partial and total inelastic reaction cross-sections σ_R^{exp} (inel.) are given in Table-4. Total experimental reaction cross-section is also equal to the sum of partial reaction cross-sections.

Table 4. Detector wise partial and total experimental reaction cross-sections using inelastic events

Detector	Reaction cross-section (mb)				
	(σ_2)	(σ_3)	(σ_4)	(σ_5)	σ_R^{exp} (inel.)
Mica	634 ± 50	2594 ± 465	832 ± 200	20 ± 10	4081 ± 500
CN-85	404 ± 96	2436 ± 427	1158 ± 240	94 ± 35	4092 ± 500

Theoretical reaction cross-section for 14.0 MeV/u Pb +Pb was 3809 ± 428 mb. The final experimental reaction cross-sections obtained by taking weighted average of elastic and inelastic reaction cross-sections, for both mica and CN-85 detectors, came out to be 3970 ± 500 mb and is graphically represented by straight line in Fig. 1.

Emission of fragment masses between 4 amu and 30 amu. The highest partial reaction cross section is for three pronged events which is almost equal in both the detectors (Table-4). It is also illustrated in Fig. 2, which shows the partial reactions cross-sections for different multiplicities in both types of the detectors.

It can also be seen (Table-4) that the partial cross section of inelastic binary events in mica is higher than that in CN-85, whereas cross-sections of 4 and 5-pronged events in mica are lower than those in CN-85.

This trend is pronounced in Fig. 3, where the ratio of cross-sections has been plotted for the ratio of various multiplicities for both type of the detectors. The cross sections of the multiplicity ratio of 2/3 and 4/5 are same, within the experimental error, in both the detectors. However, the ratio of the cross section of the ratio of 3/4 in mica is significantly higher than in case of CN-85.

Since mica is over estimating the two pronged cross-sections, and since the number of three pronged events is identical in the two detectors, it can be concluded, therefore, that in the 2-pronged events there are some events of higher multiplicities (4-or 5-pronged) in which two or even more tracks could not be registered in mica and hence could not be assigned the correct multiplicities. These types of events were, however, registered in CN-85 with correct multiplicities (4- and 5- pronged events) due to its lower registration threshold value. The deficit in the cross-section of 4- and 5-pronged events in mica indicates that there could be as many as 25% of the total events which may be accompanied with the emission fragment masses between 4 and 30 u. This conclusion is also supported by Khan *et al.* (2001) and by the fact that the ratio of the cross-sections of indirect to that of the direct events slightly increases with the increasing multiplicity of events, shown by the straight line in Fig. 4.

Since the higher multiplicity in such a reaction is associated with the higher energy dissipation (Vater *et al.*, 1986), more particles with masses between 4 and 30 u were emitted and hence more indirect events were observed in the case of higher multiplicities. The argument is further supported by the plot of differential cross-sections of even direct events to total events in each multiplicity for both the detectors, shown in Fig. 5.

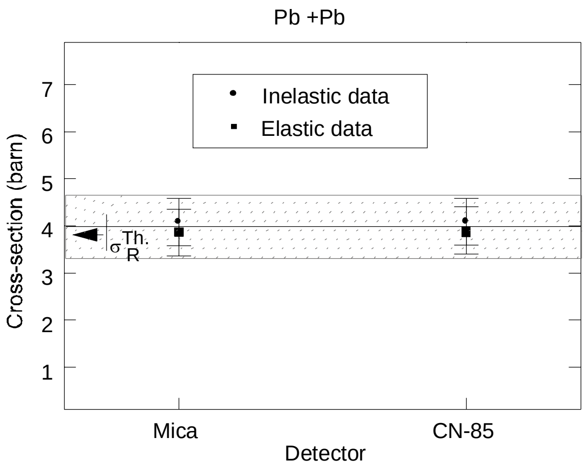

Fig. 1. Experimental reaction cross-sections along with their experimental errors. Theoretical cross-sections is also shown.

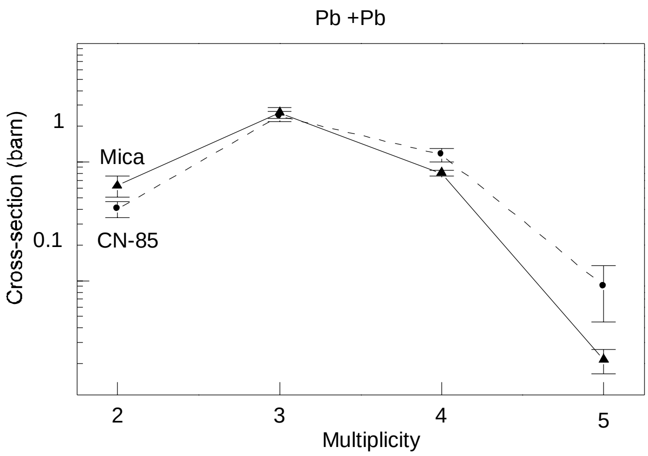

Fig. 2. Partial cross-sections of various multiplicities observed in both types of the detectors.

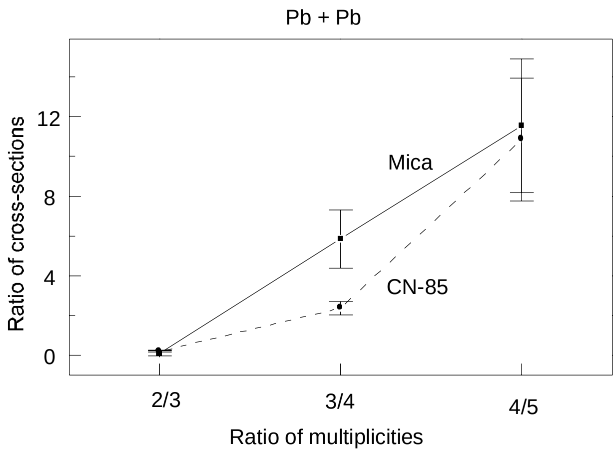

Fig. 3. Ratio of cross-sections with respect to the ratio of multiplicities for both types of detectors.

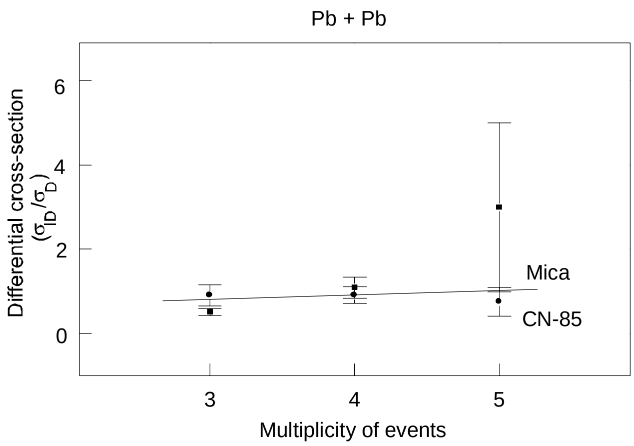

Fig. 4. Differential cross-sections of indirect to direct events for each multiplicity shown for both the reaction and both types of detectors. Error bars are the statistical errors.

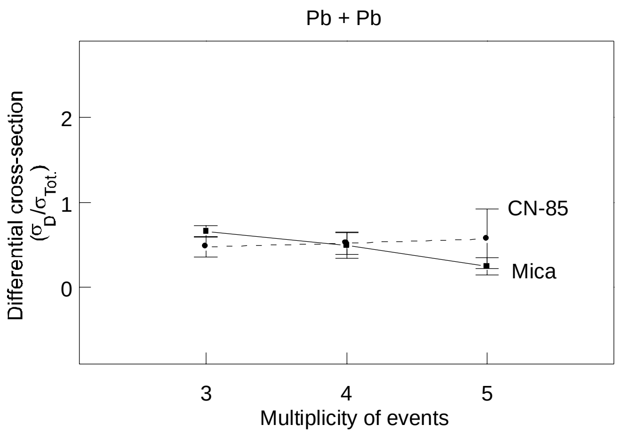

Fig. 5. Differential cross-sections of direct events to total events for each multiplicity shown for both the reactions and for both the types of detectors. Error bars are the statistical errors.

It is clearly demonstrated here that with the increasing multiplicity, the number of direct events in mica decreases while in CN-85, it is the reverse. Hence, as the multiplicity increases, more particles having masses between 4 and 30 u are emitted which mica denies to register due to its higher registration threshold. Such particles are, however, readily registered in CN-85. The emission of such particles affects the kinematics of such events which cannot, therefore, be analyzed on the basis of sequential fission process (Vater *et al.*, 1986).

Conclusion

The experimental reaction cross-sections calculated from the weighted average and derived from elastic and inelastic data sets agree reasonably well with the one calculated theoretically. The study of partial cross-sections based on different multiplicities of the reaction (14.0 MeV/u) Pb + Pb shows that the three-particle exit channel is significantly dominant as compared to other multiplicities registered in both mica and CN-85 track detectors. Moreover a significant number of light fragments having masses between 4 amu and 30 amu are emitted along with heavy fragments. An estimated upper limit for such events is 25%.

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