Emission Angles of Projectile Fragments in the Interaction of 736A MeV ^{28Si} with a Carbon Target

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Abstract

Using CR-39 detectors, an HSP-1000 high-speed imaging microscope, and PitFit track analysis software, we investigated the angular distribution of projectile fragments produced in reactions of intermediate- and high-energy 28Si with C targets. Through experimental procedures including beam irradiation, chemical etching, and track reconstruction, we present the latest experimental results on the emission angular distribution of projectile fragments from the reaction of 736 AMeV 28Si with C targets, and compare them with the emission angular distributions from 28Si + C reactions at 800 AMeV and 775 AMeV. The results indicate that the mean and width of the projectile fragment emission angular distribution are larger than the scattering angle of the 28Si beam particles; the majority of projectile fragment emission angles are less than 2.0 degrees, with few exceeding 2.0 degrees; the mean emission angles for projectile fragments with different charge numbers Z vary within a range of 1.0 degree, and both the mean and width of the angular distribution exhibit an overall decreasing trend with increasing fragment charge number Z.

Full Text

Investigation of Projectile Fragment Emission Angles in 28Si + C Collisions at 736 AMeV

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Abstract

The angular distributions of projectile fragments produced in the fragmentation of 28Si on carbon targets were investigated using CR-39 detectors, an HSP-1000 high-speed imaging microscope, and PitFit track analysis software. Through experimental procedures including beam irradiation, chemical etching, and track reconstruction, we present new experimental results for the emission angle distributions of projectile fragments from 28Si + C reactions at 736 AMeV, and compare them with corresponding distributions at 800 AMeV and 775 AMeV. The results demonstrate that both the width and average value of the projectile fragment angular distributions exceed the scattering angle of the 28Si beam particles. Most fragment emission angles are less than 2.0 degrees, with few exceeding this value. The average emission angles for fragments with different charge numbers Z fall within a range of 1.0 degree, and both the average values and widths of the angular distributions show an overall decreasing trend with increasing fragment charge number Z.

Keywords: heavy ion collision; projectile fragmentation; emission angle; angular distribution
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1. Introduction

Heavy ion collisions provide unique opportunities to study nuclear matter under extraordinary conditions. In the intermediate-to-high energy regime from several hundred AMeV to tens of AGeV, nuclear fragmentation constitutes an important research topic in nuclear physics, astrophysics, radiobiology, and applied physics. Investigating the interaction mechanisms of intermediate- and high-energy nucleus-nucleus collisions is crucial for assessing radiation damage to spacecraft equipment, calculating the propagation of heavy ions in galactic cosmic rays (GCR) through interstellar media, and understanding the composition of cosmic rays [1-3]. When the dose from heavy ions in free space is plotted as a function of atomic number, silicon stands out alongside elements such as iron, oxygen, carbon, and magnesium, with silicon's contribution to the dose equivalent in free space being second only to iron [4]. Most of these are fragmentation products from interactions between iron and other heavy particles. Charge-changing cross sections help elucidate reaction mechanisms in heavy ion collisions, and precise cross-section data are also essential in radiobiology and radiation therapy. Heavy ions are now used in cancer radiotherapy, but projectile fragmentation complicates treatment planning because the angular distribution of produced projectile fragments is larger than that of the beam particles. Consequently, information on both fragmentation cross sections and fragment emission angles for silicon at various energies interacting with different target materials is critically important.

Numerous research groups have experimentally investigated cross sections for silicon interacting with various targets at relativistic energies [4-17], providing an ideal database for further studies of heavy ion collisions. Theoretically, total cross sections are primarily calculated using models such as NUCFRG2 [18], the PHITS algorithm [19], and the Bradt-Peters semi-empirical formula [20], while empirical parameterization models including EPAX3 [21], modified EPAX2 [22], and FRACS [23] have been developed by continuously optimizing model parameters based on existing experimental data to simulate projectile fragment partial cross sections. After projectile ions collide with target nuclei, the resulting projectile fragments are emitted at larger angles, which significantly increases the radiation exposure area. Therefore, determination of fragment emission angles is vital for tumor therapy and space radiation protection, yet research on fragment emission angles remains insufficient.

Various detectors and measurement techniques have been employed to measure projectile fragment emission angles, including nuclear emulsion [24], scintillation detectors [25], silicon detectors [25], and CR-39 solid-state nuclear track detectors [16,26-33]. Semi-empirical models such as FRANG [34], the modified M-FRANG model [28], and the PHITS system [35] can calculate projectile fragment emission angles, though predictions differ among models [36]. Compared with other detectors, CR-39 solid-state nuclear track detectors offer excellent charge resolution and very precise position accuracy [36] while enabling detection of large-angle particle scattering [28], making them effective for studying fragment angular distributions. Experimentally, CR-39 detectors have been used to measure various data [16,26-33], but studies on fragment emission angles from silicon interacting with different targets remain relatively scarce, requiring more experimental data for systematic characterization of the reaction processes.

This work investigates the angular distributions of projectile fragments produced in the fragmentation of 28Si on carbon targets at 736 AMeV.

2. Experimental Procedure

The 28Si beam irradiation of carbon targets was performed at the Heavy Ion Medical Accelerator (HIMAC) of the National Institute of Radiological Sciences (NIRS) in Japan. The incident projectile beam energy was 800 AMeV with a beam density of 1250 ions/cm^2. The irradiation configuration is shown in Figure 1 [Figure 1: see original paper]. CR-39 detectors were positioned upstream and downstream of the target. After the projectile beam collided with the target nuclei, it fragmented into projectile fragments of various sizes. The thicknesses of the target and CR-39 detectors were approximately 5 mm and 0.783 mm, respectively. The energy reaching the surface of each target was calculated using the SRIM-2013 program. For this experiment, the beam energy at the surface of the fifth target was 736 AMeV.

Following irradiation, the CR-39 detectors were etched for approximately 15 hours in a 7 mol/L aqueous NaOH solution at 70°C. During etching, tracks produced by beam ions and their fragments in the CR-39 detectors appeared as conical pits on both surfaces. After etching, the upper and lower surfaces of the CR-39 detectors were scanned using an HSP-1000 high-speed imaging microscope to obtain images of the etched tracks. The PitFit track analysis software then automatically fitted these images to extract geometric information for each etched track, including cross-sectional area and position coordinates [37]. After automatic fitting, a manual inspection process was performed to correct tracks misidentified by the software, including background impurity bubbles and overlapping tracks, ensuring a final track identification efficiency approaching 100%.

The charge number Z of projectile fragments was identified through the area distribution of etched track cross sections. However, due to the charge resolution limitations of CR-39 detectors, fragments with charge numbers Z = 1-4 could not be recorded. Figure 2 [Figure 2: see original paper] shows tracks of projectile 28Si and its fragments observed in CR-39 using an optical microscope, where A represents the track of projectile 28Si and B and C represent tracks of projectile fragments. Detailed descriptions of charge identification, track matching, and track reconstruction can be found in references [10, 29-31, 38].

3. Results and Discussion

The emission angle of each projectile fragment is defined as the angle between two direction vectors: the direction vector of the projectile silicon and that of the projectile fragment. The former is determined from the coordinates of incident and emergent tracks on the upstream CR-39 detector, while the latter is obtained from the coordinates of incident and emergent tracks on the downstream CR-39 detector. The determination of projectile fragment emission angles is illustrated in Figure 3 [Figure 3: see original paper]. The target thickness is only a few millimeters, so in most cases, very few reactions occur between the projectile and target. Assuming that emitted fragments do not experience significant scattering before reaching the detectors, the emission angle of each fragment in the laboratory coordinate system can be calculated using the following formula: arccos(…).

Within the same microscope frame, the measurement precision for track dimensions and position coordinates can reach 0.1 m. The overall position precision is determined by the microscope's translation stage. The position uncertainty σp in the X-Y coordinate plane is approximately 3 m. The position uncertainty along the Z-axis is about 8 m, depending on the placement of the target and detectors and the detector thickness. Using a four-group fitting method for track reconstruction, the angular uncertainty is given by [27]:

where   is the polar angle of the fitted line. When the detector thickness h   780 m, the angular uncertainty $\sigma( )$ 0.16° at angles   up to 8°. Therefore, this angular uncertainty can be neglected in the measurement errors for projectile fragment emission angles and beam particle scattering angles. All errors reported in this paper are statistical uncertainties.

Figure 4 [Figure 4: see original paper] presents the distributions of silicon particle scattering angles and projectile fragment emission angles for 28Si + C reactions at 736 AMeV. The experimental results show that the width of the projectile fragment emission angle distribution exceeds the scattering angle of the 28Si beam particles, with most fragment emission angles distributed within 2.0 degrees.

Figure 5 [Figure 5: see original paper] shows the emission angle distributions for fragments with different charge numbers from the 736 AMeV 28Si + C reaction. Figure 6 [Figure 6: see original paper] displays the corresponding distributions from previous experimental groups at 800 AMeV and 775 AMeV [16,26]. Figures 5 and 6 reveal that most projectile fragment emission angles are less than 2.0 degrees, with few exceeding this value. As the projectile fragment charge number Z decreases, the angular distribution gradually broadens. Most angular distributions can be well fitted by a single Gaussian distribution, though some individual fragment distributions cannot be fitted due to limited statistics.

Figure 7 [Figure 7: see original paper] shows the relationship between the average projectile fragment emission angle and fragment charge number Z for the present 736 AMeV experiment, compared with previous results at 800 AMeV and 775 AMeV [16,26]. The average emission angles fall within approximately 1.0 degree and generally decrease with increasing fragment charge number Z. In this experiment, the relatively low average emission angle for fragments with Z = 9 results from limited statistics.

According to the participant-spectator model [39,40], projectile fragments with larger charge numbers Z are produced in peripheral collisions between 28Si and target nuclei, where less energy is transferred between projectile and target, resulting in smaller excitation energy and thus smaller emission angles. Conversely, fragments with smaller charge numbers Z originate from semi-central collisions with greater energy transfer that increases with the overlap region of the collision, leading to larger emission angles. Consequently, both the average values and widths of the projectile fragment angular distributions decrease with increasing fragment charge number Z.

4. Conclusion

This experiment measured the projectile fragment emission angle distributions from 28Si + C reactions at 736 AMeV and compared them with distributions at 800 AMeV and 775 AMeV. The angular distribution widths and average values of projectile fragment emission angles exceed those of the 28Si beam particle scattering angles. Both the average values and widths of the angular distributions for fragments with different charge numbers Z show an overall decreasing trend with increasing fragment charge number Z.

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