Determination of the Barrier Height for 54Cr+208Pb, 243Am Systems from Backward-Angle Quasi-elastic Scattering

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Abstract

Due to the extremely small reaction cross-sections for synthesizing superheavy nuclei and their short half-lives, experiments are protracted and costly, making the determination of appropriate beam energy through theoretical studies and indirect experimental methods crucial preparatory work. Backward quasi-elastic scattering serves as an important complementary tool to fusion reactions, providing key Coulomb barrier information and offering essential reference for the optimal incident energy in superheavy nucleus synthesis. In this work, we constructed a detector array comprising gas ionization chambers and silicon detectors to measure the backward quasi-elastic scattering excitation function for the ^{54}Cr + ^{208}Pb reaction, obtaining an average barrier height of 206.27 ±0.62 MeV, which shows good agreement with existing experimental data. Additionally, we measured backward quasi-elastic scattering data for the ^{54}Cr + ^{243}Am reaction, yielding an average barrier height of 234.66 ±0.45 MeV. These results can provide important reference for the subsequent synthesis of element 119 (Z=119) superheavy element through fusion reactions.

Full Text

Determining the Barrier Height of the 54Cr + 208Pb and 54Cr + 243Am Systems from Back-Angle Quasi-Elastic Scattering

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Abstract

Due to the extremely small reaction cross-sections and short half-lives of superheavy nuclei, experimental cycles are long and costs are high. Therefore, determining the optimal beam energy through theoretical studies and indirect experimental methods is an essential preliminary task. Back-angle quasi-elastic scattering, as a critical complement to fusion reactions, provides key Coulomb barrier information, offering valuable guidance for identifying the optimal incident energy for superheavy element synthesis. In this study, we constructed a detector array consisting of gas ionization chambers and silicon detectors. The back-angle quasi-elastic scattering excitation function for the 54Cr + 208Pb reaction was measured, yielding an average barrier height of 206.27 ± 0.62 MeV, which showed good consistency with existing experimental data. Additionally, we measured the back-angle quasi-elastic scattering experimental data for the 54Cr + 243Am reaction, obtaining an average barrier height of 234.66 ± 0.45 MeV. These results provide valuable references for future superheavy element synthesis, including the production of Z = 119.

Keywords: superheavy elements; back-angle quasi-elastic scattering; barrier distributions

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1 Introduction

In recent years, numerous studies have been devoted to exploring the boundaries of the nuclear chart, focusing primarily on the proton drip line, neutron drip line, and the synthesis of superheavy elements. Among these, the synthesis of superheavy elements and the exploration of the “island of stability” for superheavy nuclei have long been at the forefront of nuclear science research. This research direction holds significant scientific importance for understanding the limits of elemental stability, investigating the fundamental mechanisms of nuclear reactions, and validating theoretical models. Moreover, the physicochemical properties of superheavy nuclei often differ substantially from known elements, and these unique properties can be exploited to explore new materials with potential applications. Meanwhile, research and development of supporting facilities such as accelerators and detectors required for experiments can drive progress in related industries, offering considerable practical significance. Overall, research in this field possesses both profound scientific importance and broad application potential.

Currently, the synthesis of superheavy nuclei relies primarily on heavy-ion fusion reactions. This process involves selecting projectile and target nuclei and using accelerators to elevate their energy to appropriate levels. The energy must be sufficient to overcome both the Coulomb barrier and the internal fusion barrier, while simultaneously ensuring that the excitation energy of the compound nucleus remains low to avoid fission and maintain nuclear stability. The synthesis of high atomic number (Z) elements is constrained by two key factors: competition between compound nucleus formation and separation of reaction components before equilibrium is reached, and competition between fusion-fission and evaporation residue channels. Presently, two main methods are employed: "cold fusion" and "hot fusion" [1-3]. The cold fusion method is suitable for synthesizing relatively lighter superheavy elements (such as element 100), but due to limitations in target nucleus selection, current experiments indicate that this method has an upper limit for superheavy nucleus synthesis [1-2,4-9]. For superheavy elements beyond element 113, hot fusion has become the primary synthesis method. Experiments using 48Ca as the projectile and 243Am as the target have successfully produced elements 114 through 118 [10-14].

Because the reaction cross-sections for producing superheavy nuclei are extremely small and the half-lives of superheavy nuclei are short, target materials are scarce and require detection systems and data analysis with sufficiently high precision. These factors result in high experimental costs, significant material consumption, and long experimental cycles. Consequently, before formal superheavy nucleus synthesis experiments, searching for appropriate beam energies through theoretical and indirect experimental methods becomes crucial preparatory work. Experiments have shown that the interaction barrier height between heavy ions is essential for determining the optimal incident energy for superheavy element synthesis. Two approaches are typically used to study the barrier: one extracts the barrier from fusion reactions. However, due to the extremely small synthesis cross-sections for superheavy elements, measurements are too time-consuming to obtain stable excitation functions. A simpler and more feasible alternative method utilizes the complementarity between scattering probability and barrier penetration probability. During the reaction process, both reaction mechanisms operate under the same interaction potential, and the fusion probability (barrier penetration probability) T and scattering probability (barrier reflection probability) R satisfy $T = 1-R$ [15-17]. Therefore, back-angle quasi-elastic scattering can replace fusion reactions to extract energy excitation functions and barrier information. Back-angle quasi-elastic scattering offers advantages such as larger reaction cross-sections and relatively less interference from other reaction channels [16,18].

In the field of barrier extraction related to superheavy nucleus synthesis using back-angle quasi-elastic scattering, several important results have been achieved. For instance, the team of S. Mitsuoka systematically studied heavy-ion reaction systems with 48Ti, 54Cr, 56Fe, 64Ni, and 70Zn projectiles and a 208Pb target, focusing on revealing the barrier characteristics of cold fusion reactions with 208Pb [19]. The team of T. Tanaka conducted in-depth experimental studies on reaction systems including 48Ca + 208Pb, 50Ti + 208Pb, 48Ca + 238U, 22Ne + 248Cm, 26Mg + 248Cm, 30Si + 248Cm, 34S + 248Cm, 40Ar + 248Cm, 48Ca + 248Cm, and 50Ti + 248Cm. Through comparative analysis of coupled-channels model calculations and experimental evaporation residue cross-sections, they established empirical relationships between the optimal incident beam energy for superheavy element synthesis and the barrier [6,20].

In superheavy element synthesis research, the 54Cr + 243Am fusion reaction is considered one of the most promising pathways for synthesizing element Z = 119. However, its barrier has not yet been experimentally determined. This study will first measure the quasi-elastic excitation function for the 54Cr + 208Pb system to compare and validate against the experimental data of S. Mitsuoka et al. [19]. Based on this validation, we further conducted quasi-elastic excitation function measurements for the 54Cr + 243Am reaction to determine the average barrier height of this reaction system [21-22].

2 Experimental Setup

The back-angle quasi-elastic scattering experiments for the 54Cr + 208Pb and 54Cr + 243Am systems were completed at the CAFE2 linear accelerator terminal of the Institute of Modern Physics, Chinese Academy of Sciences. The experiment employed a composite detector array consisting of gas ionization chambers and silicon detectors for measurement. The array included twenty silicon detectors arranged in groups of four at five backward angles: 175.0°, 160.0°, 152.33°, 146.5°, and 141.653°. Each group of detectors was symmetrically distributed relative to the beam direction in upper, lower, left, and right positions, with an energy resolution of approximately 0.7%. Additionally, five gas ionization chamber detectors were configured at the same angular positions, with each chamber containing a four-layer structure and filled with 160 torr of CF4 gas as the working medium.

In the forward-angle region along the beam direction, six silicon detectors were deployed as a monitoring system. Four detectors were positioned at a detection angle of 35° in upper, lower, left, and right symmetric directions, while the remaining two detectors were set at 45° in the upper-right and lower-left positions. These monitoring detectors primarily served to obtain forward-angle elastic scattering energy peak information and perform elastic scattering particle counting: forward-angle elastic scattering peaks enabled precise correction of incident beam energy, while particle counting data was used to normalize the quasi-elastic scattering counts from backward-angle detectors.

This experiment utilized a 54Cr beam to measure the excitation functions for both reaction systems at 3 MeV energy intervals. For the 54Cr + 208Pb reaction system, the laboratory-frame incident energy ranged from 238.96 MeV to 284.38 MeV, corresponding to center-of-mass energy ranging from 186.03 MeV to 225.13 MeV. For the 54Cr + 243Am reaction system, the laboratory-frame incident energy ranged from 239.38 MeV to 329.23 MeV, corresponding to center-of-mass energy ranging from 191.87 MeV to 268.83 MeV. The experiment employed a 243Am target with a thickness of 0.132 mg/cm^2 and a 208Pb target with a thickness of 0.15 mg/cm^2. The LISE++ program was used to calculate and correct for half-target energy losses at different incident energies.

3 Data Processing

The nucleus-nucleus interaction potential $U(r)$ consists of the Coulomb potential $V_C(r)$, nuclear potential $V_N(r)$, and centrifugal potential $V_{cent}(r)$ (which appears in off-center collisions), expressed as $U(r) = V_C(r) + V_N(r) + V_{cent}(r)$. The Coulomb barrier is the energy extremum formed by the aforementioned interactions during nuclear collisions. Detectors at different angles experience varying centrifugal effects. The effective energy E_{eff} used in data analysis is calculated through the following formula [16,23-26]:

$$E_{\text{eff}} = \frac{2E_{\text{c.m.}}}{1 + \csc(\theta/2)},$$

where $E_{\text{c.m.}}$ is the center-of-mass incident energy and θ is the corresponding scattering angle.

Quasi-elastic scattering includes elastic scattering, inelastic scattering, and few-nucleon transfer reactions [19,27]: scattering where the internal energy and structure of the two participating particles remain unchanged is elastic scattering; scattering where the target nucleus or ejectile becomes excited due to nuclear or Coulomb interactions is inelastic scattering; reactions involving the transfer or exchange of one or a few nucleons between the projectile and target are transfer reactions. Additionally, reactions involving the transfer of many nucleons are classified as deep inelastic scattering. These different reaction channels can be reflected to some extent in experimental two-dimensional spectra. Figure 2 [Figure 2: see original paper] shows the two-dimensional spectrum from the first and second layers of the ionization chamber detector, which clearly distinguishes quasi-elastic scattering components, deep inelastic scattering components, and fission components. However, because the energy deposition from particles penetrating the first layer of the ionization chamber falls within the energy range where theoretical calculations transition from monotonically increasing to monotonically decreasing, the detector lacks sufficient precision for energy calibration, making it temporarily impossible to distinguish deep inelastic events through Q-values. Results from intuitively identifying deep inelastic scattering events using two-dimensional spectra are subject to certain subjective human factors. Therefore, the final energy excitation functions were extracted using measurements from silicon detectors.

The one-dimensional spectrum obtained from silicon detectors can be converted into a Q-value spectrum using the following Q-value formula:

$$Q = E_b + E_B - E_a = \frac{A_a A_b E_a E_b}{A_a + A_b}\left(\frac{1}{A_a} + \frac{1}{A_b} - \frac{2\cos\theta}{\sqrt{A_a A_b E_a E_b}}\right),$$

where A represents mass number, E represents particle kinetic energy in the laboratory frame, and the symbols “a”, “B”, and “b” denote the incident projectile, post-reaction target-like nucleus, and projectile-like nucleus, respectively. Figure 3 [Figure 3: see original paper] shows the Q-value spectrum obtained from the 152.33° backward-angle silicon detector. As illustrated, at low energies (208.90 MeV), most events collected by the detector are elastic scattering events with $Q = 0$ MeV, displayed as a clear single peak. As the incident beam energy increases (223.7 MeV and 234.53 MeV), quasi-elastic scattering events gradually appear, causing the elastic scattering peak to extend toward lower energies. When the incident energy increases further (243.81 MeV and 251.48 MeV), the proportion of deep inelastic scattering events gradually increases, resulting in increasingly pronounced tails in the spectrum. Quasi-elastic events become difficult to distinguish from deep inelastic events. Given that the Q-value for quasi-elastic scattering is typically greater than -20 MeV, this experiment utilizes this criterion on the Q-value spectrum to differentiate between deep inelastic and quasi-elastic scattering events, consistent with previous data processing methods in back-angle quasi-elastic scattering [6,19].

The energy excitation function represents the ratio of quasi-elastic scattering cross-section to Rutherford scattering cross-section, $d\sigma_{QE}/d\sigma_{Ru}$, as a function of energy. This ratio can be converted to the corresponding ratio of solid angles and event counts. Since the ratio of solid angles between forward-angle and backward-angle detectors is constant, and the Rutherford scattering ratio between different angles is also constant, this ratio can be obtained through event counts from forward-angle and backward-angle detectors [23-24,28]:

$$\frac{d\sigma_{QE}}{d\sigma_{Ru}} = C \times \frac{N_{QE}}{N_{Ru}} \cdot \frac{\sigma_R^{\text{front}} \Delta\Omega_{Ru}}{\sigma_R^{\text{back}} \Delta\Omega_{QE}},$$

where N_{QE} is the quasi-elastic scattering event count measured by backward-angle detectors, N_{Ru} is the Rutherford scattering event count measured by forward-angle detectors, σ_R^{front} and σ_R^{back} are the Rutherford scattering cross-sections at forward and backward angles, respectively, and $\Delta\Omega_{Ru}$ and $\Delta\Omega_{QE}$ are the solid angles for Rutherford scattering and quasi-elastic scattering, respectively.

4 Results and Discussion

Figure 4 [Figure 4: see original paper] presents the quasi-elastic scattering excitation function for 54Cr + 208Pb obtained through the above processing method, shown as solid circles. For reference, we also plot experimental data from literature [19], denoted as Exp. (Mitsuoka), using hollow squares. This experimental data also adopted $Q > -20$ MeV as the spectral condition for quasi-elastic scattering. The dashed line in the figure indicates the position of the average barrier $B_0 = 206.27 \pm 0.62$ MeV, corresponding to the point where $d\sigma_{QE}/d\sigma_{Ru} = 0.5$. The figure demonstrates that the quasi-elastic scattering excitation function extracted in this work shows good consistency with previous work, and the experimental data from this work exhibit relatively smaller fluctuations in the energy region below B_0 ($190 < E_{\text{c.m.}} < 200$ MeV).

Figure 5 [Figure 5: see original paper] shows the quasi-elastic scattering excitation function for 54Cr + 243Am. The final extracted average barrier from the energy excitation function is $B_0 = 234.66 \pm 0.45$ MeV. Compared to the quasi-elastic scattering excitation function for 54Cr + 208Pb, this system is heavier, and 243Am possesses significant deformation and well-measured multiple rotational excitation bands, resulting in a relatively smoother overall quasi-elastic scattering excitation function. In subsequent research, coupled-channels model calculations incorporating different types of collective motion coupling and transfer coupling will be required to obtain specific barrier distributions and their smoothing mechanisms. Systematic combination with other reaction systems will be necessary to provide the optimal incident energy for synthesizing element $Z = 119$ through this reaction.

In collision experiments for the 54Cr + 243Am and 54Cr + 208Pb reaction systems, this work employed ionization chambers and silicon detectors to acquire data and distinguished deep inelastic scattering from quasi-elastic scattering events through one-dimensional Q-value spectra. Using $Q > -20$ MeV as the spectral condition for quasi-elastic scattering, our measured quasi-elastic scattering experimental data for 54Cr + 208Pb show good consistency with previous work, and we successfully obtained the quasi-elastic scattering excitation function and average barrier energy for 54Cr + 243Am. The average barrier energies for the two collision systems are 206.27 ± 0.62 MeV and 234.66 ± 0.45 MeV, respectively. In subsequent work, we will combine theoretical models for further data analysis to extract the optimal incident energy for superheavy nucleus synthesis, aiming to provide a reference for beam energy selection in upcoming superheavy element synthesis experiments at the Lanzhou Institute of Modern Physics.

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Note: Figure translations are in progress. See original paper for figures.