PHYSICAL REVIEW C **86**, 057602 (2012)

Quarter-point angle for light, weakly bound projectiles

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(Received 15 August 2012; published 29 November 2012)

A new methodology is presented to analyze the threshold anomaly and to compare different kinds of reaction systems together. In this methodology, the experimental and theoretical values of the quarter-point angle are compared directly for different reaction systems. A suitable reduction method is employed to minimize the system effects. This new method can be used to evaluate and study the dynamic effects in the reaction systems.

DOI: 10.1103/PhysRevC.86.057602 PACS number(s): 25.60.Bx

Heavy-ion elastic scattering is an important research topic in nuclear physics [1]. Recently, particular interest in the weakly bound projectiles has increased [2] due to the availability of radioactive ion beams (RIBs) which can provide neutron-rich and neutron-deficient nuclei as projectiles. The studies of elastic scattering of radioactive ions can lead to the discovery of new phenomena that can verify various theoretical models [3].

It has been known that nuclear reactions with tightly bound nuclei present a phenomenon called the threshold anomaly (TA) [4]. The real and imaginary parts of the optical potential obtained from the elastic scattering fitted around the Coulomb barrier show a distinctive energy-dependent behavior. The imaginary potential decreases sharply as the energy decreases toward the barrier energy, while the real potential strength shows a strong localized peak around the barrier. At higher energies both potentials become almost energy independent. This energy-dependent behavior of the optical potential can be understood by a dynamic polarization potential, which is due to the strong coupling to the bound excited states or transfer channels. When at least one of the colliding nuclei is weakly bound, the situation changes because the breakup and/or transfer channel of the projectiles may become important and cause the excitation function to not drop sharply at the energies below the Coulomb barrier. This phenomenon has been termed as the breakup threshold anomaly (BTA) [5]. Therefore in many elastic scattering experiments, the difference between tightly bound and weakly bound projectiles has drawn much attention. To study the difference between tightly bound and weakly bound projectiles, reaction parameters of different systems must be compared directly. Total reaction cross sections which can be extracted from the optical model [6] have been used to compare the different systems. Gomes *et al.* [7] compared different systems by dividing the cross section with $(A_P^{1/3} + A_T^{1/3})^2$ and the center-of-mass energy with $Z_P Z_T/(A_P^{1/3} + A_T^{1/3})$, where Z_P and Z_T are the charges of the projectile and target, respectively. They compared different projectiles with the same target. Both Kolata *et al.* [8] and Shorto *et al.* [9] proposed using Wong's model [10] to compare reduced reaction cross sections of different reaction systems. Their goal was to use the reduced reaction cross sections to compare reactions with different kinds of projectiles and to evaluate the dynamic effects. In this report we use another reaction parameter: the quarter-point angle at which the elastic scattering cross section falls to one quarter of the Rutherford value. The quarter-point angle $\theta_{1/4}$ can be used to analyze the effects of BTA and TA in the reactions with different kinds of projectiles. In the present analysis, a large set of experimental data are used to compare the difference between the reactions with tightly bound, weakly bound, and halo projectiles in the framework of the quarter-point angle.

The angular distribution of Fresnel type elastic scattering [11] at forward angles is well characterized by the quarter-point angle, and the angle separates the illuminated or classically allowed region in angular range smaller than this angle, from the shadow or classically forbidden region beyond it, where the cross section drops far below the Rutherford value [12]. This angle is also called "grazing angle" or "rainbow angle." Both the Coulomb rainbow model [13] and the Fresnel diffraction model [14] have been proposed to explain this behavior. Even though the available experimental data disagree with them, the quarter-point angle is still an important characteristic in the elastic scattering angular distribution.

In the present work, the values of the quarter-point angles were extracted from the available experimental data of the elastic scattering where the quarter-point angles were determined by fitting the angular distribution of the differential cross sections with the optical model. The theoretical value referred to in this article is calculated by [15]

$$\theta_{1/4} = 2\arcsin\left[1\bigg/\left(\frac{2E_{\text{c.m.}}}{V_{\text{Coul}}} - 1\right)\right]. \tag{1}$$

The $^{12}\text{C} + ^{208}\text{Pb}$ reaction of the tightly bound projectile ^{12}C has been used for an in-depth analysis. The optical potential of the reaction system is taken from Refs. [16–18]. The value of the Coulomb barrier was taken from the spectrometric handbook where the values are tabulated by the code LISE++ [19]. Figure 1(a) presents the theoretical and experimental values of the quarter-point angle. There is a small difference between the

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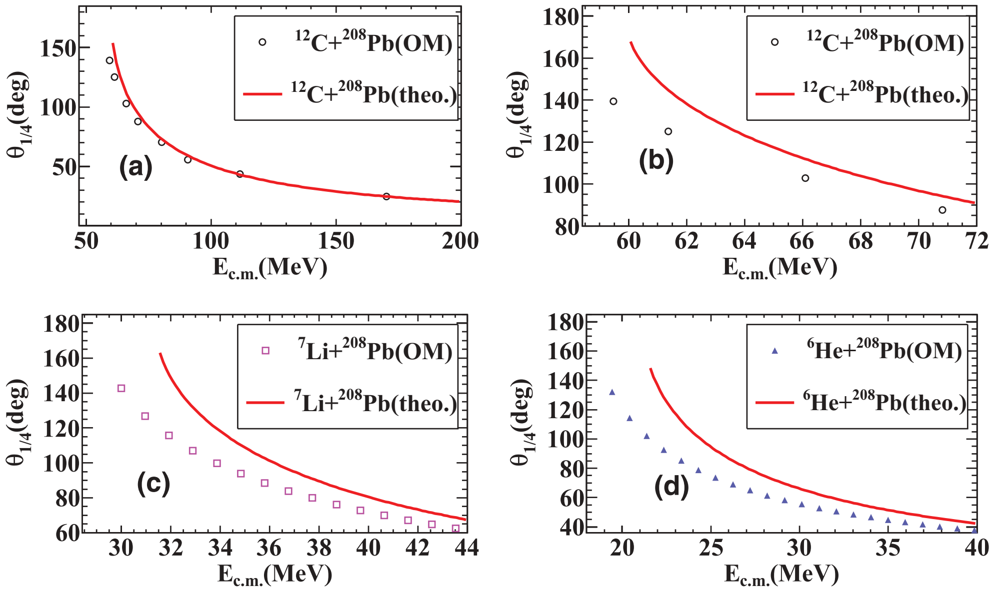

FIG. 1. (Color online) Theoretical and experimental quarter-point angle values of reactions with different projectiles with the same target (^{208}Pb).

theoretical and experimental values near the Coulomb barrier region. In Fig. 1(b), the area around the Coulomb barrier is magnified. In this region, one can see a small systematic difference between the theoretical and experimental values. At a given energy, the theoretical value is larger than the experimental value. This can be understood by the coupling effects as discussed later.

The $^{7}\mathrm{Li} + {}^{208}\mathrm{Pb}$ reaction has been selected as a typical case for weakly bound projectile reaction systems. The optical potential of this reaction system is taken from Ref. [20], in which a global potential is used for all ^{7}Li projectile reaction systems. Figure 1(c) shows that there is a clear difference between the theoretical and experimental values. This suggests that there are strong couplings to the reaction channels.

The $^{6}\mathrm{He} + {}^{208}\mathrm{Pb}$ reaction has been used as a case for halo projectile reaction systems. The global potential of ^{6}He was obtained from Ref. [21]. Figure 1(d) illustrates the result of the theoretical and experimental values. It also shows the difference between the theoretical values and experimental values, suggesting the strong coupling to the reaction channels.

In the above examples, the theoretical and experimental values of the quarter-point angle for the tightly bound, weakly bound, and halo projectiles show some difference. To compare the quarter-point angle of different reaction systems together, the dimensionless variable x is introduced, which is the center-of-mass energy divided by the Coulomb barrier energy as $x = E_{\mathrm{c.m.}}/V_{\mathrm{Coul}}$. In this way one can minimize the system effects on the quarter-point angle.

In the following, first we present an illustrative example of the application of this method. In Fig. 2(a) the quarter-point angle of the above reaction systems, $^{12}\mathrm{C} + {}^{208}\mathrm{Pb}$, $^{7}\mathrm{Li} + {}^{208}\mathrm{Pb}$, and $^{6}\mathrm{He} + {}^{208}\mathrm{Pb}$ are shown as a function of x. Here one can see a systematic deviation of the quarter-point angle from the theoretical values, depending on the tightness of the projectiles. The deviation is smallest for the tightly bound projectile, $^{12}\mathrm{C} + {}^{208}\mathrm{Pb}$, and it becomes largest for the halo projectile, $^{6}\mathrm{He} + {}^{208}\mathrm{Pb}$. This trend is generally observed for all available experimental data. In Fig. 2(b) the data are plotted as a function of x; the data are taken from $^{16}\mathrm{O} + {}^{208}\mathrm{Pb}$ [17,22], $^{8}\mathrm{B} + {}^{58}\mathrm{Ni}$ [23], $^{6}\mathrm{Li} + {}^{64}\mathrm{Ni}$ [24], $^{6}\mathrm{Li} + {}^{90}\mathrm{Zr}$ [25], $^{6}\mathrm{Li} + {}^{112}\mathrm{Sn}$ [26], $^{6}\mathrm{Li} + {}^{116}\mathrm{Sn}$ [26], $^{7}\mathrm{Li} + {}^{116}\mathrm{Sn}$ [27], $^{9}\mathrm{Be} + {}^{209}\mathrm{Bi}$ [28], and $^{16}\mathrm{O} + {}^{181}\mathrm{Ta}$ [22]. The results are similar to the one observed in Fig. 2(a). The experimental values of the quarter-point angles are well localized along a curve for a given tightness of the projectiles, and the deviation from the theoretical values becomes the smallest for the tightly bound projectiles and largest for the halo projectiles. Even though the measurement of the quarter-point angle in the elastic channel only probes the strength of the coupling to the reaction channels and does not elucidate the reaction mechanism behind, we drew the possible scenarios for the deviation in conjunction with the existing knowledge and experimental data.

In the case of the halo projectile systems, the halo nucleons are weakly bound and the projectiles are easily breakup. This is likely to cause the largest deviation from the theoretical values. For the case of the weakly bound projectiles, the physics behind may be more complicated. Recently Luong *et al.* [29] made a complete breakup channel measurement in ^{6}Li, $^{7}\mathrm{Li} + {}^{208}\mathrm{Pb}$ reactions near and below the Coulomb barrier. They measured all decayed particles by multisegmented Si telescopes at backward hemisphere. Form the Q-value and relative energy analysis for the decay products, they concluded as follows: (1) For the ^{6}Li case, a neutron transfer followed by a prompt decay to $\alpha + p$ is the dominant breakup process which causes the 30% suppression of the fusion cross section at this energy region. (2) For the ^{7}Li case, a proton pickup followed by a prompt two-α decay as well as the direct $\alpha + t$ breakup are the dominant breakup processes. Therefore their observation indicates that the reaction mechanism of the weakly bound projectiles may be different for each projectile and needs to be

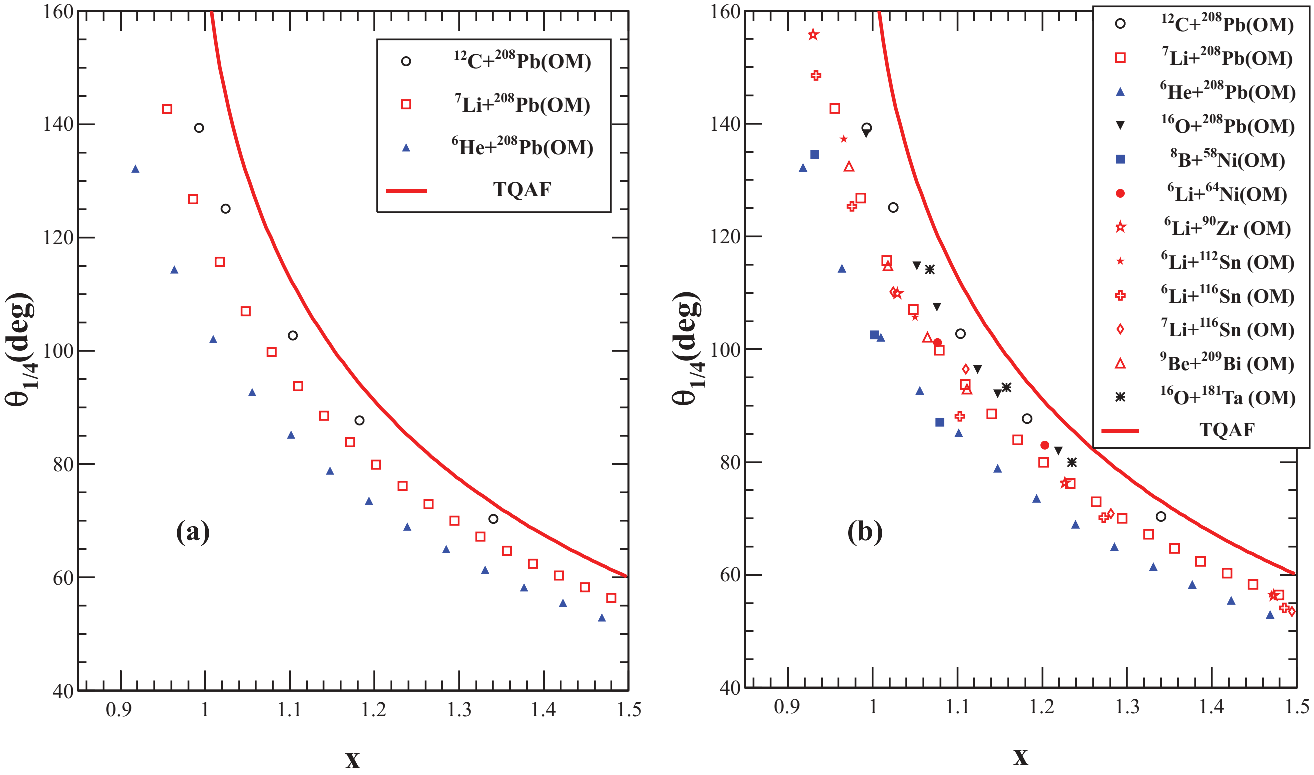

FIG. 2. (Color online) Theoretical and experimental quarter-point angle values of reactions with different projectile and target systems. The theoretical quarter-point angle function is labeled TQAF.

determined by a complete experimental measurement of the decayed products for each case. However, our observation in Fig. 2(b) indicates that all experimental data are well localized along the curve, indicating that the coupling to the reaction channels from the elastic channel, either a direct breakup or a prompt decay followed by a nucleon transfer or pickup, has similar strength. For the tightly bound projectile, the observed deviation suggests that a small coupling to the reaction channels exists. In Ref. [18], using a coupled reaction channel analysis it was shown that the tightly bound projectiles have small couplings to the bound excited states of the target nucleus or transfer channels. This coupling may cause the elastic scattering cross sections to fall down faster than those of no coupling cases.

A new simple method to analyze the threshold anomaly for the different kinds of projectiles has been proposed. In this paper, the experimental and theoretical values of the quarter-point angle for tightly bound, weakly bound, and halo projectile systems were examined. A reduction method was used to minimize the system effects in order to make direct comparisons for the different kinds of projectiles. The following conclusions were obtained: (1) The quarter-point angle for the different tightness of projectiles, i.e., tightly bound, weakly bound, and halo projectiles, can be compared directly when the scaled energy x is used. (2) The available experimental quarter-point angles for a given tightness of the projectiles are well localized along a curve when they are plotted as a function of x, and the curve deviates systematically from the theoretical curve, depending on the tightness of the projectiles. The deviation becomes larger when the tightness becomes weaker. (3) For the halo nuclei, the deviation becomes largest and is likely to be caused by the weekly bound nucleon(s) and the projectile can easily decay through breakup channels before or near the closest approach of the two nuclei. (4) For the weekly bound nuclei, the deviation may be caused by different reaction mechanisms. However, it is still a very interesting observation that the deviation of all available experimental data shows a similar deviation from the theoretical values at a given reduced energy x. This indicates that the strength of the coupling to the reaction channels are of similar order, independent of the actual reaction mechanisms behind. Therefore it is very useful to examine the quarter-point angle as a function of the reduced energy x to study the strength of the coupling to the reaction channels. (5) For the tightly bound projectiles, a notable deviation is observed from the theoretical values. This suggests that small couplings to the reaction channel may exist.

This work is supported by the Major State Basic Research Development Program of China (973 Program: New Physics and Technology at the Limits of Nuclear Stability), the Natural Science Foundation of China (NSFC) (Grants No. 11005127, No. 11075190, and No. 10905076), and the Directed Program of Innovation Project of Chinese Academy Sciences (Grant No. KJCX2-YW-N44). One of the authors (S.M.) thanks ICTP, Trieste, Italy, and Chinese Academy of Sciences for financial help to travel to China for this work under the TWAS Associateship Program. We are grateful to Dr. G. L. Zhang and Dr. Yiu-Wing Lui for fruitful discussions.

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