Barrier distribution from ^{9}Be + ^{208}Pb quasielastic scattering: Breakup effects in the interaction processes

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Excitation function of the quasielastic (QEL) scattering at a backward angle was measured for the weakly bound projectile ^{9}Be, which bombarded a ^{208}Pb target at near-barrier energies. Barrier distribution was extracted by means of the first derivative of the experimental cross sections with respect to the effective energies. Theoretical fusion barrier distribution has been calculated with the coupled-channels model and compared with the experimental barrier distribution. By this comparison, it is shown that the experimental barrier distribution extracted from QEL scattering is shifted to low energy by 1.5 MeV as compared with the theoretical one. This energy discrepancy between the theoretical prediction and the experimental data indicates the breakup is an important reaction mechanism in the colliding processes of the weakly bound projectile ^{9}Be on a spherical target ^{208}Pb.

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Coulomb barrier distributions in heavy-ion reactions give us important information about the interaction potential and reaction dynamics for nucleus-nucleus collisions. Experimentally, the fusion barrier distribution can be obtained from the fusion excitation function $\sigma_{\text{fus}}(E)$ with respect to the center-of-mass energy E by taking the second derivative of the product $E\sigma_{\text{fus}}$ [1]. With high-precision measurements of fusion cross sections, this method has been proven to be effective in intermediate-mass systems. Similar information could be obtained from the elastic and quasielastic (QEL) scattering because of the conservation of the reaction flux (i.e., $R + T = 1$), where R is the reflection probability and T is the transmission probability. Here, QEL scattering is the sum of all direct reactions, which include elastic, inelastic, transfer, and breakup processes. It has been proposed that to obtain the interaction barrier, QEL scattering should be measured at backward angles of nearly 180°, where head-on collision is dominant. The barrier distribution is extracted by taking the first derivative of the QEL cross section relative to the Rutherford cross section, that is, $-d(d\sigma_{\text{QEL}}/d\sigma_{\text{Ru}})/dE$ [2]. It has been proven that for the tightly bound reaction systems in the intermediate-mass region, the barrier distributions derived from the data of fusion and QEL are roughly the same, although the latter is somewhat smeared because of the weakly coupled channels of the many noncollective states and, thus, is less sensitive to the nuclear structure effect [3]. Since the QEL experiment is usually not as complex as the fusion measurements, they are well suited to survey the interaction potential and reaction dynamics for many reaction systems.

The light radioactive nuclei, especially the halo nuclei, such as ^{11}Be, ^{6}He, and ^{8}B are usually weakly bounded, hence, are easy to break up in the colliding processes. However, because of the low-light radioactive beam intensity, at present, it is difficult to obtain highly accurate data in the radioactive beam experiments. The stable nuclei ^{9}Be and ^{6}Li are loosely bound with the binding energies 1.57 and 1.47 MeV, respectively. Because of stability, the experiments performed with the ^{9}Be and ^{6}Li beams can obtain experimental data with statistical accuracy much higher than those of the radioactive beam experiments. Recently, there has been considerable interest in the breakup effects on the fusion and scattering reactions. Particular emphasis is put on the influence of coupling to the breakup channels in the barrier distributions. Interactions of the most weakly bound stable nuclei display some kind of anomalous behaviors, which all attributed to the low-threshold energy for the breakup into their constituents [4]. In fusion of weakly bound nuclei, two independent processes of complete fusion (CF) and incomplete fusion (ICF) occur. The two fusion processes are connected to the dynamics of the projectile fragment. However, it is still difficult to unambiguously predict CF and partial-fusion cross sections [5]. The fusion reaction of ^{9}Be + ^{208}Pb has been studied by Dasgupta *et al.* [6]; the complete fusion cross sections at energies around and above the barrier are suppressed by 30% compared with reactions of nuclei, which have a high-energy threshold against breakup, and the suppression ascribes to the breakup effect. The reduction of the fusion cross section indicates that the real part of the polarization potential associated with breakup coupling is repulsive.

So far, there are only a few works [7–9] on the QEL barrier distributions for weakly bound systems. An expression [7,10] was proposed as $R + T = 1 - P_{\text{BU}}$, where P_{BU} is the breakup probability before reaching the classical turning point. Monteiro *et al.* [11] compared the barrier distributions of ^{6}Li + ^{144}Sm from fusion and backward QEL excitation functions and found a low-energy shift for the latter one. For ^{6}Li + ^{232}Th [9], the D_{QEL} value for the ^{6}Li channel is shifted to low energy by about 1.9 MeV as compared with the ^{6}Li + α and ^{6}Li + α + d channels. Otomar *et al.* [12] analyzed the QEL barrier distributions of ^{6,7}Li + ^{144}Sm and found that the net dynamical effect of the coupling to the continuum breakup channels results in the increase of an effective Coulomb barrier. Additionally, Signorini *et al.* [13] found that the barrier distribution extracted from fusion data is narrower than the one from elastic scattering data, although

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this discrepancy may be caused by the poor angle resolution of the detectors in the experiment.

In the present Brief Report, we have measured the QEL of ^{9}Be + ^{208}Pb with high precision at a backward angle at the energies around the Coulomb barrier and extracted the barrier distribution from the excitation function of QEL. Our present result may provide further evidence for the effects of breakup on the fusion reactions at near-barrier energies.

The experiment was performed with a collimated ^{9}Be beam at the HI-13 tandem accelerator at CIAE, Beijing. A Versa-Module-Eurocard (VME) data acquisition system was used to accumulate the particle spectra. The target consisted of evaporations of ^{208}Pb (100 μg/cm^2 in thickness and 3 mm in diameter) onto a carbon backing of 30 μg/cm^2 in thickness. Two Si(Au) detectors located at $\theta_{\rm lab} = 25^\circ$ with respect to the beam were used to measure the Rutherford scattering events to monitor the beam and to normalize the cross sections. The QEL particles were measured by an Si(Au) detector at a backward angle of $\theta_{\rm lab} = 170^\circ$ relative to the beam direction, and the corresponding angular aperture was 1.1°. The QEL was measured in the laboratory energies range from 25 to 46 MeV (40% below and above the nominal Coulomb barrier), with energy steps of $\Delta E = 1.5$ MeV for the lower energies and 1.0 MeV for the higher ones. The terminal voltage of the accelerator was increased monotonically to reduce magnetic hysteresis effects. Beam currents ranged from 10 to 70 pnA. The statistical errors are 1.5% for the lower energies and increase to 10% for the highest energy.

A typical spectrum for the ^{9}Be + ^{208}Pb system taken at a beam energy of 33.0 MeV and $\theta_{\rm lab} = 170^\circ$ is shown in Fig. 1. The QEL events are indicated by the two dashed lines. A strong inclusive α channel could be observed at the low-energy side of the spectrum. Events associated with $Z = 2$ were not used in the subsequent analysis of the QEL processes, since it was not possible to clearly distinguish the corresponding reaction channels, such as noncapture breakup and transfer and evaporation of the CF and ICF compound nuclei. For this reason, we will define QEL as the sum of elastic and inelastic scattering channels in the following analysis. This means that, in fact, the data do not correspond strictly to a full QEL cross section, but rather a lower limit of it.

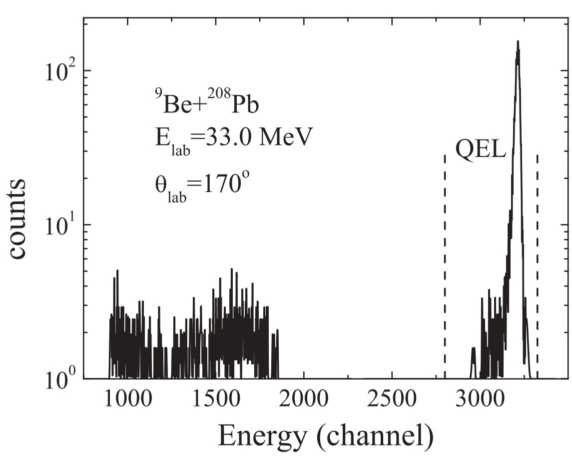

FIG. 1. Typical energy spectrum of the scattered particles for ^{9}Be + ^{208}Pb.

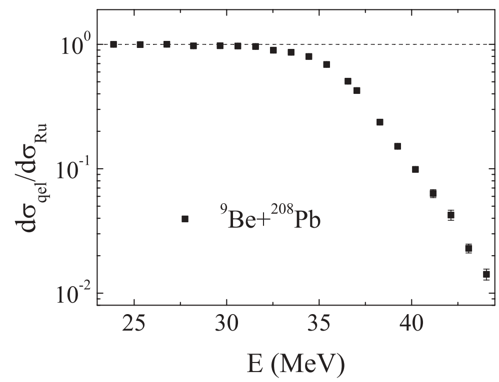

FIG. 2. The ratio of the differential QEL cross sections relative to the Rutherford scattering cross sections measured at $\theta_{\rm lab} = 170^\circ$ for ^{9}Be + ^{208}Pb.

The cross sections of QEL were normalized with the counts of elastic scattering in the two monitors. Energy loss in the carbon backing and the target was considered in the data analysis. The ratio QEL/Rutherford scattering was obtained by means of the expression:

$$\frac{d\sigma_{\rm QEL}}{d\sigma_{\rm Ru}}(\theta_{\rm QEL}) = \frac{N_{\rm QEL}}{N_{\rm M}} \frac{d\sigma_{\rm Ru}(\theta_M)}{d\sigma_{\rm Ru}(\theta_{\rm QEL})} \frac{\Delta\Omega_M}{\Delta\Omega_{\rm QEL}}, \quad (1)$$

where θ is the fixed angle of the detector and N is the corresponding number of detected events of interest in the solid angle $\Delta\Omega$. The solid angle ratio was determined by a calibrated ^{241}Am α source and the elastic scattering of ^{9}Be + ^{208}Pb at very low beam energies for which the elastic scattering cross sections follow the Rutherford formula; the final ratio was estimated to be 0.0558 ± 0.0008 (1.4% statistical uncertainty). The experimental errors include only the statistical error of the event counts. Figure 2 shows the excitation function of QEL scattering measured at 170° for ^{9}Be + ^{208}Pb. The cross sections are listed in Table I.

The barrier distribution from the QEL scattering excitation function can be deduced [2] as follows:

$$D_{\rm QEL}(E) = -\frac{d}{dE}\left[\frac{d\sigma_{\rm QEL}}{d\sigma_{\rm Ru}}(E)\right], \quad (2)$$

where $d\sigma_{\rm QEL}$ is the QEL scattering differential cross section. The cross section should be the differential cross section at

TABLE I. The QEL cross sections measured at $\theta_{\rm lab} = 170^\circ$ for ^{9}Be + ^{208}Pb. Quoted errors are statistical uncertainties only.

E (MeV)	$d\sigma_{\rm QEL}/d\sigma_{\rm Ru}$	E (MeV)	$d\sigma_{\rm QEL}/d\sigma_{\rm Ru}$
23.9	1.000 ± 0.015	35.4	0.689 ± 0.012
25.3	0.995 ± 0.014	36.6	0.505 ± 0.009
26.8	1.001 ± 0.015	37.0	0.425 ± 0.009
28.2	0.973 ± 0.015	38.3	0.237 ± 0.005
29.6	0.975 ± 0.015	39.2	0.152 ± 0.004
30.6	0.969 ± 0.015	40.2	0.099 ± 0.003
31.6	0.960 ± 0.015	41.2	0.063 ± 0.005
32.5	0.897 ± 0.015	42.1	0.042 ± 0.004
33.5	0.864 ± 0.016	43.1	0.023 ± 0.002
34.4	0.798 ± 0.014	44.0	0.014 ± 0.001

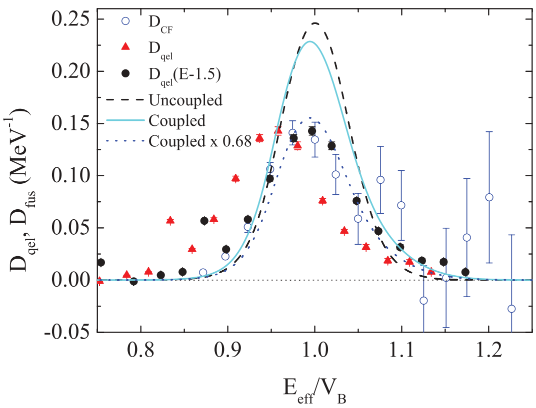

FIG. 3. (Color online) A comparison of the barrier distributions extracted from the excitation functions of the QEL scattering (filled triangles) and the complete fusion (open circles) for the $^{9}Be + {}^{208}Pb$ system.

$\theta \approx 180^\circ$ in theory; experimentally, the detectors were usually located at large backward angles as close to 180° as possible. Therefore, the center-of-mass E should be depressed by the centrifugal energy E_{cent},

$$E_{\text{cent}} = E\frac{\operatorname{cosec}(\theta/2) - 1}{\operatorname{cosec}(\theta/2) + 1}, \quad (3)$$

by considering the extra centrifugal potential for the partial wave, which contributes to the scattering at θ when the barrier distribution was deduced, where θ is the angle in the center-of-mass system. With Eq. (2), the barrier distribution for $^{9}Be + {}^{208}Pb$ was obtained from the QEL excitation function at the angle $\theta_{\text{lab}} = 170^\circ$, shown in Fig. 3 as filled triangles. The relative errors of the data for the barrier distribution increase from 2% to 13% with the increasing energy. The errors in the figure are a little larger or are less than the size of the data point.

The figure also shows the deduced fusion barrier distribution from the CF excitation function as open circles taken from Ref. [15]. The shape of the two distributions is similar, but an energy shift exists between the two peaks. The solid circles represent the QEL barrier distribution, which is shifted to higher energy by 1.5 MeV. From this comparison, we could see that the main part of the shape of the two barrier distributions is consistent after the energy shift of the QEL barrier.

Coupled-channels calculation has been performed by using the code CCDEF [14]. The ground rotational state with an effective value of $\beta_2 = 0.92$ for ^{9}Be was used. For the target, the 3^- and 5^- vibrational states with $\beta_3 = 0.122$ and $E_x = 2.615$ MeV, $\beta_5 = 0.08$ and $E_x = 3.198$ MeV were included. The barrier distributions were obtained from the calculated fusion excitation functions and compared with the experimental data in Fig. 3. The coupled-channel calculation, which ignores breakup effects gives a wider distribution and a better fit to the experimental data as compared with the single-channel calculation. It seems that the coupling calculation gives an overall trend of the experimental data on the whole but carries a larger weight near the barrier energies. This discrepancy might be attributed to the absence of the ^{9}Be breakup channel in the coupling scheme. The dotted line is the result of the coupled-channels calculation scaled by 0.68; the complete fusion suppression factor is found in Ref. [15].

Energy shifts between the distributions were also found in the $^{6}Li + {}^{144}Sm$ [11] and $^{6,7}Li + {}^{208}Pb$ [7] systems. The downward centroid shift of the QEL barrier distribution of $^{9}Be + {}^{208}Pb$ is in basic agreement with the result of $^{6}Li + {}^{144}Sm$ [11]. This shift is ascribed to the breakup of the projectiles before reaching the classical turning point caused by the similar time scales of the fusion and fast breakup reactions. Therefore, for such systems, the breakup channel must be included as one of the QEL processes [12]. The barrier distributions extracted from the excitation functions of the sum of the QEL scattering and breakup are almost the same as the one extracted from the CF excitation functions for $^{6,7}Li + {}^{208}Pb$. This result indicates that barrier distribution not only bears the information of nuclear structures but also contains the knowledge of the reaction mechanism [7]. Recently, Pereira *et al.* [16] have proved that breakup at near-barrier energies can be attributed to dissipative processes. Since the total reaction cross section is larger than the fusion cross section, the QEL barrier distribution (or reaction threshold distribution, which follows Zagrebaev's interpretation [17]), obtained from QEL (elastic + inelastic) scattering, must be shifted to the low-energy side, when compared with the fusion barrier distribution obtained from fusion cross section measurement. It agrees with the expression $R + T = 1 - P^{\text{BU}}$. Hence, it is necessary to get the breakup data and to perform the continuum discretized coupled-channels calculations to include the breakup coupling for further understanding of the reaction dynamics.

To summarize, the QEL excitation function of the $^{9}Be + {}^{208}Pb$ system at a backward angle has been measured at near-barrier energies. The corresponding barrier distribution has been deduced from the first derivative of the experimental cross sections with respect to the effective energies. Coupled-channels calculation, which includes the low-inelastic states has been performed to compare the data. Combined with the $^{6}Li + {}^{144}Sm$ data (almost the same energy shift 1.5 MeV), it can be concluded that the discrepancy between the theoretical prediction and the data indicates a large breakup effect in the QEL scattering of the weakly bound nucleus. Other reaction channels not included in the calculation might be needed to eliminate the discrepancy between experimental data and theoretical estimations. Based on the experimental results, Zagrebaev proposed that the barrier distribution derived from backward QEL scattering of heavy ions represents the total reaction threshold distribution rather than the fusion barrier [17]. The present result supports this idea. This means that the barrier distribution not only contains the information about the coupling effects and the nuclear structures, but also reflects the reaction mechanism to some extent.

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[1] N. Rowley, G. H. Satchler, and P. H. Stelson, Phys. Lett. B **254**, 25 (1991).
[2] H. Timmers, J. R. Leigh, M. Dasgupta, D. J. Hinde, R. C. Lemmon, J. C. Mein, C. R. Morton, J. O. Newton, and N. Rowley, Nucl. Phys. A **584**, 190 (1995).
[3] E. Piasecki *et al.*, Phys. Rev. C **80**, 054613 (2009).
[4] L. F. Canto, P. R. S. Gomes, R. Donangelo, and M. S. Hussein, Phys. Rep. **424**, 1 (2006).
[5] A. Diaz-Torres, I. J. Thompson, and C. Beck, Phys. Rev. C **68**, 044607 (2003).
[6] M. Dasgupta *et al.*, Phys. Rev. C **70**, 024606 (2004).
[7] C. J. Lin *et al.*, Nucl. Phys. A **787**, 281c (2007).
[8] D. S. Monteiro *et al.*, Phys. Rev. C **79**, 014601 (2009).
[9] S. Mukherjee, B. K. Nayak, D. S. Monteiro, J. Lubian, P. R. S. Gomes, S. Appannababu, and R. K. Choudhury, Phys. Rev. C **80**, 014607 (2009).
[10] J. Lubian, T. Correa, P. R. S. Gomes, and L. F. Canto, Phys. Rev. C **78**, 064615 (2008).
[11] D. S. Monteiro, P. R. S. Gomes, and J. Lubian, Phys. Rev. C **80**, 047602 (2009).
[12] D. R. Otomar *et al.*, Phys. Rev. C **80**, 034614 (2009).
[13] C. Signorini *et al.*, Eur. Phys. J. A **5**, 7 (1999).
[14] J. Fernández-Niello, C. H. Dasso, and S. Landowne, Comput. Phys. Commun. **54**, 409 (1989).
[15] M. Dasgupta *et al.*, Phys. Rev. Lett. **82**, 1395 (1999).
[16] D. Pereira, J. Lubian, J. R. B. Oliveira, D. P. de Sousa, and L. C. Chamon, Phys. Lett. B **670**, 330 (2009).
[17] V. I. Zagrebaev, Phys. Rev. C **78**, 047602 (2008).