PHYSICAL REVIEW C **68**, 044605 (2003)

Near barrier fusion excitation function of ^{6}Li+^{208}Pb

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(Received 7 September 2002; revised manuscript received 15 May 2003; published 10 October 2003)

The fusion cross sections of ^{6}Li+^{208}Pb system at energies near the barrier have been measured by means of the evaporation residue method and have been calculated in terms of the coupled-channels model, taking into account single and double phonon octupole excitations of ^{208}Pb and the 3^+ rotational state of ^{6}Li. By comparing the experimental results with the theoretical calculations and with the fusion cross section of ^{16}O+^{208}Pb, in which no breakup happens, we conclude that the fusion cross sections of ^{6}Li+^{208}Pb are suppressed at above-barrier energies due to the effects of ^{6}Li breakup, but below the barrier, the effects of breakup are not clear.

DOI: 10.1103/PhysRevC.68.044605 PACS number(s): 25.70.Jj, 24.10.Eq, 21.60.Ev, 27.80.+w

I. INTROUDCTION

In recent years, near barrier fusion and breakup reactions of halo and weakly bound nuclei led to a strong theoretical and experimental interest. Such nuclei are proved by recent experiments [1,2] to have a high probability of breakup during the colliding processes. This should strongly influence fusion around the Coulomb barrier. There are several theoretical works devoted to this topic, which bring out conflicting predictions. Hussein *et al.* [3,4] and Takigawa *et al.* [5] suggested that the breakup reaction would take away a certain fraction of incoming flux in the entrance channel and, as a consequence, the fusion cross section would decrease. However, according to Dasso *et al.* [6,7], breakup should be considered as the doorway state to fusion; its coupling with the entrance channel would enhance the fusion probability. Recently, Hagino *et al.* [8] performed an improved coupled-channels calculation to reconcile the conflicting approaches, predicting enhancement of fusion cross sections at sub-barrier energies, and a reduction at above-barrier energies.

This problem has been studied experimentally in many systems, but no definite conclusion is extracted so far. Different results have been obtained. For ^{38}S+^{181}Ta [9], ^{6}He+^{209}Bi [10,11], and ^{6}He+^{238}U [12] systems, an enhancement of sub-barrier fusion is claimed. For ^{9}Be+^{208}Pb [13], ^{9}Be+^{209}Bi [14], and ^{6,7}Li+^{209}Bi [15] systems, a large fusion suppression above the barrier has been observed. ^{7}Li+^{165}Ho [16] reaction shows a reduction above the barrier and an enhancement below the barrier energies. But for ^{11}Be+^{209}Bi [17,18] and ^{17}F+^{208}Pb [19] systems, the authors claim that the effects of breakup process on the fusion cross section could be ignored. A recent work on ^{12}C+^{7}Li [20] also reached the same conclusion. Finally, the recently measured ^{6,7}Li+^{59}Co systems [21] show a small enhancement of total fusion for the ^{6}Li projectile at sub-barrier energies compared to the more tightly bound ^{7}Li, while similar cross sections are found at and above the barrier for both reactions. From the aforementioned results, we can see that this problem is still open and further work is necessary both theoretically and experimentally to obtain more definite conclusion. Since experimental results with high precision are not easy to obtain under current conditions of radioactive beams, in this work we choose a weakly bound stable nucleus ^{6}Li, with separation energy s_α=1.475 MeV, to study this problem.

II. EXPERIMENTAL DESCRIPTION

The experiments were performed at the HI-13 tandem accelerator, China Institute of Atomic Energy, Beijing. ^{208}Pb targets were bombarded by the collimated beam of ^{6}Li with incident energies varying from 25.75 to 39.06 MeV in 0.58-MeV-energy steps. The targets were about 350 μg/cm^2 in thickness, evaporated onto Cu foils thick enough to stop completely the recoiling heavy residues. Two Si (Au) detectors, located at angles of ±24.3° with respect to the beam direction, and positioned at 14.6±0.1 cm from the target, were used to monitor the Rutherford scattering and to normalize cross sections. Two sets of $\Delta E-E$ silicon detector telescope with apertures of 4.36 and 4.18 mm in diameter, respectively, located at mean angles of ±160° with respect to the beam direction, measured α particles emitted by the evaporation residues. Their distances from the target were 6.4±0.1 and 6.8±0.1 cm, respectively. A new target was used for each beam energy. The irradiated target removed from the target frame was put into another low vacuum chamber and set close to a silicon detector of 20 mm diameter to detect α particles emitted by the long-lived evaporation residues in off-beam measurements.

The compound nucleus ^{214}At formed following complete fusion of ^{6}Li with ^{208}Pb deexcites dominantly through 1n,

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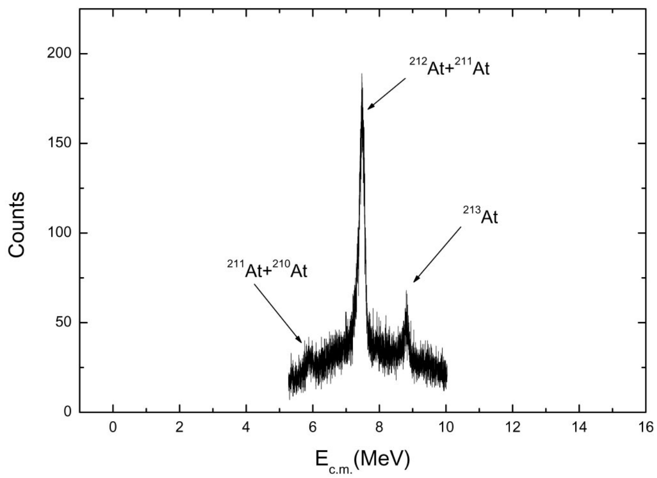

FIG. 1. A typical one-dimensional total energy spectrum from online analysis.

$2n$, $3n$, $4n$ evaporation and results in a series of residual isotopes ^{213}At, ^{212}At, ^{211}At, ^{210}At. The yields of ^{213}At are low in the present experiment, and their cross sections are negligible. The proton evaporation residues were not observed. ^{210}Bi formed following incomplete fusion, if any, cannot be separated from complete fusion residues, because through β^- decay it decays to the same ^{210}Po daughter nucleus as that of ^{210}At. The evaporation residues and their daughters which are formed following the α decay of At nuclei, decay via emitting α particles. They can be identified by their distinctive α energies and half-lives. ^{212}At emits an α particle with the energy of 7.681 MeV and the half-life of 0.314 s. Due to its short lifetime, we obtained the cross sections of $2n$ evaporation channel in in-beam measurements. The results of other channels were obtained in off-beam measurements because of their long half-lives. The fission events were not measured. Anyway, the fission yields are much lower than those of evaporation residues according to PACE2 [22] calculations. In addition, the contribution of fission events to the total fusion cross section for ^{9}Be+^{208}Pb is less than 1% [13]. Because fission probability is quite sensitive to the fissility parameter, and the fissility of ^{6}Li+^{208}Pb system is less than that of ^{9}Be+^{208}Pb system, the contribution of fission to the total fusion cross sections can be ignored for the former system. Then the complete fusion cross section can be obtained by the sum of those of the evaporation residues ^{212}At, ^{211}At, ^{210}At.

A typical energy spectrum obtained from in-beam measurement is shown in Fig. 1. The 7.681-MeV peak of ^{212}At ($2n$ evaporation channel) is quite clear in the figure. The isotope ^{211}At ($3n$ evaporation channel) decays into two branches, in which 41.7% branching ratio belongs to α decay with the energy of 5.867 MeV and the remainder being the orbital electron capture into ^{211}Po. The daughter nucleus ^{211}Po($T_{1/2}$=0.516 s) emits an α particle with the energy of 7.45 MeV which was also observed in in-beam measurements, and mixed into the $2n$ channel peak because their α particle energies are not so different. So they must be subtracted from the cross sections of $2n$ channel. Figure 2 shows a spectrum obtained in off-beam measurement, which was immediately performed after irradiation. In the figure, one can see clearly that there are three groups of α particles with distinctive energies. The group with the lowest energy (5.305 MeV) belongs to the α decay of ^{210}Po($T_{1/2}$ =138.38 day), which itself is a daughter nucleus of ^{210}At ($4n$ evaporation channel). The other two groups with the energies of 5.867 MeV and 7.450 MeV correspond to the two branches of ^{211}At with $T_{1/2}$=7.214 h.

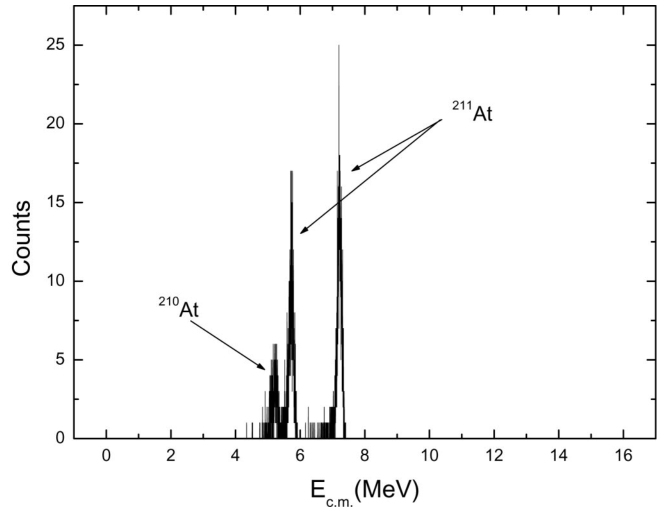

FIG. 2. A spectrum from offline measurements, with three peaks corresponding to 5.305, 5.867, and 7.450 MeV, respectively. The last two groups are of α decay from ^{211}At, the other one is from ^{210}Po which is a daughter nucleus of ^{210}At.

III. RESULTS AND DISCUSSIONS

The absolute cross section normalization was deduced from ^{6}Li Rutherford scattering on ^{208}Pb. The ^{6}Li elastic peak on Pb was clearly resolved from that of Cu in the spectra of the monitor detectors at 24°, as shown in Fig. 3. The measured absolute cross sections for $2n$, $3n$, $4n$ evaporation residues ^{212,211,210}At are shown by the solid squares with error bars in Fig. 4. The solid lines represent the results of the

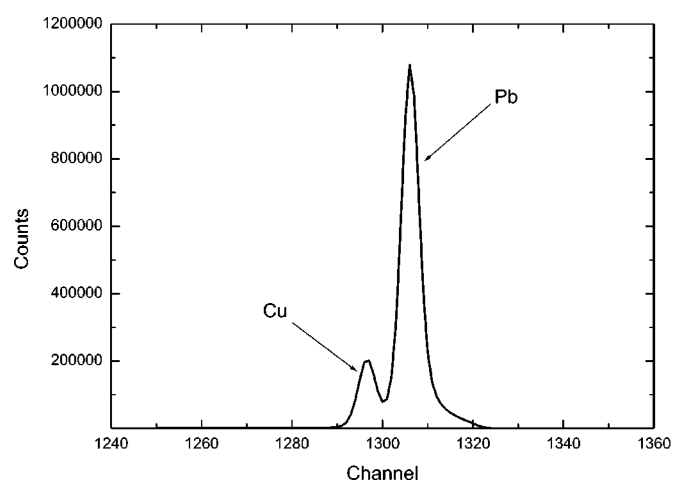

FIG. 3. A typical spectrum of the elastic peaks of ^{6}Li on the ^{208}Pb target and on the ^{64}Cu backing.

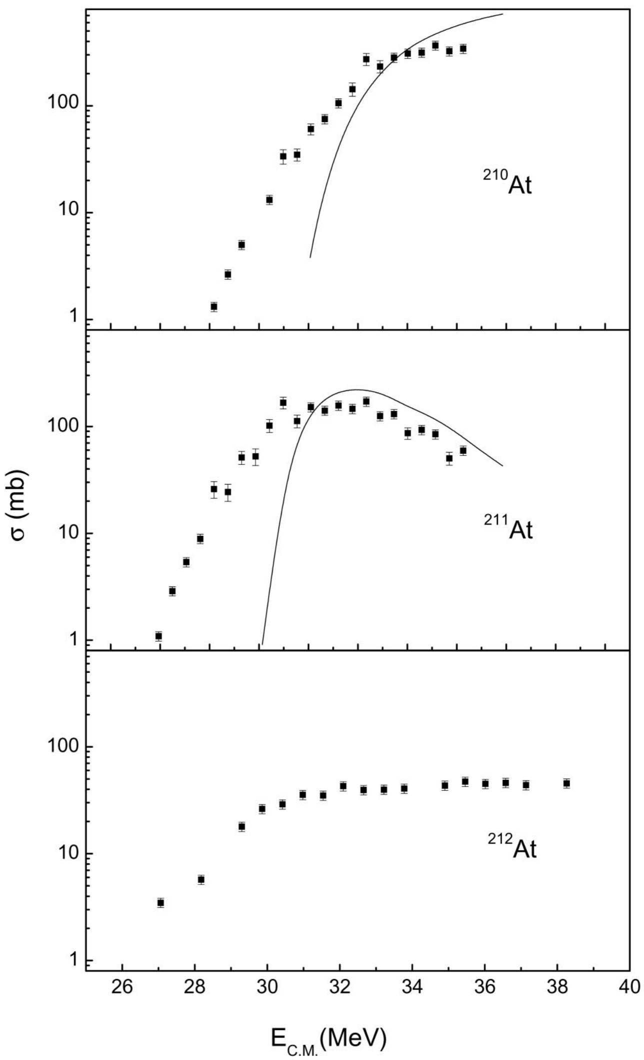

FIG. 4. The measured cross sections of At isotopes. The solid lines are the results of PACE2 calculations.

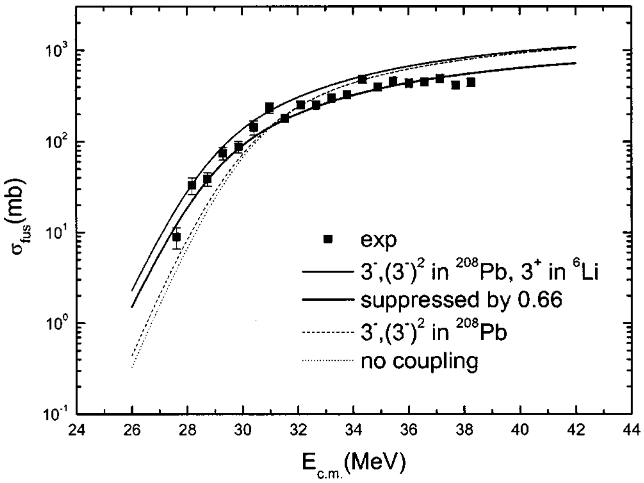

FIG. 5. Total fusion cross sections for ^{6}Li+^{208}Pb. The solid squares are results of this experiment. The solid and dashed lines correspond to the coupled-channels code CCFULL [21,23] calculations taking into account single and double phonon 3^{-} excitations in ^{208}Pb and the spectroscopic quadrupole moment of the ^{6}Li nucleus, with and without coupling to its 3^{+} unbound excited state, respectively. The dotted line corresponds to the one-dimensional barrier penetration model and the thick solid line corresponds to the full-couplings calculation, multiplied by the constant suppression factor 0.66. For the parameters used in the calculations, see text.

calculations with the statistical model PACE2. In these model calculations, the parameters of optical potentials of the neutron, proton, and α particle are automatically introduced by the code without any adjustable parameters. For the cross sections of $2n$ evaporation channel, the uncertainties are estimated to be about 10%, mainly due to statistical and systematic uncertainities which will be mentioned below. For the cross sections of $3n$, $4n$ channels, the uncertainties are estimated to be about 10%, mainly arising from the systematic uncertainties, i.e., uncertainties of solid angles and α peak resolutions in off-beam measurements. According to the statistical model, the excitation function of $2n$ channel should have a declining trend above the barrier, whereas the experimental one is almost flat in that region. We attribute this most likely to the systematic uncertainties due to the subtraction of α particles of ^{211}At from the peaks of $2n$ channel. In order to subtract these counts, we first have to use the data of $3n$ channel obtained from off-beam measurements. But as mentioned above, there are relatively large uncertainties in off-beam measurements, so the subtractions might cause large uncertainties as well. Fortunately, the contributions of the cross section of $2n$ channel to the total fusion cross sections are small, hence these uncertainties have no significant influence on the total fusion cross sections. In addition, as a statistical model the PACE2 code does not include the quantum tunnel effect; for this reason, its predictions cannot give a good description of the experimental data below the barrier.

The total absolute fusion cross sections for ^{6}Li+^{208}Pb are presented in Fig. 5. The solid squares are the results obtained in this experiment. The solid and dashed lines correspond to the coupled-channels code CCFULL [23–25] calculations taking into account the spectroscopic quadrupole moment $Q = -0.082$ fm^{2} of the ^{6}Li nucleus, with and without coupling to its 3^{+} unbound excited state, respectively. The dotted line corresponds to the one-dimensional barrier penetration model. In addition to the reorientation terms, the remaining inputs to the model calculations are the nucleus-nucleus potential parameters, and the excitation energies and the transition strengths of the coupled rotational states. The standard Akyuz-Winther nuclear potential was used, with parameters given by V_0=47.60 MeV, r_0=1.177 fm, and a_0=0.619 fm, giving an average height of fusion barrier B_0=30.1 MeV, barrier radius R_B=11.09 fm, and the curvature for the average barrier of $\hbar\omega_0$=5.20 MeV. The other relevant parameters in our calculations are the 3^{-} state in ^{208}Pb, 2.615 MeV, $B(E3;0^{+}\rightarrow 3^{-})$=0.611 e^{2}b^{3} [26] (one- and two-phonon excitations were included with the harmonic limit); and the 3^{+} rotational excitation in ^{6}Li, 2.186 MeV, $B(E2;1^{+}\rightarrow 3^{+})$ =21.8 e^{2} fm^{4} [27]. The effects of target phonon excitations are rather weak. For taking into account the excitation to the unbound 3^{+} excited state in ^{6}Li a modified version of CCFULL [21] made for odd-odd nuclei with finite ground state spin

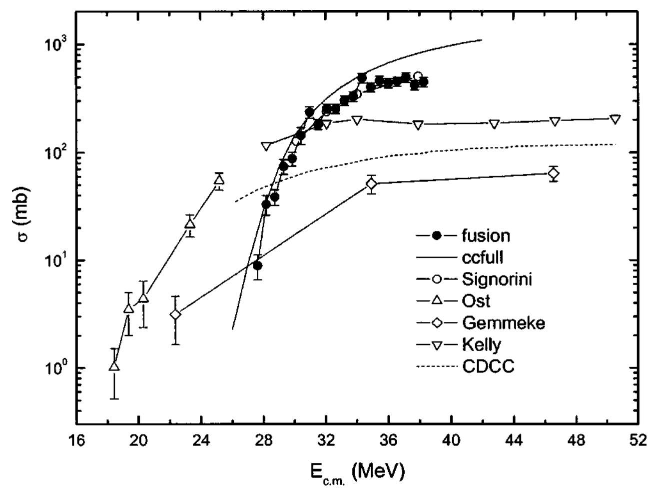

FIG. 6. A comparison of the fusion cross sections and those of breakup for the system of ^{6}Li+^{208}Pb. The open symbols are the data of breakup quoted from Refs. [1,2,28,29]. The solid and dashed lines are the predictions of CCFULL and CDCC [2] for fusion and breakup reactions, respectively.

was used. The coupled-channels code does not consider the influence of breakup effect on fusion.

In Fig. 5, one can see that the full-couplings CCFULL calculation (solid line) seems to overestimate the fusion cross sections over the whole energy range, though this effect is less clear at sub-barrier energies due to some fluctuations in the fusion excitation function. In other words, there is a suppression of fusion cross sections, indicating the significant role of breakup on fusion. The fusion suppression factor is of the same order of magnitude as the one recently observed for the very close system ^{6}Li+^{209}Bi [15], as one can see from the thick solid line in Fig. 5, which corresponds to the full-coupling calculations multiplied by the constant factor 0.66.

In order to illustrate the importance of breakup mechanism, we plotted the fusion cross sections together with the data [1,2,28,29] of breakup cross section in Fig. 6. Although the data measured by different groups are not quite in agreement, the breakup cross sections are large. Therefore, the breakup mechanism should have strong effects on fusion. As is well established, above the barrier the coupled-channel effects become relatively small, while the breakup influence (as a reduction of the incoming flux in the entrance channel due to the projectile breakup) may manifest itself on fusion. In Fig. 7, we compare the present results with those of the other two similar systems, ^{9}Be+^{208}Pb [13] and ^{16}O+^{208}Pb [30]. The results show that these three systems have similar behavior near their barriers. As we know, ^{16}O and ^{208}Pb are spherical nuclei, and the projectile ^{16}O is not expected to breakup in the fusion reaction process, so its reduced fusion cross sections provide reference to examine the effects of breakup on fusion for the similar systems such as ^{6}Li +^{208}Pb and ^{9}Be+^{208}Pb. From the comparison one can see that above the barrier, the fusion cross sections for ^{6}Li +^{208}Pb and ^{9}Be+^{208}Pb are suppressed as a consequence of the breakup of the weakly bound projectile. On the other hand, the cross section of ^{6}Li+^{208}Pb are enhanced below the barrier as compared with the other two systems. We guess that this enhancement is most likely due to the strong coupling of ^{6}Li nucleus as seen from Fig. 5.

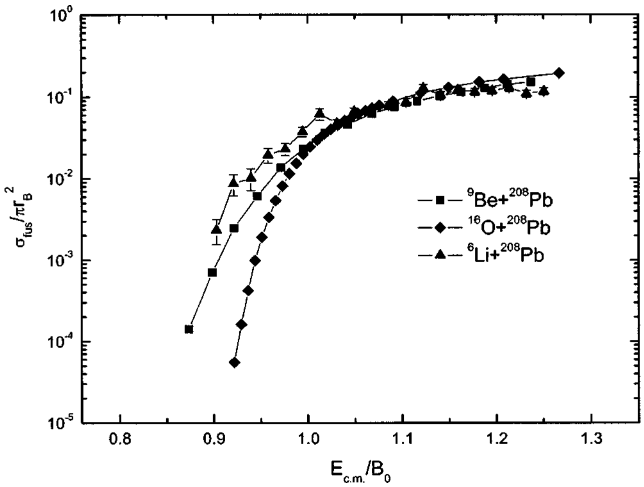

FIG. 7. The reduced fusion excitation functions of three similar systems ^{9}Be+^{208}Pb [13], ^{16}O+^{208}Pb [30], and ^{6}Li+^{208}Pb.

IV. SUMMARY

The fusion excitation function of ^{6}Li+^{208}Pb system at energies near the barrier has been measured by means of the evaporation residue method and has been calculated in terms of the coupled-channels model (CCFULL code) taking into account single and double phonon octupole excitations of ^{208}Pb and the 3^{+} rotational state of ^{6}Li. By comparison of the experimental results with the theoretical calculations and with the fusion cross sections of ^{16}O+^{208}Pb, in which no breakup happens, we conclude that the fusion cross sections of ^{6}Li+^{208}Pb are suppressed at above barrier energies due to the effects of ^{6}Li breakup, but below the barrier, the effects of breakup are not clear.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China under Grant Nos. 10275095 and 10235030, and the Major State Basic Research Development Program of China under Grant No. G2000077400. We would like to thank the staff of the HI-13 Tandem accelerator at the CIAE for their patient conduct and for providing good conditions. One of the authors (Y.W.W.) heartily thanks Professor Y. X. Liu of Peking University (China) for worthy help.

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