Near-barrier fusion of weakly bound ^{6}Li and ^{7}Li nuclei with ^{59}Co

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(Received 24 February 2003; published 2 May 2003)

Excitation functions for sub- and near-barrier total (complete + incomplete) fusion cross sections are presented for the ^{6,7}Li+^{59}Co reactions. Evaporation residues were identified by their characteristic γ rays and the corresponding yields measured with both the IReS Garel+ array at the Vivitron facility and with the São Paulo Ge array at the 8UD Pelletron tandem facility using standard γ-ray techniques. The data extend to medium-mass systems previous works exploring the coupling effects (hindrance versus enhancement) in fusion reactions of both lighter and heavier systems. The results indicate a small enhancement of total fusion for the more weakly bound ^{6}Li at sub-barrier energies, with similar cross sections for both reactions at and above the barrier.

DOI: 10.1103/PhysRevC.67.054602 PACS number(s): 25.70.Jj, 25.70.Mn, 25.70.Gh

I. INTRODUCTION

A number of experimental and theoretical studies have explored the effect of coupling to collective degrees of freedom on the fusion process [1–5]. A significant enhancement of the sub-barrier fusion cross section is often found compared to predictions of one-dimensional barrier penetration models. This is understood in terms of the dynamical processes arising from couplings to collective inelastic excitations of the target and projectile [5]. However, in the case of reactions where at least one of the colliding nuclei has a sufficiently low binding energy so that breakup becomes an important process, conflicting model predictions and experimental results have been reported [6–15].

Projectile breakup is likely to have a strong influence on reactions with radioactive ion beams. For example, a projectile such as ^{11}Li might be expected to break up by emitting its two weakly bound neutrons. In order to understand such a process, however, it is essential to see first if the fusion of the stable lithium isotopes ^{6,7}Li can be understood and to see on which targets the most interesting results might be obtained. Here again, however, breakup processes could still be important due to the cluster structure of these nuclides, and one should test whether simple inelastic excitations are adequate to describe this physics. Of course, another element in this problem is that incomplete fusion (ICF) may also be important for cluster systems. This introduces complications both experimentally and theoretically.

Although the coupling to collective degrees of freedom is known to systematically enhance the complete fusion (CF) cross section [1–5], the expected tendency to break up for weakly bound nuclei at barrier energies can also lead to a suppression of the CF cross section [9]. Some experimental results suggest that, above the Coulomb barrier, nuclear breakup is a major factor limiting fusion in light heavy-ion systems involving weakly bound nuclei [10]. However, these results have recently been challenged [13]. Little is known about the effect of breakup on the sub-barrier fusion of such systems. For massive systems, where Coulomb effects might be expected to dominate, the influence of projectile breakup is also controversial, even though there has been considerable experimental work on the issue [16–23]. In general, the data seem to indicate a suppression of fusion above the barrier in systems with a significant breakup probability. The magnitude of the suppression may be consistent with the "missing" yield that goes into ICF channels [19]. Sub-barrier studies using weakly bound projectiles on heavy targets have not shown a consistent pattern of suppression or enhancement [24–27]. Coupled-channel calculations for the ^{9}Be+^{208}Pb system performed without couplings to breakup channels underestimate the fusion data, which may indicate fusion enhancement at energies below the barrier [19]. The CF suppression in the ^{9}Be+^{208}Pb reaction has been recently

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investigated through the the sub-barrier breakup yields of ^{9}Be [23].

For both ^{6}He+^{209}Bi [24,25] and ^{6}He+^{238}U [26,27] fusion reactions, with a weakly bound neutron-halo projectile, a large sub-barrier enhancement is observed, though no enhancement is observed using a proton-rich projectile in the ^{17}F+^{208}Pb reaction [18]. Clearly, a full understanding of the effects of breakup on near-barrier fusion will require systematic measurements covering a wide range of systems and energies.

In the present paper we choose to study the fusion of ^{6,7}Li with the intermediate-mass target ^{59}Co. In addition to complementing existing systematics for light systems [15,28,29], this choice is also partly motivated by the proposed experimental technique of detecting characteristic γ rays emitted from the resulting evaporation residues (ER), which could in principle, also allow us to distinguish between CF and ICF.

The paper is organized as follows. The experimental techniques are described in detail in Sec. II and the experimental results are given in Sec. III. Data analysis and coupled-channel calculations are discussed in Sec. IV, and our conclusions presented in Sec. V.

II. EXPERIMENTAL DETAILS

The total fusion excitation functions were measured by the γ-ray spectroscopy method [30]. This technique has been shown to work well in mass regions with well-established level schemes and with a small number of long-lived isomeric states. In particular, it has been employed in the same medium-mass region in a study of the ^{16}O+^{46,50}Ti reactions near the Coulomb barrier [31].

The potential problem of not being able to observe part of the ground-state populations of residual nuclei (direct side feeding into the ground state) is not significant in the mass and energy regions being studied here, as demonstrated in Refs. [30–32]. The alternative technique used to study most lighter systems involves detecting the energy loss of ER's in gas and/or solid-state detectors. However, the very low recoil velocities available when studying medium-mass systems make such measurement impractical at beam energies near the Coulomb barrier. The energy-loss technique has, nevertheless, been recently employed for ^{6,7}Li+^{64}Zn CF reaction studies at energies above the barrier [22].

The ^{6}Li and ^{7}Li beams, with energies between 11 and 26 MeV and intensities of 5–10 pnA, were provided by both the Vivitron electrostatic tandem accelerator of the IReS and the 8UD Pelletron tandem facility of the University of São Paulo. The targets consisted of thin foils of ^{59}Co of areal density $\approx$600 μg/cm^2, leading to an average energy loss $\Delta E_{beam}\approx$500 keV, backed by 48-mg/cm^2-thick Pb (Strasbourg) or very thick Ta (São Paulo), with thin ($\approx$65 μg/cm^2 thick) Al buffer layers between the Co foils and the backing material. This Al layer is necessary to prevent any diffusion of the Co material into the Pb backing. The backings were used to avoid Doppler shifts of the γ lines.

For the Strasbourg measurements, the γ-ray events were detected with part of the Garel+ spectrometer array [33] configured with 14 Compton-suppressed, high-efficiency Eurogam-type [34] Hp Ge detectors together with one LEPS (low-energy photon spectrometer) detector. The LEPS detector was used to enhance the detection efficiency and resolution of low-energy transitions. The beam was not stopped in the Pb target backing. Consequently, the beam current, measured on a Faraday cup after the target, was integrated in order to obtain the charge accumulated at each energy. The absolute efficiency for the set of Ge detectors was (1.20 $\pm$0.16)% for a calibrated ^{60}Co source. The uncertainties in the total fusion cross sections come from statistical errors in the determination of the γ-ray yields, background subtraction, absolute efficiency of the detectors, and systematic errors resulting from measurements of the target thickness and the integrated beam current. Sufficient data were collected for the γ decays of the dominant ER's to allow estimates of the effect of long-lived isomeric states. These states do not alter the cross sections deduced for the major channels. At each energy, the activity buildup was measured without beam with runs of approximately 1 h duration. Relative normalizations at different energies were checked by simultaneous measurements of x-ray emission and of γ rays from inelastic scattering of beam particles in the target and backing.

For the São Paulo measurements, the beam was stopped in the target backing and the beam current was integrated on the isolated and biased target holder. Dead-time corrections were determined using radioactivity peaks. Relative normalizations at different energies were checked using γ-ray yields from inelastic scattering. The absolute efficiency of the São Paulo Ge detector array was (0.48$\pm$0.04)% for a calibrated ^{60}Co source.

III. EXPERIMENTAL RESULTS

The ER excitation functions for both the ^{6}Li and ^{7}Li induced reactions are presented in Figs. 1(a) and 1(b), respectively. They were obtained from the observed decays of ER's from the ^{65}Zn and ^{66}Zn compound nuclei, respectively, and combine the data taken both in Strasbourg and São Paulo. Defining CF experimentally is not always straightforward as both ER and fusion-fission cross sections should be measured in the same experiment, though for the studied systems fission is unimportant [36]. Therefore the ER cross sections are here considered to be the total fusion cross sections. The uncertainty in the total fusion cross section is approximately $\pm$5% (statistics) and $\pm$20% (systematics). The figure displays the excitation functions for all fusion events (CF+ICF), as well as for the dominant ER's. In the past, fusion has implicitely included CF yields and ICF yields; however, with the advent of radioactive ion beams, it will be important to distinguish between these processes. In principle, it should be possible to estimate the ICF contribution by studying the population patterns of ER states exploiting statistical-model calculations. The present data, however, do not have sufficient statistics to perform such a difficult analysis. In addition, the (αn) channel, populated both through the CF and the ICF mechanisms, is stronger than statistical-

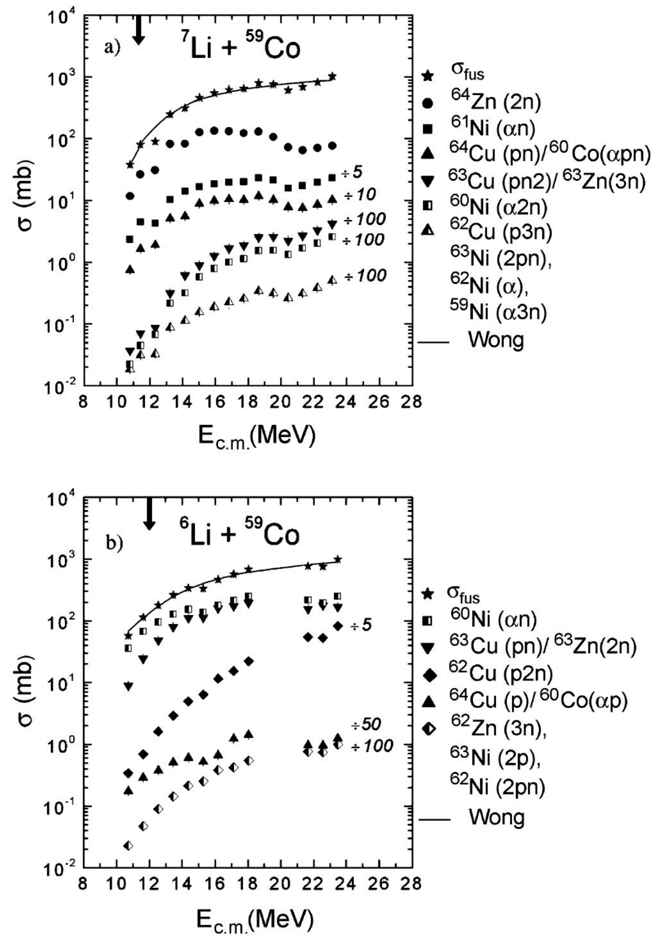

FIG. 1. (a) Excitation functions for the dominant ER channels for the ^{7}Li+^{59}Co reaction. The upper excitation function represents the sum of all the observed decay channels and is associated with the total (CF+ICF) fusion cross section. Unresolved ER's are separated by a sign. Weaker channels, delimited by commas, are summed. (b) Same for the ^{6}Li+^{59}Co reaction. Dashed lines correspond to fits to the data with the SBPM formula of Wong [37]. Statistical errors are smaller than the symbols. Systematic errors are not shown. The arrows indicate the Coulomb barriers of the Wong formalism.

model predictions for CF given by the code CASCADE [35] (not shown) by almost a factor of 10 for both reactions at all energies. Consequently, the following discussion will focus on the total (CF+ICF) fusion cross sections.

Most of the fusion yield is concentrated in just a few dominant ER channels. However, there are some ambiguities in the assignments to these channels. Transitions leading to ^{63}Zn and ^{63}Cu [corresponding to the $(2n)$ and (pn) channels for ^{65}Zn and to $(3n)$ and $(p2n)$ for ^{66}Zn] are identified by the same two γ rays (669 keV and 962 keV) in ^{63}Cu, populated either directly or following ^{63}Znβ decay. Thus, in both reactions, these yields are presented by their sum. The statistical model predicts comparable ^{63}Zn and ^{63}Cu yields for ^{6}Li+^{59}Co, but predicts an appreciable yield only for ^{63}Cu in the ^{7}Li+^{59}Co reaction. A similar situation occurs for ^{64}Cu and ^{60}Co [corresponding to the (p) and (αp) channels for the ^{6}Li induced reactions and to (pn) and (αpn) for ^{7}Li] since a 278-keV γ ray is present in both nuclei. Thus, the sum of the yields is again presented in Figs. 1(a) and 1(b). Here, the statistical-model calculations suggest that ^{60}Co should dominate for the ^{6}Li reaction, whereas ^{64}Cu should dominate for ^{7}Li. The sum of the weaker channels (less than 10% of the total fusion cross section) is represented by the half-filled triangles or diamonds.

The average fusion excitation functions, obtained by fitting the data with the single-barrier penetration model (SBPM) of Wong [37], are shown in Figs. 1 by the solid lines. The relevant parameters are the barrier radius R, the "curvature" $\hbar\omega$ of the barrier, and the barrier height B. For ^{7}Li these parameters have the respective values 7.5 fm, 4.2 MeV, 11.3 MeV and for ^{6}Li the values are 7.6 fm, 8.1 MeV, and 12.0 MeV. The values obtained for the barrier parameters agree well with those extracted from similar fits of the ^{6,7}Li+^{64}Zn fusion data [22]. However, in both cases the derived values of the barrier radii are slightly smaller than those extracted either from the semiempirical fusion barriers of Vaz and Alexander [1] or from the fusion barrier systematics established by Kovar *et al.* [28], and recently extended and revised [15,29]. This may be considered as an indication of the impact of direct breakup on the fusion cross section. However, these fits should be viewed simply as parametrizations of the experimental data since they do not take into account coupling effects or the angular momentum dependence of the barrier parameters. As a whole, these parametrizations describe the general trends of the two excitation functions well. They also serve to demonstrate that although the data require a lower barrier for ^{7}Li, as one would expect, the cross section for ^{6}Li is larger at the lowest energies. This is simulated by a larger value of the curvature in this case. It is apparent that some form of coupling is more important for the lighter projectile than for the heavier one. This is discussed further in the following section based on the inspection of Fig. 2.

IV. DISCUSSION

In order to better isolate the effects of possible couplings, the ratio of the total fusion cross sections $\sigma_F(^{6}\mathrm{Li})/\sigma_F(^{7}\mathrm{Li})$ is given in Fig. 2 as a function of the center-of-mass energy $E_{\mathrm{c.m.}}$. Here, the ^{6}Li data have been interpolated between the data points in order to have results at the corresponding ^{7}Li energies. The solid curve in this figure also shows the ratio calculated by the model of Wong [37] using the independent fits of the two SBPM parametrizations discussed in the preceding section. If the only difference between the two lithium isotopes was the $A^{1/3}$ dependence of the radius, one would expect a simple shift in energy due to the corresponding difference in barrier heights. This shift should be around 0.14 MeV and the dotted curve gives the resulting ratio in Fig. 2; the latter clearly goes in a direction opposite to the experimental data at sub-barrier energies.

Besides the obvious difference in spin (the ground-state spins of ^{6}Li and ^{7}Li are 1 and 3/2, respectively), ^{6}Li differs from ^{7}Li in other important aspects. The two nuclei have small, but different separation energies: ^{6}Li breaks up into $\alpha+d$ with a smaller breakup threshold $S_\alpha=1.47$ MeV com-

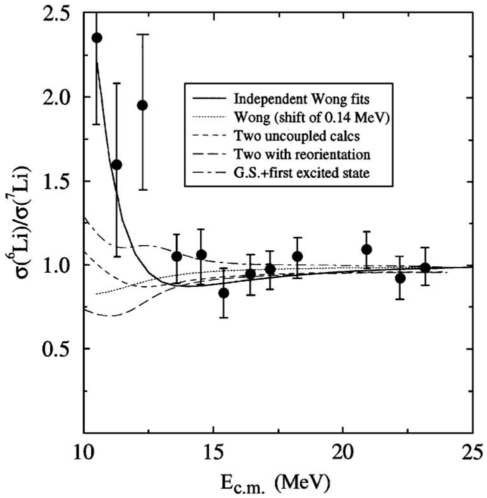

FIG. 2. Energy dependence of the ratio of the total fusion cross sections for ^{6}Li+^{59}Co and ^{7}Li+^{59}Co reactions. Error bars reflect the large systematic errors. The solid and dashed curves correspond to SBPM [37] fits of the ratios as explained in the text. The dotted curves correspond to two uncoupled CCFULL calculations [38] with and without reorientation effects, whereas the dot-dashed curve is the result of CCFULL calculations including the coupling to the first excited state.

pared to ^{7}Li breaking into $\alpha+t$ with $S_\alpha=2.47$ MeV. ^{6}Li is spherical in its ground state, whereas ^{7}Li is deformed. ^{7}Li has a bound $1/2^-$ excited state at 0.478 MeV, wheras the first excited state of ^{6}Li is unbound. Therefore, microscopic differences in the structures of the two isotopes lead to different reorientation terms in the channel couplings (spectroscopic quadrupole moment is $Q=-0.082$ fm^2 for the spherical ^{6}Li nucleus and -4.06 fm^2 for the more deformed ^{7}Li nucleus) as well as to different quadrupole couplings between the ground state and first excited state [$B(E2)\uparrow=21.8$ e^2 fm^4 for ^{6}Li and 8.3 e^2 fm^4 for ^{7}Li]. The dashed curves in Fig. 2 are CCFULL [38] calculations with and without reorientation effects. The potential parameters were taken to be identical for both projectiles: $V_o=74.0$ MeV, $a=0.63$ fm, and $r_o=1.05$ fm. As one might expect from the above values of the quadrupole moments, one sees that the ^{7}Li cross section is enhanced over the ^{6}Li value. Without the coupling, the ratio of cross sections is about 0.96 at high energies. This deviation from 1 is due to geometrical effects (mainly the difference of the Coulomb barrier height). However, when coupling to the first excited state in each projectile (i.e., to the unbound 3^+, 2.186-MeV level for ^{6}Li, and to the bound $1/2^-$, 0.478-MeV state for ^{7}Li, respectively) is included, the ratio of cross sections displayed by the dot-dashed line now becomes about 1, and is consistent with the experimental data. The effects of target phonon excitations have been verified to be rather weak. Although we were not able to extract the CF yields from the measured total fusion cross section, it is clear that all the details of the data, particularly at sub-barrier energies, are not reproduced by the present calculations. More realistic coupled-channel calculations (see Refs. [11,14]), taking account the interplay between projectile breakup and fusion, should be undertaken.

In Fig. 2, the observed total fusion yields are seen to be similar for both systems at energies above the barrier. We interpret this observation as a lack of breakup related suppression for the total fusion cross section above the barrier, although the possibility that both fusion cross sections are suppressed to the same degree cannot be ruled out. The lack of a breakup effect is expected since the data are given as a sum of CF and ICF contributions, for which the incident flux would be conserved at energies above the barrier and, consequently, there is no mechanism for fusion suppression. This experimental result is also supported by theoretical investigations of other reactions induced by ^{6,7}Li projectiles [39] on both a light ^{16}O target and a heavy ^{208}Pb target, using a SBPM model with a potential that includes the real part of the dynamic polarization potential obtained from continuum-discretized coupled-channel (CDCC) calculations. Similar fusion excitation functions for the two lithium isotopes in the two reactions were obtained. The CDCC results can be expected to be the same for a target with intermediate mass such as ^{59}Co. It will be also of interest to investigate if this lack of suppression for the ^{6}Li+^{59}Co system above the barrier, in agreement with systematics [15,28,29], can also be observed for the ^{6}He+^{59}Co system. The γ-ray spectroscopy method could be used with low-energy radioactive beams of ^{6}He, which are now available for fusion studies in some facilities [24,26].

V. CONCLUSION

Measurements of the excitation functions for sub- and near-barrier total fusion (complete fusion + incomplete fusion) have been presented for the stable, weakly bound projectiles ^{6}Li and ^{7}Li on the medium-mass ^{59}Co target. Evaporation residues were identified by their characteristic γ rays and the corresponding yields measured using the γ-ray spectroscopy method. Above the Coulomb barrier, the fusion yields are found to be very close for both systems, in agreement with rather simple coupled-channel calculations [11]. The results are consistent with there being no significant fusion hindrance caused by breakup effects as long as fusion is defined as the sum of CF and ICF contributions. The absence of a breakup-related suppression of the total fusion cross sections above the barrier appears to be a common feature of ^{6,7}Li induced reactions, regardless of target mass. An enhanced yield is observed below the Coulomb barrier for the weakly bound ^{6}Li projectile as compared to that found for the more tightly bound ^{7}Li, although requiring a lower barrier at the lowest energies. This result may be relevant to future studies of nuclides far from stability created using weakly bound, radioactive ion beams such as ^{6}He. Experiments using charged particle spectroscopy techniques are being carried out to measure the total reaction cross section (inelastic and transfer) as well as the light-particle breakup channels for both ^{6,7}Li+^{59}Co reactions. These measurements are essential [23] to determine the coupling strength to the breakup channel that will be introduced in full coupled-channel calculations to be performed in the framework of the CDCC formalism [14] or using a microscopic interaction (with a reduced real part of the optical model) for weakly bound and halo systems [27].

ACKNOWLEDGMENTS

The Garel+ project was supported in part by grants from the French IN2P3. Additional support was provided by the International Programs Office (U.S.-France and U.S.-Brazil) of the U.S. National Science Foundation and the U.S. Department of Energy under Contract Nos. DE-FG03-96ER40981 and W-31-109-ENG38. We would like to thank the Vivitron and Pelletron accelerator staffs for the excellent conditions under which these difficult experiments were performed. We would also like to thank J. Devin for his valuable technical assistance during the Strasbourg experiment, and both J. Greene (ANL) and M. A. Saettel (IReS) for providing the ^{59}Co targets.

[1] L.C. Vaz, J.M. Alexander, and G.R. Satchler, Phys. Rep. **69**, 373 (1981).
[2] M. Beckerman, Phys. Rep. **129**, 145 (1985); Rep. Prog. Phys. **51**, 1047 (1988).
[3] S.G. Steadman and M.J. Rhoades-Brown, Annu. Rev. Nucl. Part. Sci. **36**, 649 (1986).
[4] R. Vandenbosch, Annu. Rev. Nucl. Part. Sci. **42**, 447 (1992).
[5] M. Dasgupta, D.J. Hinde, N. Rowley, and A.M. Stefanini, Annu. Rev. Nucl. Part. Sci. **48**, 401 (1998).
[6] M.S. Hussein, M.P. Pato, L.F. Canto, and R. Donangelo, Phys. Rev. C **46**, 377 (1992); **47**, 2398 (1993).
[7] N. Takigawa, M. Kuratani, and H. Sagawa, Phys. Rev. C **47**, R2470 (1993).
[8] C.H. Dasso and A. Vitturi, Phys. Rev. C **50**, R12 (1994); C.H. Dasso, J.L. Guisado, S.M. Lenzi, and A. Vitturi, Nucl. Phys. **A597**, 473 (1996).
[9] L.F. Canto, R. Donangelo, P. Lotti, and M.S. Hussein, Phys. Rev. C **52**, 1 (1995); L.F. Canto, R. Donangelo, L.M. de Matos, M.S. Hussein, and P. Lotti, *ibid.* **58**, 1107 (1998).
[10] J. Takahashi *et al.*, Phys. Rev. Lett. **78**, 30 (1997).
[11] K. Hagino, A. Vitturi, C.H. Dasso, and S.M. Lenzi, Phys. Rev. C **61**, 037602 (2000).
[12] A. Mukherjee and B. Dasmahapatra, Phys. Rev. C **63**, 017604 (2000); A. Mukherjee *et al.*, Nucl. Phys. **A645**, 13 (1999).
[13] A. Mukherjee, M. Dasgupta, D.J. Hinde, H. Timmers, R.D. Butt, and P.R.S. Gomes, Phys. Lett. B **526**, 295 (2002); A. Mukherjee *et al.*, Nucl. Phys. **A635**, 305 (1998).
[14] A. Diaz-Torres and I.J. Thompson, Phys. Rev. C **65**, 024606 (2002).
[15] R.M. Anjos *et al.*, Phys. Lett. B **534**, 45 (2002).
[16] A. Yoshida, C. Signorini, T. Fukuda, Y. Watanabe, N. Aoi, M.T. Hirai, Y.H. Pu, and F. Scarlassara, Phys. Lett. B **389**, 457 (1996).
[17] C. Signorini *et al.*, Eur. Phys. J. A **2**, 227 (1998); **5**, 7 (1999).
[18] E. Rehm *et al.*, Phys. Rev. Lett. **81**, 3341 (1998).
[19] M. Dasgupta *et al.*, Phys. Rev. Lett. **82**, 1395 (1999).
[20] M. Dasgupta *et al.*, Phys. Rev. C **66**, 041602(R) (2002).
[21] V. Tripathi, A. Navin, K. Mahata, K. Ramachandran, A. Chatterjee, and S. Kailas, Phys. Rev. Lett. **88**, 172701 (2002).
[22] I. Padron *et al.*, Phys. Rev. C **66**, 044608 (2002).
[23] D.J. Hinde, M. Dasgupta, B.R. Fulton, C.R. Morton, R.J. Wooliscroft, A.C. Berriman, and K. Hagino, Phys. Rev. Lett. **89**, 272701 (2002).
[24] J.J. Kolata *et al.*, Phys. Rev. Lett. **81**, 4580 (1998); J.J. Kolata, Eur. Phys. J. A **13**, 117 (2002).
[25] E.F. Aguilera *et al.*, Phys. Rev. Lett. **84**, 5058 (2000).
[26] M. Trotta *et al.*, Phys. Rev. Lett. **84**, 2342 (2000).
[27] N. Alamanos, A. Pakou, V. Lapoux, J.L. Sida, and M. Trotta, Phys. Rev. C **65**, 054606 (2002).
[28] D.G. Kovar *et al.*, Phys. Rev. C **20**, 1305 (1979).
[29] A. Szanto de Toledo *et al.*, Nucl. Phys. **A679**, 175 (2000).
[30] P.R.S. Gomes, T.J.P. Penna, R. Liguori Neto, J.C. Acquadro, C. Teneiro, E. Crema, N. Carlin Filho, and M.M. Coimbra, Nucl. Instrum. Methods Phys. Res. A **280**, 395 (1989).
[31] R. Liguori Neto, J.C. Acquadro, P.R.S. Gomes, A. Szanto de Toledo, E. Crema, C. Teneiro, N. Carlin Filho, and M.M. Coimbra, Nucl. Phys. **A512**, 333 (1990).
[32] S.B. Moraes *et al.*, Phys. Rev. C **61**, 064608 (2000).
[33] W. Meczynski *et al.*, Eur. Phys. J. A **3**, 311 (1998).
[34] C.W. Beausang *et al.*, Nucl. Instrum. Methods Phys. Res. A **313**, 37 (1992).
[35] F. Pühlhofer, Nucl. Phys. **A280**, 267 (1977).
[36] S.J. Sanders, A. Szanto de Toledo, and C. Beck, Phys. Rep. **311**, 487 (1999).
[37] C.Y. Wong, Phys. Rev. Lett. **31**, 766 (1973).
[38] K. Hagino, N. Rowley, and A.T. Kruppa, Comput. Phys. Commun. **123**, 143 (1999).
[39] N. Keeley, K.W. Kemper, and K. Rusek, Phys. Rev. C **65**, 014601 (2002); **66**, 044605 (2002).