IOP Publishing — Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **36** (2009) 015109 (9pp) doi:10.1088/0954-3899/36/1/015109

Disentangling static and dynamic effects of low breakup threshold in fusion reactions

L F Canto[1], P R S Gomes[2], J Lubian[2], L C Chamon[3] and E Crema[3]

[1] Instituto de Física, Universidade Federal do Rio de Janeiro, C.P. 68528, 21941-972 Rio de Janeiro, Brazil
[2] Instituto de Física, Universidade Federal Fluminense, Av. Litorânea, 24210-340 Niteroi, Brazil
[3] Instituto de Física, Universidade de São Paulo, C.P. 66318, 05389-970 São Paulo, Brazil

Received 15 August 2008
Published 7 November 2008
Online at stacks.iop.org/JPhysG/36/015109

Abstract

A new technique to analyze fusion data is developed. From experimental cross sections and results of coupled-channel calculations a dimensionless function is constructed. In collisions of strongly bound nuclei this quantity is very close to a universal function of a variable related to the collision energy, whereas for weakly bound projectiles the effects of breakup coupling are measured by the deviations with respect to this universal function. This technique is applied to collisions of stable and unstable weakly bound isotopes.

The interest in nuclear reactions with weakly bound nuclei has increased considerably during the last few decades [1]. Investigations of such reactions have important implications in astrophysics and some of these reactions may be important doorways to the production of super heavy elements. In a collision involving weakly bound projectiles, fusion is influenced by two factors. The first one, of a static nature, is that the fusion barrier has different characteristics, as compared to the barrier for a tightly bound isotope with the same target. Owing to the longer tail of the density, the barriers are lower. There is a general understanding that this feature leads to larger fusion cross sections at sub-barrier energies. The second factor is the dynamic effect of the coupling of the elastic channel with breakup, inelastic and transfer channels. It is well established that inelastic excitations of bound states and direct transfer channels enhance the fusion cross sections at sub-barrier energies. However, the breakup process has different characteristics, since it feeds continuum states, and the effect of couplings with channels in the continuum is controversial. As a consequence of the weak binding, breakup is quite large and its coupling with the elastic channel is very strong. In this way, it may play a relevant role in the fusion cross section, together with the usual couplings with inelastic and transfer channels.

In collisions of weakly bound projectiles, there are different mechanisms contributing to fusion. First there is a direct complete fusion (DCF), in which the whole projectile fuses with the target, without going through breakup. The second is the incomplete fusion (ICF). In this case, the projectile breaks up into two or more fragments, of which at least one, but not all, is absorbed by the target. From the experimental point of view, it may be hard to distinguish ICF from the direct (one-step) transfer of the same fragment to the target. The third process is the sequential complete fusion (SCF), in which all the breakup fragments are absorbed by the target sequentially. This process cannot be distinguished from DCF. Only complete fusion (CF), which is the sum of DCF and SQF, can be measured. Moreover, most experiments are more inclusive, giving only the total fusion (TF), which is the sum of all fusion processes. Some experiments with stable weakly bound projectiles on heavy targets find that CF at energies slightly above the barrier is hindered as compared with the results for a more tightly bound isotope. The reduction is found to range from 10 to 30% [1–6]. The CF suppression is attributed, in those works, to the ICF, which corresponds to the Ò missingÓ CF cross section. In fact, the calculations are in good agreement with the experimental TF cross sections [4, 5]. However, CF for stable weakly bound nuclei on lighter targets has shown no significant hindrance [7]. On the other hand, other experiments with unstable beams on heavy targets have led to different conclusions [8–13], showing that transfer may be considered as the process with prominent role for energies below the barrier. Actually, most of the large sub-barrier fusion enhancement reported in [14] for the ^{6}He + ^{238}U system was found to be, in fact, one- and two-neutron transfer cross section [8].

From the theoretical point of view, the situation is not very clear. The first calculations, based on very schematic pictures, have led to conflicting conclusions [15–17]. Presently, more reliable calculations based on the continuum discretized coupled channel (CDCC) method [18–24] have been performed and they qualitatively indicate that CF is enhanced at low energies and hindered at high energies.

In order to determine whether CF of weakly bound projectiles is enhanced or hindered, there is a preliminary question: enhancement or hindrance with respect to what? It is necessary to choose a standard fusion cross section to which the data should be compared. There are two different approaches in the literature, which are discussed below.

The first approach is to compare fusion data for the weakly bound projectile with data for a tightly bound isotope, both incident on the same target. If one wants to compare data for different systems, it is necessary to suppress trivial differences, arising from sizes and charges of the collision partners. This can be done in different ways. The most frequent one is to normalize the collision energy with respect to the barrier height and to divide the cross section by its geometrical value. That is, to plot $\sigma_F/\pi R_B^2$ against $E_{\text{c.m.}}/V_B$, where R_B and V_B are respectively the s-wave barrier radius and height [25, 26]. However, special care must be taken when weakly bound projectile nuclei are involved. If the barrier parameters are influenced by the special features of the projectile's density, the normalization procedure will wipe out the static effects of weak binding on the fusion cross section. If one wants to preserve this effect, the barrier parameters should depend exclusively on the masses and charges of the collision partners, Z_P, A_P, Z_T, A_T. This procedure has been adopted in [27], where the authors plot $\sigma_F/\left(A_P^{1/3} + A_T^{1/3}\right)^2$ versus $E_{\text{c.m.}}\left(A_P^{1/3} + A_T^{1/3}\right)/Z_P Z_T$. However, this procedure has also limitations since it takes into account the lowering of the barrier for the weakly bound projectile but ignores the change in the barrier curvature, $\hbar\omega$, defined as

$$\hbar\omega = \sqrt{\frac{\hbar^2|V''(R_B)|}{\mu}}. \tag{1}$$

Above, μ is the projectile–target reduced mass and V is the real part of the total optical potential. For instance: the barrier curvature parameter for the ^{6}He + ^{238}U is $\hbar\omega = 4.0$ MeV, while it is 5.7 MeV for ^{4}He + ^{238}U. The effect of curvature has been previously reported in [28, 29].

The second approach is to compare fusion data with predictions of quantum-mechanical calculations which do not take into account couplings with the breakup channel. The simplest procedure is to perform single-channel optical model calculations. One should have in mind that this procedure may lead to different conclusions for different choices of the optical potential. If one adopts optical potentials with constant diffusivity and radii depending smoothly on the mass numbers (e.g. through $A_P^{1/3} + A_T^{1/3}$), the calculated fusion cross sections for stable and unstable projectiles will show minor differences, arising from trivial geometric factors. In this way, comparisons of theoretical fusion cross sections for halo nuclei with the corresponding data will show global effects of statical and dynamical factors. The situation is different for optical potentials calculated by folding models, based on realistic nuclear densities. In this case, the fusion barrier for halo nuclei is lower and the calculated cross section at sub-barrier energies is larger than that for the stable isotopes. In this way, differences between the calculated cross sections and the data can only be attributed to dynamical channel-coupling effects. A better procedure for assessing the effects of coupling with the breakup channel is to compare the data with coupled-channel (CC) calculations using folding potentials, that include the couplings with all relevant bound channels. In this case, the difference between theory and experiment arises exclusively from breakup coupling.

The first step to follow this procedure is to select an appropriate folding model for the CC calculations. Recently it has been shown [30] that the double folding parameter-free São Paulo potential (SPP) [31] can be used as a reliable bare interaction for studying the fusion of weakly bound systems, since its predictions were in good agreement with experimental values obtained from barrier distributions. More recently, this potential was used to calculate fusion cross sections for ^{4}He and ^{6}He beams on ^{64}Zn, ^{209}Bi and ^{238}U targets [32]. For beams of the strongly bound ^{4}He projectiles, the predictions were in very good agreement with the data [8–10]. The predictions for the ^{6}He halo nucleus overestimated the data at above-barrier energies for the three targets, indicating a net effect of fusion suppression. At sub-barrier energies, this study found no significant enhancement or suppression of the fusion cross section.

In order to perform a systematic study of fusion cross sections in collisions of weakly bound nuclei, it is necessary to select a standard behavior to which the data should be compared. In this paper we propose an original way to compare data for systems of both stable and unstable nuclei. This methodology allows one to distinguish static and dynamic effects on the fusion cross section and also disentangle dynamic effects arising from couplings to inelastic and breakup channels. We believe that in this way we can bring new insights in this fascinating subject and contribute to the understanding of the role of the breakup process in fusion reactions induced by weakly bound nuclei. The first step is to use the function F of a dimensionless variable, x, defined as [25, 28]

$$F(x) = \frac{2E}{\hbar\omega\, R_B^2}\sigma_F, \qquad x = \frac{E - V_B}{\hbar\omega}, \tag{2}$$

The fusion function $F(x)$ is obtained from experimental or calculated values of the fusion cross section and from barrier parameters, extracted from the optical potential. For a consistent discussion of the fusion function, the optical potential should be based on a systematic treatment which takes into account the detailed shape of the projectile and target densities. For this task, the folding model is the natural candidate. In the present work, we adopt the SPP of [31], although any other reliable folding potential with realistic interactions and nuclear densities could be used. In table 1 we list the values of the barrier parameters for the systems studied in the present work.

Table 1. Barrier parameters for the systems studied in the present work.

System	$Z_P Z_T$	R_B (fm)	V_B (MeV)	$\hbar\omega$ (MeV)
^{4}He + ^{209}Bi	166	10.6	21.2	5.6
^{4}He + ^{238}U	184	10.9	22.9	5.7
^{6}He + ^{209}Bi	166	11.6	19.3	3.9
^{6}He + ^{238}U	184	11.9	20.9	4.0
^{6}Li + ^{16}O	24	7.9	4.0	2.5
^{6}Li + ^{59}Co	81	9.0	12.8	3.7
^{6}Li + ^{209}Bi	249	11.3	29.8	4.8
^{7}Li + ^{16}O	24	8.1	3.9	2.3
^{7}Li + ^{209}Bi	249	11.5	29.4	4.4
^{11}Li + ^{16}O	24	8.6	3.7	1.9
^{9}Be + ^{27}Al	52	8.5	8.1	2.8
^{9}Be + ^{208}Pb	328	11.5	38.5	4.4
^{16}O + ^{144}Sm	496	10.9	61.4	4.4
^{16}O + ^{154}Sm	496	11.0	60.4	4.3

Note that the transformations of equation (2) take into account the radius and height of the fusion barrier, as in other reduction procedures. However, these transformations consider also the barrier curvature, which has been overlooked so far in the literature. This parameter is directly related to tunelling probabilities and therefore plays a very important role at sub-barrier energies.

The above fusion function is inspired on Wong's formula for the fusion cross section [25],

$$\sigma_F^W = R_B^2 \frac{\hbar\omega}{2E} \ln\left[1 + \exp\left(\frac{2\pi(E - V_B)}{\hbar\omega}\right)\right]. \tag{3}$$

In the case of systems for which the fusion cross section is accurately described by the Wong's formula, $F(x)$ reduces to

$$F_0(x) = \ln[1 + \exp(2\pi x)]. \tag{4}$$

We call $F_0(x)$ the universal fusion function (UFF), since it does not depend on the system. In this way, data for different systems can be compared directly. Any deviation from the UFF should be attributed to channel-coupling effects and the intensity of the coupling could be estimated by the strength of the deviation.

However, Wong's formula is not accurate for light systems at sub-barrier energies. This is illustrated in figure 1, in which the UFF is compared with fusion functions obtained from single-channel optical model calculations, $F_{\text{opt}}(x)$. The comparisons were made for several systems in different mass ranges at energies around the Coulomb barrier. At energies above the barrier, the fusion functions are in very good agreement with the UFF for all systems. For the heaviest systems, with $Z_P Z_T > 500$, $F_{\text{opt}}(x)$ is very close to the UFF, even at sub-barrier energies. For lighter systems, however, the agreement is worse in this energy region, since the UFF overestimates $F_{\text{opt}}(x)$. The situation gets progressively worse as $Z_P Z_T$ decreases. This arises from the fact that the parabolic approximation for the fusion barrier of light systems is poor [1]. This is certainly true as showed first by Kovar *et al* [33] in their barrier systematics, recently expanded in [34] and revised in [35]. Figure 1 also illustrates an important feature of the fusion functions. Panel (a) shows fusion functions for the halo nucleus ^{11}Li and for the stable isotopes ^{6,7}Li. The differences in the densities of these nuclei lead to folding potentials with rather different barrier heights and

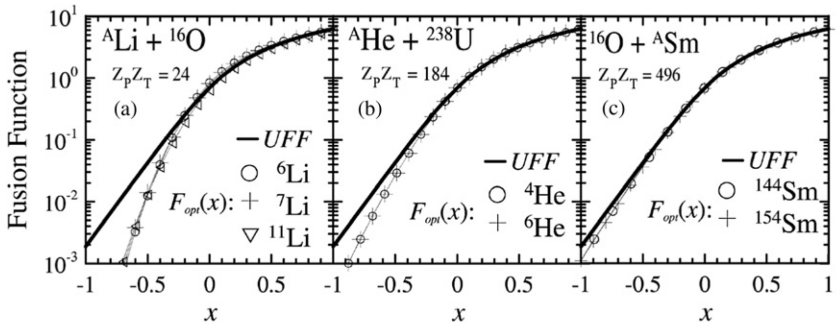

Figure 1. Comparison of the UFF (solid line) with fusion functions obtained from quantum-mechanical single-channel calculations for several systems (symbols and thin guiding lines).

curvatures (see table 1). The differences in the fusion barrier have a strong influence on the fusion cross sections. However, this static effect is eliminated in the fusion functions. Indeed, the results for the stable isotopes are almost identical to those for ^{11}Li. Similar situations are found in the other panels which show fusion functions for beams of different isotopes on the same target. Deviations of experimental fusion functions with respect to the UFF, $F_0(x)$, should then arise exclusively from dynamical channel-coupling effects, at least in situations where Wong's approximation is reliable (collisions of systems with $Z_P Z_T > 500$ at near-barrier energies or collisions of lighter systems at above the barrier). Therefore, through comparisons of this kind, one can assess the global effect of channel coupling in the fusion process. The basic idea is to evaluate an experimental fusion function, $F_{\mathrm{exp}}(x)$, obtained from the experimental fusion cross section through equation (2), and compare it to the UFF.

The above discussed procedure has two limitations. The first one is that it cannot be directly applied when Wong's formula is not a good approximation for the single-channel cross section. This is an important limitation in the case of collisions of ^{6}He at sub-barrier energies, even with heavy targets. The second limitation is that the deviations of $F_{\mathrm{exp}}(x)$ with respect to the UFF give only the global effect of couplings with bound and unbound channels. Since in most cases, the couplings with inelastic channels are well accounted for in CC calculations, the interesting effect to be investigated is the coupling to the breakup channel. However, these shortcomings can be eliminated through the introduction of the renormalized fusion function,

$$\bar{F}_{\mathrm{exp}}(x) = F_{\mathrm{exp}}(x)\frac{\sigma_F^W}{\sigma_{\mathrm{CC}}}, \tag{5}$$

or

$$\bar{F}_{\mathrm{exp}}(x) = F_{\mathrm{exp}}(x)\frac{F_0(x)}{F_{\mathrm{CC}}(x)}. \tag{6}$$

In the above equations, σ_F^W is the fusion cross section in the single-channel case approximated by the Wong model (equation (3)), σ_{CC} is the fusion cross section predicted by CC calculations including all relevant couplings to bound channels and $F_{\mathrm{CC}}(x)$ is the fusion function associated with σ_{CC}, through equation (2). Note that $\bar{F}_{\mathrm{exp}}(x)$ has been defined so that in an ideal collision of strongly bound nuclei in which all channel-coupling effects are accurately described by the CC calculation it will coincide with the UFF. Therefore, deviations of $\bar{F}_{\mathrm{exp}}(x)$ from the UFF, $F_0(x)$, may only arise from couplings with the breakup channel, assuming that all other relevant couplings have been accounted for.

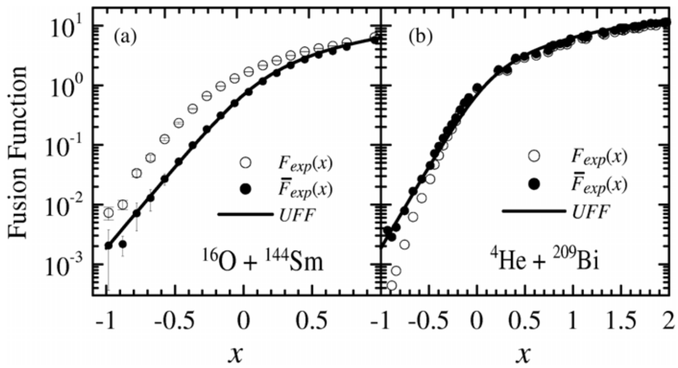

Figure 2. Fusion functions for (a) $^{16}O + ^{144}Sm$ [36] and (b) $^{4}He + ^{209}Bi$ [37–39]. The open square and the solid circles are respectively the experimental fusion functions with and without renormalization. The solid line corresponds to the UFF.

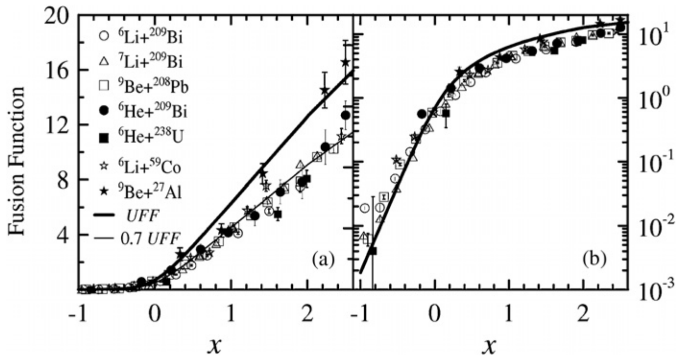

Figure 3. Fusion functions $\bar{F}_{\rm exp}(x)$ for light projectiles on heavy targets. The experimental data are from [3, 4] ($^{6,7}Li + ^{209}Bi$), [2, 4] ($^{9}Be + ^{208}Pb$), [9] ($^{6}He + ^{209}Bi$), [8] ($^{6}He + ^{238}U$), [29] ($^{6}Li + ^{59}Co$) and [42] ($^{9}Be + ^{27}Al$).

This procedure is illustrated in figure 2 with two examples of tightly bound systems: $^{16}O + ^{144}Sm$ and $^{4}He + ^{209}Bi$. In both cases there are significant differences between $F_{\rm exp}(x)$ and the UFF. In the former case they are due to strong channel-coupling effects while in the latter they result from the poor approximation of Wong's formula. However, when the fusion function is renormalized according to the prescription of equation (6), these effects are eliminated and $\bar{F}_{\rm exp}(x)$ is very close to the UFF.

By using this procedure, one is able to isolate the effect of breakup on the fusion cross section of weakly bound systems. However, the inclusion of transfer channels in calculations of σ_{CC} may be a difficult task, specially in collisions with large positive transfer Q-values. When transfer channels are important and they are not included in the CC calculation, the differences between $\bar{F}_{\rm exp}(x)$ and the UFF should be assigned to the combined effects of couplings to breakup and transfer channels [8–12, 40, 41].

In figure 3, we apply the above procedure to investigate CF data in collisions of several weakly bound projectiles with heavy targets, where breakup effects are expected to be large. For comparison, we also include in the figure results for TF data in the cases of one medium mass, $^{6}Li + ^{59}Co$ [29], and one light target, $^{9}Be + ^{27}Al$ [42] systems. For the renormalization procedure, we used the code FRESCO [43] and considered in the CC calculations the channels associated with the target excitations. In each case, we use the same channels and coupling parameters as in the original papers [4, 8, 9, 20, 22, 42]. Couplings with projectile states above the breakup thresholds were not included in the CC calculations. In this way, the only projectile excitation taken into account was the $1/2^-$ state in ^{7} Li. Apart from this difference, the details of the calculations for the ^{208}Pb, ^{209}Bi targets are the same as in [4]. The results are shown both in linear and logarithmic scales. Inspecting the results at above-barrier energies, we conclude that all data show a pronounced suppression, which is about the same for the stable and unstable projectiles. The only exception is ^{9}Be + ^{27}Al (black stars), for which $\bar{F}_{\rm exp}$ is very close to the UFF. The same trend is found in TF cross sections for the similar light systems, such as ^{6,7}Li + ^{27}Al [44] and ^{7}Li + ^{27}Al [45–47] (not shown). All the other data are well fitted by the UFF multiplied by an attenuation factor of the order of 0.7 (thin solid line). This result is not strongly dependent on the details of the CC calculations, since they are restricted to energies above the barrier. As far as the stable projectiles are concerned, this conclusion is consistent with those of [2–4] in their comparison between the CF data with CC calculations. Actually, one can observe in figure 3 that the attenuation factor is slightly larger for ^{6}Li + ^{209}Bi than for ^{7}Li + ^{209}Bi, as observed in [3, 4], where it is pointed out that the smaller the breakup threshold energy, the larger is the CF suppression. The CF suppression was attributed to the loss of flux going into ICF, following breakup. In this way, the breakup process hinders the CF cross section. The reduction corresponds to the amount of flux emerging as ICF. In those works, direct transfer processes leading to the same exit channel were assumed to be negligible. This assumption was confirmed later by particle-gamma coincidence measurements for the similar ^{7}Li + ^{165}Ho system [48].

The situation below the Coulomb barrier ($x < 0$) is different. The data show some enhancement with respect to the UFF, arising from couplings neglected in the CC calculation, namely, the combined couplings with breakup and transfer channels. We should point out that as far as sub-barrier energies are concerned, our conclusions are not the same as those of [2–4], where no sub-barrier enhancement was found. This fact stems from the differences between the CC calculations of these authors and those of the present work. In the former case, the CC calculations include couplings to resonances. In this way, only the influence of prompt breakup is left out. Since prompt breakup leads to suppression of CF, these authors find that the experimental cross section is hindered with respect to the results of their CC calculations. Our CC calculations do not include resonances. In this way, the differences between experiment and theory arises from both prompt and resonant breakup. Since the enhancement produced by the coupling to resonances is stronger than the reduction resulting from direct breakup, the net result is some enhancement in this energy region.

We now consider the data for the unstable weakly bound projectile, ^{6}He, in collisions with ^{209}Bi and ^{238}U. Qualitatively, the results are very similar to those for stable weakly bound nuclei: a suppression of about 30% above the barrier and some enhancement below. As in the previous case, this enhancement can arise from the coupling of either the breakup or/and the transfer channels, although the large error bars for the data points at sub-barrier energies do not support strong conclusions. However, it should be pointed out that the results for heavy targets in figure 3 are based on fusion data of different kinds: CF for the stable projectiles and TF for ^{6}He. In the case of ^{6}He collisions with heavy targets, this difference should not be relevant, since the ^{4}He fragment produced projectile's breakup carriers roughly 2/3 of the projectile's energy while its barrier is about 2 MeV higher than that for the incident projectile. In this way, the tunneling probability for ^{4}He is expected to be much lower and incomplete fusion for this system should be negligible. Therefore, the CF suppression above the barrier for neutron halo systems might be attributed to transfer and/or NCBU channels, rather than to ICF. At sub-barrier energies resonant breakup is, as for stable weakly bound systems, responsible for some fusion enhancement. At this energy regime, transfer of one and two neutrons have the largest cross sections [8–12, 40, 41].

In summary, we propose a new benchmark to analyze fusion data, based on the evaluation of a dimensionless fusion function extracted from the data. We show that, when the couplings with all bound channels are accounted for, the experimental results converge to a universal function. This technique has been used to ellucidate the effects of the breakup channel on complete fusion data for collisions of weakly bound projectiles on heavy targets. We have shown that the fusion functions for both stable and unstable weakly bound projectiles on heavy targets are rather similar, presenting a suppression of about 30% above the barrier and a slight enhancement below it.

Acknowledgment

This work was supported in part by the FAPERJ, CNPq, FAPESP and the PRONEX.

References

[1] Canto L F, Gomes P R S, Donangelo R and Hussein M S 2006 *Phys. Rep.* **424** 1
[2] Dasgupta M *et al* 1999 *Phys. Rev. Lett.* **82** 1395
[3] Dasgupta M *et al* 2002 *Phys. Rev.* C **66** 041602
[4] Dasgupta M *et al* 2004 *Phys. Rev.* C **70** 024606
[5] Gomes P R S *et al* 2006 *Phys. Lett.* B **634** 356
[6] Signorini C *et al* 1999 *Eur. Phys. J.* A **5** 7
[7] Moraes S B, Gomes P R S, Lubian J, Alves J J S, Anjos R M, Sant'Anna M M, Padrón I and Muri C 2000 *Phys. Rev.* C **61** 064608
[8] Raabe R *et al* 2004 *Nature* **431** 823
[9] Kolata J J *et al* 1998 *Phys. Rev. Lett.* **81** 4580
[10] Di Pietro A *et al* 2004 *Phys. Rev.* C **69** 044613
[11] Navin A *et al* 2004 *Phys. Rev.* C **70** 044601
[12] Penionzhkevich Yu E, Zagrebaev V I, Lukyanov S M and Kalpakchieva R 2006 *Phys. Rev. Lett.* **96** 162701
[13] Signorini C *et al* 2004 *Nucl. Phys.* A **735** 329
[14] Trotta M *et al* 2000 *Phys. Rev. Lett.* **84** 2342
[15] Hussein M S, Pato M P, Canto L F and Donangelo R 1992 *Phys. Rev.* C **46** 377
[16] Takigawa N, Kuratani M and Sagawa H 1993 *Phys. Rev.* C **47** R2470
[17] Dasso C H and Vitturi A 1994 *Phys. Rev.* C **50** R12
[18] Hagino K, Vitturi A, Dasso C H and Lenzi S M 2000 *Phys. Rev.* C **61** 037602
[19] Diaz-Torres A and Thompson I J 2002 *Phys. Rev.* C **65** 024606
[20] Diaz-Torres A, Thompson I J and Beck C 2003 *Phys. Rev.* C **68** 044607
[21] Keeley N, Kemper K W and Rusek K 2001 *Phys. Rev.* C **65** 014601
[22] Rusek K, Keeley N, Kemper K W and Raabe R 2003 *Phys. Rev.* C **67** 041604
[23] Beck C 2007 *Nucl. Phys.* A **787** 251c
[24] Beck C, Diaz-Torres A and Keeley N 2007 *Phys. Rev.* C **75** 054605
[25] Wong C Y 1973 *Phys. Rev. Lett.* **31** 766
[26] Glas D and Mosel U 1974 *Phys. Rev.* C **10** 2620 See also
Glas D and Mosel U *Nucl. Phys.* A **237** 1975 429
[27] Gomes P R S, Lubian J, Padrón I and Anjos R M 2005 *Phys. Rev.* C **71** 017601
[28] Gasques L R, Chamon L C, Pereira D, Alvarez M A G, Rossi E S, Silva C P and Carlson B V 2004 *Phys. Rev.* C **69** 034603
[29] Beck C *et al* 2003 *Phys. Rev.* C **67** 054602
[30] Crema E, Chamon L C and Gomes P R S 2005 *Phys. Rev.* C **72** 034610
[31] Chamon L C, Carlson B V, Gasques L R, Pereira D, De Conti C, Alvarez M A G, Hussein M S, Cândido Ribeiro M A, Rossi Jr E S and Silva C P 2002 *Phys. Rev.* C **66** 014610
[32] Crema E, Gomes P R S and Chamon L C 2007 *Phys. Rev.* C **75** 037601
[33] Kovar D G *et al* 1979 *Phys. Rev.* C **20** 1305

[34] Anjos R M *et al* 2002 *Phys. Lett.* B **534** 45
[35] de Toledo A Szanto, Added N, Cardenas W H Z, Carlin N, de Moura M M, Munhoz M G, Suaide A A P, Szanto E M and Takahashi J 2000 *Nucl. Phys.* A **679** 175
[36] Leigh J R *et al* 1995 *Phys. Rev.* C **52** 3151
[37] Kelly E L and Segre E 1949 *Phys. Rev.* **75** 999
[38] Ramler W J, Wing J, Henderson D J and Huizenga J R 1959 *Phys. Rev.* **114** 154
[39] Barnett A R and Lilley J S 1974 *Phys. Rev.* C **9** 2010
[40] Bychowski J P *et al* 2004 *Phys. Lett.* B **596** 26
[41] DeYoung P A *et al* 2005 *Phys. Rev.* C **71** 051601
[42] Martí G V *et al* 2005 *Phys. Rev.* C **71** 027602
[43] Thompson I J 1988 *Comput. Phys. Rep.* **7** 167
[44] Padrón I *et al* 2002 *Phys. Rev.* C **66** 044608
[45] Sinha M *et al* 2007 *Phys. Rev.* C **76** 027603
[46] Sinha M, Majumdar H, Basu P, Roy S, Bhattacharya R, Biswas M, Pradhan M K and Kailas S 2008 *Phys. Rev.* C **78** 027601
[47] Kalita K *et al* 2006 *Phys. Rev.* C **73** 024609
[48] Tripathi V, Navin A, Nanal V, Pillay R G, Mahata K, Ramachandran K, Shrivastava A, Chatterjee A and Kailas S 2005 *Phys. Rev.* C **72** 017601