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Systematics of the breakup probability function for ^{6}Li and ^{7}Li projectiles

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Abstract

Experimental non-capture breakup cross sections can be used to determine the probability of projectile and ejectile fragmentation in nuclear reactions involving weakly bound nuclei. Recently, the probability of both type of dissociations has been analyzed in nuclear reactions involving ^{9}Be projectiles onto various heavy targets at sub-barrier energies. In the present work we extend this kind of systematic analysis to the case of ^{6}Li and ^{7}Li projectiles with the purpose of investigating general features of projectile-like breakup probabilities for reactions induced by stable weakly bound nuclei. For that purpose we have obtained the probabilities of projectile and ejectile breakup for a large number of systems, starting from a compilation of the corresponding reported non-capture breakup cross sections. We parametrize the results in accordance with the previous studies for the case of beryllium projectiles, and we discuss their systematic behavior as a function of the projectile, the target mass and the reaction Q-value.

Keywords: Weakly bound projectiles; Non-capture breakup cross sections; Breakup probability function

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1. Introduction

The first experimental studies on weakly bound stable nuclei were undertaken more than fifty years ago [1–4], but it was the relatively recent advent of radioactive ion beam facilities which caused a renewed interest in the physics associated with these nuclei. When a light weakly bound nucleus collides with a usually heavier target, one of the processes that can occur is the breakup of the former into two or more fragments. Furthermore, it has been observed in many cases that the weakly bound fragment that actually breaks up is the ejectile that follows an intermediate nucleon-transfer reaction, rather than the projectile itself. Indeed, the authors of the Refs. [5,6] have found that the n-stripping channel — which is the trigger for the subsequent breakup of the remaining projectile-like fragment — is the principal source amongst the several breakup modes present in the studied systems. The situation is further complicated because the breakup itself — either projectile or ejectile fragmentation — might be just the initial stage of more complex processes that can be classified according to the subsequent fate of the corresponding breakup fragments [7]. If all the breakup products manage to fly away, the reaction is usually referred to as non-capture breakup (NCBU). Alternatively some of the fragments, or all of them, can be captured by the target, processes known as incomplete fusion (ICF) and breakup followed by complete fusion (CFBU), respectively. Therefore total cross sections (integral or differential) for the breakup of the projectile, $\sigma_{proj\text{-}BU}$, or of the ejectile, $\sigma_{ejec\text{-}BU}$, can be thought of as the sum of the individual contributions from these three processes: $\sigma_{NCBU} + \sigma_{ICF} + \sigma_{CFBU}$. It is worthwhile to point out that in the case of NCBU the fragment that breaks up can be unambiguously identified — either as the projectile or as the ejectile following a more complex process — by means of the simultaneous detection of both breakup products in a kinematical coincidence experiment.

A magnitude of interest, connected with both projectile and ejectile breakup, is the probability of occurrence of these reactions. The presentation of data in terms of probabilities has been relatively common for other reactions, mainly for distant transfer processes. Experimentally, the probability of any peripheral process at a given distance of closest approach is usually obtained as the ratio between the differential cross section of the relevant channel and the Rutherford cross section at the scattering angle indicated by the deflection function. In terms of this kind of description, the probabilities depend on the energy and impact parameter of the classical trajectory in principle solely through the correlation imposed by the deflection function. In the particular case of transfer processes, this way of presenting the data is especially useful because the characteristic exponential decay that can be observed for the most distant reactions (e.g. Refs. [9–11]) can be interpreted in the framework of semiclassical models based on the quantum penetration of the transferred particle through an effective potential barrier created by the donor and acceptor cores (e.g. Ref. [12]). The exponential-decay constants can be obtained accordingly from relatively simple tunneling considerations [13]. In the case of breakup, the earliest presentation in terms of probabilities and the discussion of the usefulness of such description were done by Hinde et al. [8] in the bombardment of ^{208}Pb with ^{9}Be projectiles. For this system it has been shown that the dominant breakup mode involves ^{8}Be ejectiles formed via one of two processes: i) one-neutron transfer from the projectile to the target, or ii) projectile dissociation. A similar analysis of different breakup modes for reactions of ^{9}Be with several heavy targets (^{144}Sm, ^{168}Er, ^{186}W, ^{196}Pt, ^{208}Pb, and ^{209}Bi) at sub-barrier energies was later performed using the results of kinematical coincidence measurements [6]. The cross sections used in the evaluation of the probabilities for either projectile or ejectile breakup were obtained from measurements of just the corresponding non-capture component, σ_{NCBU}. This approximation obeys to the fact that the measurements have been carried out at low bombarding energies and/or at forward scattering angles. These ranges correspond to sufficiently distant collisions for which both the ICF and CFBU components are largely suppressed due to the usually insurmountable Coulomb barriers involved.

All the experimental breakup probabilities discussed above exhibit an exponential decrease with increasing internuclear distances, which qualitatively resembles the behavior of transfer probabilities. At least to some extent this might reflect the already mentioned fact that, precisely in these systems, breakup itself is predominantly triggered by transfer. From a fully quantal perspective the exponential behavior could also be reproduced by CDCC calculations [14]. Although these calculations were restricted to the case of projectile breakup (i.e., ^{8}Be was considered to be the projectile), the results prompted the authors to postulate the following dependence of the breakup probability P_{BU} as a function of the internuclear distance for all distant collisions:

$$P_{BU}(D) = e^{(-\alpha D+\beta)} \tag{1}$$

where α and β are the breakup function parameters that can be derived from experimental data and can be used as the basic ingredients for simplified classical dynamic model calculations [14–16].

In view of the above discussion and in order to attain a comprehensive picture of projectile and ejectile breakup in reactions with stable weakly bound projectiles, in this work we have undertaken a systematic study of breakup probabilities for reactions induced by ^{6}Li and ^{7}Li. The study is based on the reported results of a large number of experiments in which absolute cross sections for different non-capture breakup modes could be measured. For all these cases we place particular emphasis on whether the asymptotic exponential behavior is observed not only for breakup triggered by transfer (as it is mostly the case for ^{9}Be-induced reactions) but for projectile breakup as well. In this framework we analyze the validity of the empirical parameterization of Eq. (1) and we discuss the dependence of the probabilities and the obtained parameters on basic properties of the reaction systems, including comparisons with those previously reported from experiments with ^{9}Be.

2. Systematic analysis of non-capture breakup cross sections

Reactions that involve ^{6}Li and ^{7}Li projectiles impinging onto targets with a wide range of masses have been experimentally investigated by several authors through the application of the kinematical coincidence technique [5,17–27]. These exclusive measurements have provided unambiguous evidence for a variety of reactions that range from direct projectile breakup to more complex processes that involve transference of nucleons followed by the breakup of the corresponding weakly bound transfer product. A summary of the main breakup channels is presented in Table 1. From the standpoint of the present work, which requires the availability of absolute cross sections to obtain breakup probabilities, we have been able to consider only the α–d partition in the case of ^{6}Li (i.e. projectile breakup) and the α–t and α–d channels in the case of ^{7}Li (i.e. projectile and ejectile fragmentations, respectively). This latter partition, which has been experimentally identified in Refs. [5,26–28] for ^{65}Cu, ^{144}Sm, ^{207,208}Pb and ^{209}Bi targets, follows the n-stripping reaction.

As an example of the data, Fig. 1 shows the probabilities of NCBU via the 2.18 MeV (3+) resonant state of ^{6}Li for the ^{6}Li + ^{59}Co system at $E_{\mathrm{lab}} = 25.5$ MeV, as a function of both the distance of closest approach assuming a Rutherford trajectory (lower horizontal axis) and the scattering angle (upper horizontal axis). The vertical arrows indicate the corresponding values for a grazing collision, D_{gr} and θ_{gr}. These grazing values qualitatively divide the measured range

Table 1
Main breakup modes present in reactions with ^{6}Li and ^{7}Li as incident particles.

BU particle	Primary mechanism	Partition
$^6\mathrm{Li} + {}^A\mathrm{X}$:		
projectile	scattering	$^6\mathrm{Li}^* \to \alpha + d$
ejectile	d-pickup	$^8\mathrm{Be}^{gs,*} \to \alpha + \alpha$
ejectile	n-stripping	$^5\mathrm{Li}^{gs,*} \to \alpha + p$
ejectile	p-stripping	$^5\mathrm{He}^{gs,*} \to \alpha + n$
$^7\mathrm{Li} + {}^A\mathrm{X}$:		
projectile	scattering	$^7\mathrm{Li}^* \to \alpha + t$
ejectile	p-pickup	$^8\mathrm{Be}^{gs,*} \to \alpha + \alpha$
ejectile	d-stripping	$^5\mathrm{He}^{gs,*} \to \alpha + n$
ejectile	n-stripping	$^6\mathrm{Li}^* \to \alpha + d$

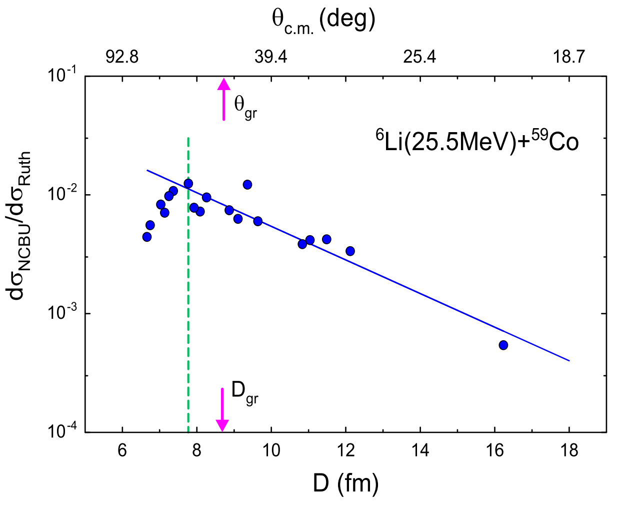

Fig. 1. Non-capture projectile breakup probabilities for the $^6\mathrm{Li} + {}^{59}\mathrm{Co}$ reaction at $E_{\mathrm{lab}} = 25.5$ MeV as a function of the distance of closest approach (lower axis) and of the center of mass scattering angle (upper axis). The solid line corresponds to an exponential least-squares fit to the data points for distant collisions. The vertical dashed line shows the lower threshold chosen for this fit and, for comparison, the arrows indicate the calculated grazing angle θ_{gr} and corresponding distance D_{gr} (see text for details). Data obtained from Ref. [18].

into two regions with different behaviors. On the left region the NCBU probabilities decrease markedly towards closer distances as a consequence of the increasing contribution of other processes. On the right region ($D \gtrsim D_{\mathrm{gr}}$) we can see that NCBU probabilities — which are expected to account for total breakup in this range of distances — can be approximately described by an exponential decay such as that represented by Eq. (1). This general behavior of the breakup probabilities, especially the exponential decrease at long distances, has been observed in the results obtained for all the experiments analyzed in the present work, regardless of whether breakup is triggered by a transfer reaction. In this way, for all these studied systems the parameters α and β of Eq. (1) can be extracted through least-squares fits to the exponential region of the data, whose lower limit (illustrated by the vertical dashed line) is found to be close to the grazing angle. We have applied this fitting procedure to all data found in the literature for ^{6}Li and ^{7}Li projectiles on several target nuclei (in some cases projectile breakup and in others ejectile fragmentation), and we have assumed a uniform uncertainty of 25% for all the data points (not shown in the figure).

The fitted values of the breakup-probability parameters α and β for all the evaluated systems and reported final partitions are displayed in Table 2, which also includes basic features of the reactions and of the experiments such as the bombarding energy in units of the Coulomb barrier, the covered angular range and the measured breakup mode (α–d for both projectiles and α–t for the ^{7}Li case). The fifth column of the table states the character of the breakup process, since, due to the different measurement techniques, the results for the various systems are either not always strictly equivalent or they are not presented by the authors in a directly comparable way. In fact, depending on each particular case the reported cross sections may correspond to total NCBU or to particular resonant (sequential) or non-resonant (direct) components. In the cases where the authors report separately more than one component of NCBU we have appropriately added up the individual cross sections before calculating the probabilities. In other cases the data correspond to a nucleon transfer followed by ejectile NCBU (e.g., $^{7}\mathrm{Li} + {}^{A}\mathrm{X} \rightarrow {}^{6}\mathrm{Li}^{*} + {}^{A+1}\mathrm{X} \rightarrow \alpha + d + {}^{A+1}\mathrm{X}$), being this the dominant breakup process.

The global behavior of the probabilities — obtained using the values of α and β reported in Table 2 — for all the compiled systems over the ranges of D covered by the measured angular range is summarized in Fig. 2. The systems have been grouped in two panels according to the type of particle that breaks up: projectile or ejectile, respectively. The reactions analyzed in the present compilation for the projectile breakup are represented in the top panel (Fig. 2(a)) by the solid blue curves ($^{6}\mathrm{Li}^{*} \rightarrow \alpha + d$) and dashed red curves ($^{7}\mathrm{Li}^{*} \rightarrow \alpha + t$). The data of the ^{6}Li projectile seem to be grouped into two target-mass ranges indicating greater breakup probabilities for the heavier targets over the whole range of distances of closest approach. For the case of ^{7}Li the probabilities are systematically lower than for ^{6}Li, but it is difficult to draw similar definite conclusions regarding the target-mass dependence because of the relatively few available systems for the former projectile. The bottom panel (Fig. 2(b)) shows the breakup probabilities of the ^{6}Li and ^{8}Be ejectiles emitted in n-stripping reactions with ^{7}Li [5,26] and ^{9}Be [6] projectiles, respectively. In spite of having only two targets (^{65}Cu and ^{144}Sm) for ^{7}Li it is evident that their probabilities of n-stripping reaction followed by ejectile breakup are systematically lower than those for ^{9}Be onto various heavy targets.

From these results one can find a qualitative connection between the maximum values of P_{BU} (occurring at the shortest distances) and the Q-values associated with the three-particle exit channels relevant to the systems under analysis (Table 2 and Ref. [6]). This correlation is illustrated in Fig. 3, that shows the probability — both projectile and ejectile breakup — evaluated at the internuclear distance corresponding to a grazing collision as a function of Q-value. The group of data points with the largest probabilities corresponds to ^{9}Be projectiles and can be related to the positive breakup threshold of the unbound ^{8}Be nucleus (0.09 MeV) which is created following the Q-value favored transfer of one neutron from the projectile to the target [6]. For the systems analyzed in the present work the positive Q-values for this dominant mode in ^{9}Be-induced reactions range between 2.36 MeV and 5.18 MeV. The next lower probabilities are observed for reactions with ^{6}Li projectiles that break up into $\alpha + d$ with a binding energy of 1.47 MeV ($Q = -1.47$ MeV). Similarly, the group of points that on average have the lowest breakup probabilities comprise the reactions induced by ^{7}Li projectiles and can be associated with the most negative Q-values: -2.47 MeV for the $\alpha + t$ projectile breakup channel. The two measurements corresponding to one-neutron transfer followed by breakup of ^{6}Li for ^{7}Li projectiles seem to qualitatively confirm the correlation, i.e., larger probabilities corresponding to slightly less negative Q-values (-1.66 MeV and -1.97 MeV for ^{65}Cu [5] and ^{144}Sm [26] targets, respectively).

Table 2
α and β parameters of the breakup probability function derived from non-capture breakup cross sections measured for several systems involving ^{6}Li and ^{7}Li projectiles. The corresponding parameters for the $^{6}\mathrm{Li} + {}^{144}\mathrm{Sm}$ system were taken from Ref. [19] where the authors performed an exponential fit to all NCBU cross sections without distinguishing between the four different bombarding energies studied in that work. In the case of the $^{7}\mathrm{Li} + {}^{120}\mathrm{Sn}$ system [25], different components of NCBU have been individually measured and reported by the authors. The corresponding total NCBU probabilities have been obtained as described in the text and the resulting values of α and β are (0.25 ± 0.06) fm^{-1} and -3.50 ± 0.72, respectively. We have included in the list one of the experiments for $^{7}\mathrm{Li} + {}^{12}\mathrm{C}$ [24], although in this case the data could not be used to extract probabilities since the measurements were only performed in a backward angular region with respect to the grazing angle, where total breakup is no longer dominated by the non-capture process.

System	E/V$_b$	Angle (deg)	Channel	Direct/sequential	α (fm^{-1})	β
$^{6}\mathrm{Li} + {}^{28}\mathrm{Si}$ [17]	1.47	29.0–75.9	α–d	total	0.36 ± 0.05	-1.84 ± 0.51
$^{6}\mathrm{Li} + {}^{59}\mathrm{Co}$ [18]	1.25	32.2–76.4	α–d	$^{6}\mathrm{Li}^{3+}$	0.41 ± 0.06	-1.18 ± 0.73
$^{6}\mathrm{Li} + {}^{59}\mathrm{Co}$ [18]	1.55	23.0–76.4	α–d	$^{6}\mathrm{Li}^{3+}$	0.33 ± 0.04	-1.87 ± 0.44
$^{6}\mathrm{Li} + {}^{59}\mathrm{Co}$ [18]	1.84	21.2–75.0	α–d	$^{6}\mathrm{Li}^{3+}$	0.33 ± 0.03	-1.96 ± 0.34
$^{6}\mathrm{Li} + {}^{59}\mathrm{Co}$ [18]	2.13	23.3–74.4	α–d	$^{6}\mathrm{Li}^{3+}$	0.25 ± 0.08	-2.63 ± 0.77
$^{6}\mathrm{Li} + {}^{65}\mathrm{Cu}$ [5]	1.72	28.1–83.0	α–d	$^{6}\mathrm{Li}^{3+}$	0.38 ± 0.05	-1.27 ± 0.51
$^{6}\mathrm{Li} + {}^{65}\mathrm{Cu}$ [5]	1.72	31.7–79.4	α–d	$^{6}\mathrm{Li}^{2+}$	0.60 ± 0.08	-0.34 ± 0.84
$^{6}\mathrm{Li} + {}^{144}\mathrm{Sm}$ [19]	0.92–1.15	47.7–130.4	α–d	$^{6}\mathrm{Li}^{3+}$ ($\approx$ total)	0.28 ± 0.05	-0.66 ± 0.66
$^{6}\mathrm{Li} + {}^{208}\mathrm{Pb}$ [20]	0.98	43.5–155.4	α–d	total	0.41 ± 0.03	1.45 ± 0.45
$^{6}\mathrm{Li} + {}^{208}\mathrm{Pb}$ [20]	1.04	43.7–155.4	α–d	total	0.39 ± 0.04	1.24 ± 0.56
$^{6}\mathrm{Li} + {}^{208}\mathrm{Pb}$ [20]	1.11	43.3–155.4	α–d	total	0.40 ± 0.04	1.31 ± 0.68
$^{6}\mathrm{Li} + {}^{208}\mathrm{Pb}$ [20]	1.23	43.5–155.4	α–d	total	0.45 ± 0.05	1.52 ± 0.68
$^{6}\mathrm{Li} + {}^{208}\mathrm{Pb}$ [21]	4.94	1.54–12.0	α–d	$^{6}\mathrm{Li}^{3+}$	0.13 ± 0.01	-4.61 ± 0.37
$^{6}\mathrm{Li} + {}^{209}\mathrm{Bi}$ [22]	1.13	54.8–111.7	α–d	$^{6}\mathrm{Li}^{3+}$ ($\approx$ total)	0.48 ± 0.09	1.62 ± 1.28
$^{6}\mathrm{Li} + {}^{209}\mathrm{Bi}$ [22]	1.25	54.7–142.2	α–d	$^{6}\mathrm{Li}^{3+}$ ($\approx$ total)	0.49 ± 0.09	1.91 ± 1.22
$^{7}\mathrm{Li} + {}^{12}\mathrm{C}$ [23]	10.3	3.7–17.0	α–t	direct	0.40 ± 0.06	-5.50 ± 0.38
$^{7}\mathrm{Li} + {}^{12}\mathrm{C}$ [24]	13.4	21.2–52.6	α–t	direct	–	–
$^{7}\mathrm{Li} + {}^{65}\mathrm{Cu}$ [5]	1.73	30.5–93.0	α–t	$^{7}\mathrm{Li}^{7/2-}$	0.57 ± 0.07	-1.19 ± 0.75
$^{7}\mathrm{Li} + {}^{120}\mathrm{Sn}$ [25]	3.24	12.1–42.3	α–t	$^{7}\mathrm{Li}^{7/2-}$	0.30 ± 0.05	-3.47 ± 0.60
$^{7}\mathrm{Li} + {}^{120}\mathrm{Sn}$ [25]	3.24	12.4–42.2	α–t	direct	0.05 ± 0.03	-6.79 ± 0.40
$^{7}\mathrm{Li} + {}^{197}\mathrm{Au}$ [23]	1.77	13.5–36.0	α–t	direct	0.38 ± 0.06	-0.54 ± 1.45
$^{7}\mathrm{Li} + {}^{208}\mathrm{Pb}$ [24]	2.24	16.0–40.5	α–t	$^{7}\mathrm{Li}^{7/2-}$	0.31 ± 0.03	-2.93 ± 0.52
$^{7}\mathrm{Li} + {}^{65}\mathrm{Cu}$ [5]	1.73	30.0–91.8	α–d	n-transfer $\rightarrow$ $^{6}\mathrm{Li}^{3+}$	0.28 ± 0.04	-3.33 ± 0.42
$^{7}\mathrm{Li} + {}^{144}\mathrm{Sm}$ [26]	1.66	52.1–127.5	α–d	n-transfer $\rightarrow$ $^{6}\mathrm{Li}^{3+}$	0.78 ± 0.09	3.80 ± 1.19

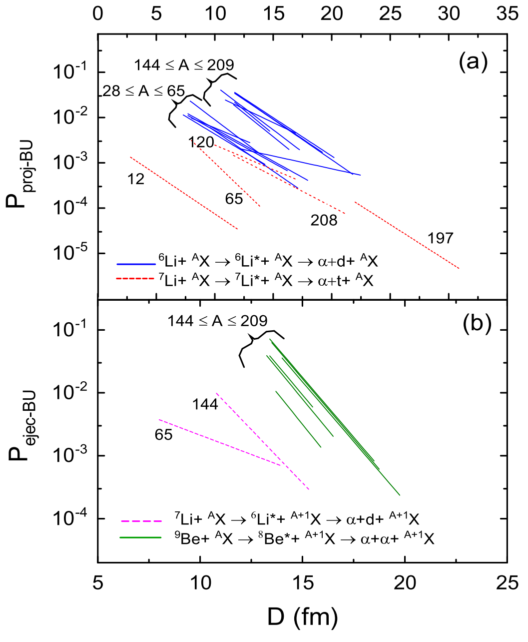

Fig. 2. Breakup probability as a function of the distance of closest approach D. Panel (a) displays logarithmic representations of the projectile breakup (^{6}Li* $\to \alpha + d$ and ^{7}Li* $\to \alpha + t$). Panel (b) shows the same information for the fragmentation of the ejectile (^{6}Li* $\to \alpha + d$ and ^{8}Be* $\to \alpha + \alpha$) resulting from a primary n-transfer reaction (according to the presentation of the results made by the authors of Ref. [6], the ^{9}Be data includes a very small component of projectile excitation (^{9}Be* $\to$ ^{8}Be $+ n$) and excludes the population of the ^{8}Be ground state). The curves have been obtained using Eq. (1) with the parameters α and β extracted in this work (and shown in Table 2) and those reported in Ref. [6]. In all cases, the number on each curve corresponds to the target mass involved in the reaction.

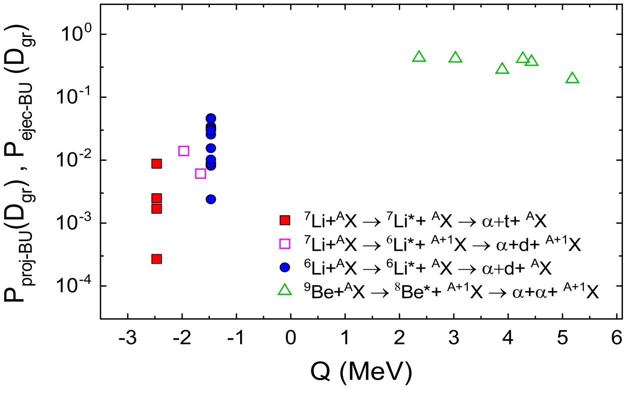

Fig. 3. Breakup probabilities (of projectile and ejectile particles) evaluated at grazing distance as a function of the reaction Q-value for the systems of Table 2 and Ref. [6]. Different shapes of the data points indicate different projectiles. Open symbols for a given shape (projectile) indicate that the breakup channel is preceded by one-neutron transfer to the target nucleus.

Another issue that could deserve a more detailed study relates to the strict validity of the description provided by Eq. (1). The postulated dependence of the probability solely on the dis-

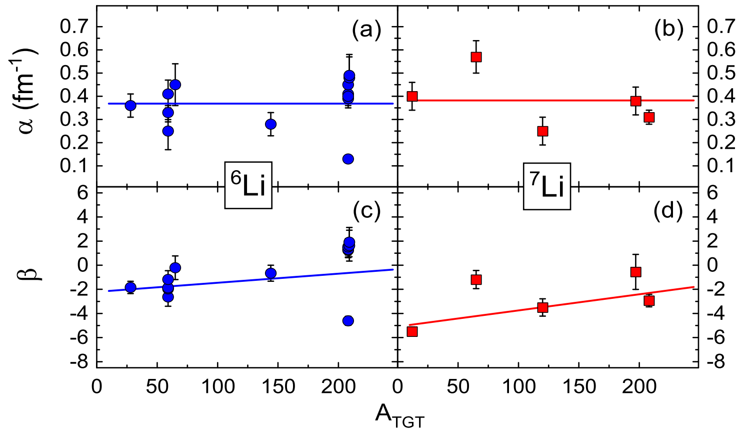

Fig. 4. α ((a) and (b)) and β ((c) and (d)) parameters of the breakup probability function for several reactions induced by ^{6}Li ((a) and (c)) and ^{7}Li ((b) and (d)) projectile as a function of the mass number of the target nucleus. The solid lines shown in (a) and (b) correspond to the average of all the α parameters derived in the present work. Similarly, in panels (c) and (d) the lines are the result of a fit under the assumption of a linear relation between β and the target mass (see text for details).

tance of closest approach and not, for instance, on the bombarding energy, can be experimentally tested using some of the measurements with ^{6}Li for a given target at different bombarding energies (Refs. [18–20,22]). Although the results are not conclusive it can be noticed from Table 2 that whereas for ^{59}Co the slope parameter exhibits some significant dependence on the energy, the data for the heavier ^{144}Sm, ^{208}Pb and ^{209}Bi targets are consistent, within uncertainties, with a single value for all the measured energies.

Finally, we present an analysis of the global behavior of each projectile in terms of the dependence upon the mass of the heavy reaction partner. This is illustrated in Fig. 4 where the parameters of the probability (only projectile breakup) are plotted as a function of the target-mass number, based on the information contained in Table 2. The upper panels of this figure, Figs. 4(a) and 4(b), correspond to the slope parameter for $^6\text{Li} \to \alpha + d$ and $^7\text{Li} \to \alpha + t$, respectively. Within the observed scatter of the values, the data for both nuclei seem to be consistent with constant values (i.e. independent of the target mass) equal to (0.37 ± 0.10) fm^{-1} for ^{6}Li and (0.38 ± 0.10) fm^{-1} for ^{7}Li.

Similarly, the lower panels of the figure, Figs. 4(c) and 4(d), illustrate the behavior of the parameter β for both projectiles. In this case we can see a weak dependence on the target mass which, for simplicity, is represented by a least-squares linear fit to the data, shown in the figure with a solid line.

3. Discussion and summary

It has been shown that the basic features of the reactions that lead to the breakup of a weakly bound projectile-like fragment can be systematically analyzed in terms of the probability of occurrence of such processes as a function of the distance of closest approach between the reaction partners [6,8]. Given the usefulness of this approach, in this work we have extended this kind of analysis to a large number of reaction systems towards a global description of all the breakup processes induced by weakly bound projectiles. For that purpose we have obtained breakup probabilities from data available in the literature for reactions involving the weakly bound ^{6}Li and

^{7}Li nuclei as projectiles and we have analyzed their dependence upon the projectile–target system, the projectile/ejectile scission and the reaction Q-value. We have considered the results of experiments that could determine absolute non-capture breakup cross sections — of either the projectile or the weakly bound ejectile of a previous transfer reaction — from the coincident detection of the emitted light breakup products. For all these reactions, we have corroborated an exponential behavior of the probabilities at long distances and we have investigated the validity of the probability function originally proposed in Ref. [8] and the systematic behavior of its parameters.

The exponential decrease of the breakup probabilities as a function of increasing distances between the projectile and the target that was found for such a large number of reaction systems and breakup modes, appears to be part of an even more general pattern that can be observed for many other peripheral processes (e.g. Refs. [9–11,19]). The case of nucleon transfer reactions lends itself to a relatively intuitive and straightforward semiclassical interpretation. In the light of a similar interpretation and under the assumption of independent sequential processes, it can also be expected that in the case of distant nucleon-transfer reactions followed by the breakup of the weakly bound transfer product, the corresponding probabilities would also exhibit an exponential behavior, as had already been observed and described for reactions induced by ^{9}Be. In those cases an additional contribution from the breakup itself to the overall probabilities could result in a faster decrease as the collisions become more distant. Even though the results of our analysis suggest such behavior, it is difficult to draw a definite conclusion in this respect due to the relatively few cases available for a significant comparison. A quantitative indication of the probabilities of pure breakup can be in turn provided precisely by the results of most of the studies using ^{6}Li and ^{7}Li projectiles. Since the breakup can be described as the excitation of the weakly bound nucleus to energy levels in the continuum of the two breakup fragments, the projectile-breakup probability function in these cases might reflect the exponential falloff of the probabilities as a function of the distance of closest approach [19].

For the slope parameter that governs the exponential decay as a function of the distance of closest approach, a similar mean value α has been found for both projectile fragmentations $^6\mathrm{Li}^* \to \alpha + d$ and $^7\mathrm{Li}^* \to \alpha + t$. The intercept parameter β for these partitions, closely related to the largest probabilities at the shortest distances, shows instead a small dependence on the target mass. In this global analysis we have included previous results for ^{9}Be projectiles on heavy mass targets ($A = 144$–209) [6] where the dominant breakup channel corresponds to the n-stripping reaction followed by the ejectile fragmentation ($^8\mathrm{Be}^* \to \alpha + \alpha$). These data were compared to those for ejectile breakup following similar transfer reactions with ^{7}Li projectiles which give rise to $^6\mathrm{Li}^* \to \alpha + d$.

From this systematic investigation we have also concluded that for the available data — both projectile and ejectile fragmentation — breakup probabilities increase on average with the reaction Q-value, which to a large extent reflects the threshold energy of the weakly bound nucleus that breaks up. This nucleus may be either the weakly bound projectile or a weakly bound transfer product. Projectile breakup probabilities ($P_{proj\text{-}BU}$) for both lithium nuclei exhibit very similar behaviors as a function of the minimum internuclear distance, while the data for n-stripping reactions followed by ejectile fragmentation ($P_{ejec\text{-}BU}$) with ^{9}Be present a much more rapid decrease. The different breakup modes seem to have a common characteristic: the breakup probabilities increase with the target mass.

In summary, we have systematically analyzed the available reported absolute cross sections for ^{6}Li and ^{7}Li induced breakup reactions in order to obtain the corresponding breakup probabilities. We have compared the results with those previously obtained for ^{9}Be and we have analyzed general trends of the probability functions as a function of the main characteristics of the reaction systems. The picture that emerges from this analysis shows global behaviors that may provide additional motivation to the development of theoretical models to explain these reactions, especially those involving complex mechanisms through which the breakup of a given weakly bound fragment appears to be mediated by nucleon transfer, a mechanism that probably deserves a more refined understanding. From the experimental perspective, it is our belief that this effort would highly benefit from additional data resulting from systematic measurements specifically designed to tackle some current shortcomings. Indeed, in order to make the comparison between different reaction systems more significant it would be highly desirable to be able to achieve a complete characterization of the reaction, for example in aspects such as the determination of the resonant or non-resonant origin of the breakup, the identification of the breakup mode (direct projectile or triggered-by-transfer breakup) and the relative contribution of all these components. The development and systematic application of large-efficiency devices for these exclusive measurements would be very helpful to reach this goal. Finally, it seems worthwhile to make specific experimental efforts to investigate the influence of various structural aspects on breakup probabilities, for example, the role played by nuclear deformation which is known to have a decisive impact on other sub-barrier or distant processes through the use of heavy deformed target nuclei.

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