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Short Note

Excitation of ^{6}Li above the breakup threshold in the ^{6}Li + ^{208}Pb system around the Coulomb barrier

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Abstract. The excitation energy above the breakup threshold of the $\alpha + d/^6$Li system, after the interaction of ^{6}Li nuclei with a ^{208}Pb target, was deduced from the invariant mass of the $\alpha + d$ system. Data were collected with a large-solid-angle detector set-up at four beam energies around the Coulomb barrier. The excitation of the ^{6}Li nucleus above the breakup threshold (1.47 MeV) has a quite similar behavior at each measured beam energy and angle; it is peaked at ~ 1 MeV above the threshold and shows an exponential decay on the high energy side, which is a clear signature of a direct breakup process. The experimental excitation energies are reproduced both in shape and absolute value by 1) fully quantum-mechanical Coupled-Channel calculations with coupling to discretized-continuum ^{6}Li excitations, 2) semi-classical Coupled-Channel approach, where the relative motion is treated along a classical trajectory.

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The breakup process, occurring between two colliding nuclei at Coulomb barrier energies, is expected to be relevant when at least one of the partners is loosely bound. Consequently, the breakup is expected to strongly influence the whole interaction scenario in this energy domain. Only few stable beams (d, ^{6}Li, ^{7}Li ,^{9}Be) turn out to be loosely bound, among them the most weakly bound nucleus is ^{6}Li with $S_d = 1.47$ MeV. This low S_d makes ^{6}Li similar to many unstable nuclei like ^{6}He, ^{8}B, ^{11}Be, ^{11}Li, ^{17}F. This field of investigation gives results which become more attractive and appealing in view of the new RIBs (Radioactive Ion Beams) facilities that have already delivered the first beams and that will be improved in the near future. Several experimental results involving light loosely bound beams and heavy targets have already been discussed and interpreted in the framework of a more or less relevant contribution from the breakup process: ^{11}Be + ^{209}Bi [1], ^{9}Be + ^{209}Bi [2], ^{9}Be + ^{208}Pb [3,4], ^{6}He + ^{209}Bi [5], ^{6,7}Li + ^{209}Bi [6].

The present work is part of a research line on the dynamics of the breakup process of ^{6}Li from a ^{208}Pb target at Coulomb barrier energies. These studies on the ^{6}Li + ^{208}Pb system have investigated both experimentally and theoretically the ^{6}Li inclusive breakup cross-section, with at least one fragment (the α-particle) in the exit channel [7,8], and then the exclusive one via α-d and α-p coincidences [9]. The main outcomes were: a) the inclusive breakup channel is quite strong and typical of weakly bound nuclei, b) the exclusive breakup channels are definitely smaller than the inclusive one. This underlines the relevance of a "new" interaction process at the barrier called "stripping breakup". All these features modify the current description of the interaction dynamics at the Coulomb barrier based on experiments with stable nuclear beams and have to be correctly included in the theoretical description of the interaction. Among the still missing

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information, one turns out to be important to approach a more comprehensive description of the process, *i.e.* the details of the projectile excitation during the interaction, or the projectile energy states in the continuum involved in the interaction.

Up to now similar information was obtained with loosely bound/halo radioactive ion beams only at much higher energies where the interaction is expected to be mainly of electromagnetic dipole nature. The differential Coulomb dissociation cross-sections measured for several of such nuclei like ^{11}Li [10–12], ^{11}Be [13] and ^{8}B [14] are strongly peaked around half a MeV excitation above the breakup threshold with an exponential decrease in the high-energy side. These data, while extensively discussed in the frame of a possible low-lying soft-dipole mode (the so-called pigmy resonance), were eventually interpreted in the frame of a dissociation via a direct breakup mechanism (without intermediate resonances). In any case, no data were available at Coulomb barrier energies. In this energy range, in addition to the Coulomb part, the nuclear contribution to the excitation mechanism is expected to be significant.

For the ^{6}Li + ^{208}Pb system two experiments were performed at energies much higher than the Coulomb barrier ($E_{\mathrm{coul}} \sim 31$ MeV), namely 60 MeV [15] and 156 MeV [16]. They were focused onto the breakup via the ^{6}Li unbound state at 2.19 MeV, $J^{\pi} = 3^{+}$, 0.71 MeV above the threshold and consequently only a limited excitation range of ~ 1 MeV above the threshold was investigated.

As already said, our investigation aimed to get data in the Coulomb barrier energy region for the ^{6}Li + ^{208}Pb system for a large excitation range. For this purpose we used, as in our previous experiments [7,9] with ^{6}Li, the large-solid-angle detector set-up 8πLP [17] of the INFN, Laboratori Nazionali di Legnaro. The specific goal was to see how ^{6}Li continuum states above the breakup threshold are excited during the breakup process in $\alpha + d$ by measuring the differential cross-section dependence on the ^{6}Li excitation energy.

The experiment was based onto the determination of the invariant mass M of the $\alpha + d$ system. The excitation energy E_{rel} above the breakup threshold S_d can be deduced from the invariant mass M of the system with help of the formula

$$M = \sqrt{\left(\sum_i \frac{E_i}{c^2}\right)^2 - \left(\sum_i \frac{\mathbf{P}_i}{c}\right)^2} = \frac{E_{\mathrm{rel}}}{c^2} + \sum_i m_i \,,$$

with E_i, $\mathbf{P}_i$, m_i, respectively, total energy, momentum and mass of the two fragments, α and deuteron, produced in the ^{6}Li breakup process. The energy E_{rel} is related to the ^{6}Li excitation energy E_x by the equation: $E_x = E_{\mathrm{rel}} + S_d$. To evaluate the $\alpha + d$ system invariant mass, one needs to measure E_α, E_d and the angle τ between the α and d in coincidence.

The ^{6}Li beam at energies of 31, 33, 35 and 39 MeV was delivered by the LNL Tandem Van de Graaff accelerator; the target was enriched, self-supporting, 200 μg/cm^2 thick ^{208}Pb. It is useful to remind that the section of the 8πLP

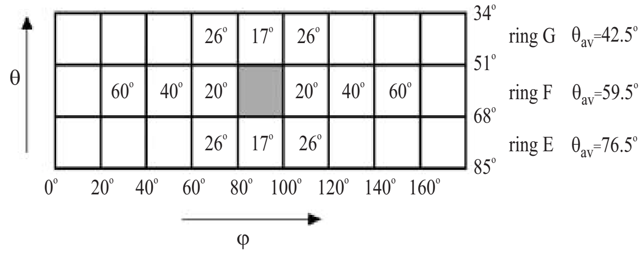

Fig. 1. Schematic picture of a portion of the 8πLP detector set-up. Each square represents a detector telescope with the indicated polar and azimuthal angles. With respect to the α-particle detected in the central shaded detector, the coincident deuterons can be detected at the following average angles: 17°, 20°, 26°, 40°, 60°.

apparatus utilized consists of 126 telescopes for charged-particle detection (each one consisting of a Si ΔE, 300 μm thick, and of a CsI(Tl) E_{res} 5 mm thick and covering a solid angle of 17° (θ) $\times$ 20° (ϕ)); this apparatus spans a total polar angle θ ranging from 34° to 85° (3 rings E, F, G in the forward direction) and 95° to 163° (4 rings A, B, C, D in the backward direction); for any additional detail see refs. [7] and [9].

The ^{6}Li was found to break up mainly in two channels: $\alpha+d$ with a Q-value of -1.47 MeV and $\alpha+p+n$ with a Q-value of -3.70 MeV, with a cross-section around a factor 2 smaller than the first channel [9]. The 8πLP set-up is well suited for a good identification of the $\alpha + d$ channel, since it has only charged outgoing fragments (while the other channel has also one neutron) and the angular size of each telescope is not larger than the α-d kinematics cone, which ranges from 17° to 20° for a sequential breakup process, *i.e.* first ^{6}Li scattering and then dissociation, with an excitation energy corresponding to the Coulomb barrier of the $\alpha + d$ system. This allows to measure the kinetic energies (E_i) of both α and d in coincidence in two telescopes as well as their relative mean angle τ. Deuteron and α-particle kinetic energies were determined summing the ΔE and E_{res} coincident signals; the relative accuracy of the total-energy determination was estimated around 5%, mainly due to the calibration uncertainty of the CsI detector. The detector geometry, shown in fig. 1, allows to have a given number of possible average angles τ (listed in the following) between the momentum of the α-particle, detected for example in the central shaded-area detector, and of the deuteron in coincidence in one of the surrounding detectors. These possible angles were: $\tau = 17°$, 20°, 26°, 40° and 60°.

The invariant mass was evaluated for all the detectors of the ring F, central ring in the forward direction with $\theta_{\mathrm{av}} = 59.5°$, of the ring B, $\theta_{\mathrm{av}} = 137.5°$ and of the ring C, $\theta_{\mathrm{av}} = 120.5°$, the two central rings in the backward directions. In these cases the coincidences could be obtained between the α-particles in the "central detector" and the deuterons in at least two neighboring detectors with the same average angle with respect to the α one (see fig. 1). The data of the four remaining rings were not evaluated since the statistical accuracy was smaller, and *a posteriori*

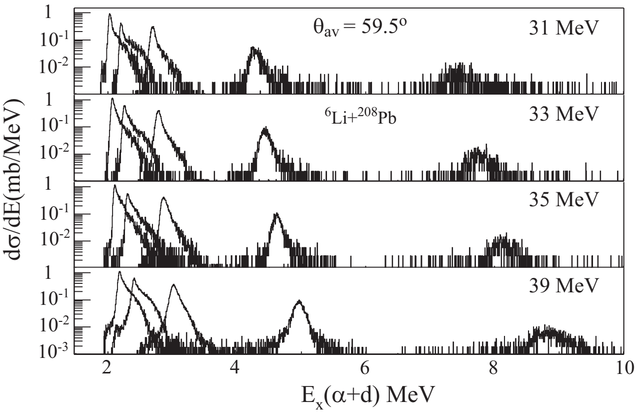

Fig. 2. Invariant-mass spectra evaluated at the 5 average angles between α and d momenta allowed by the detector set-up, for four ^{6}Li beam energies and $\theta_{\mathrm{av}} = 59.5°$.

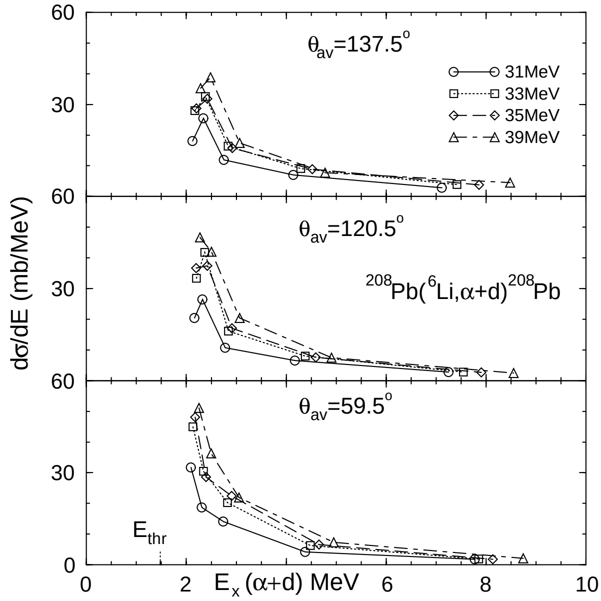

Fig. 3. Excitation energies of the $\alpha + d/^6$Li system evaluated as a function of ^{6}Li beam energies and θ_{av}. E_{thr} indicates the deuteron separation energy $S_d = 1.47$ MeV.

we found that the results show only a slight dependence on the polar angle, legitimating our omission. An example of the invariant-mass spectra evaluated for the four ^{6}Li beam energies at $\theta_{\mathrm{av}} = 59.5°$ (*i.e.* ring F) is shown in fig. 2. No significant coincidence events were found with α-d average angles larger than 60°. The data of fig. 2 are normalized in such a way that the sum of the bumps of each panel adds up to the total breakup cross-section already measured [9]. The energy resolution of the invariant mass is given mainly by the uncertainty of the angles between the α and the deuteron in coincidence which is around ±20°. The final values range from 0.4 MeV for the lowest E_{rel} points to 1.7 MeV for the highest ones.

The whole analysis procedure was verified through Monte Carlo simulations of the ^{6}Li breakup process in the $\alpha + d$ channel with the following assumptions: a) Breakup was schematized to occur along a Rutherford trajectory, during the scattering process. So we deal always with a two-body process: on the one hand the scattering of the center of mass of the ^{6}Li, and on the other the separation of the two fragments. b) Scattered ^{6}Li ions are randomly emitted in θ and ϕ. c) The angle between the ^{6}Li and α or d momenta in the CM frame is randomly chosen both in θ (0°–180°) and ϕ (0°–360°). The assumption c) is realistic since the α-d direction should have no privileged emission angles. The assumption b) for the polar scattering angle was made considering the quite flat trend of the already measured exclusive breakup cross-sections [9]. Finally the assumption a) has been verified *a posteriori* by the self-consistency of all the analysis procedure. In fact we cannot exclude *a priori* also a three-body breakup process occurring close to the ^{208}Pb target. The Monte Carlo calculations were done for each ^{6}Li beam energy with a distribution of the excitation energies similar to the experimental one.

These simulations essentially confirm within 2°–4° the values of the 5 average angles τ between the α and d momenta assumed in the evaluation of the invariant mass of the system. In addition, the invariant-mass spectra evaluated via these simulations are very similar to the experimental results: this is a self-consistency check of the simulations. The simulations allow also to evaluate the amount of lost coincidences, due to the two fragments hitting the same detector within its 17° × 20° acceptance cone; they are around 20% of the total coincident events. These events correspond to small angles between α and d, *i.e.* to small values of E_{rel}. An effect of this can be seen in the asymmetry of the first peaks in fig. 2; however, its effect on the centroid of these peaks, resulting from the simulations, is small. In conclusion, the experimental technique adopted and the relative analysis procedure result, from these simulations, to be self-consistent.

The excitation energies of the $\alpha + d/^6$Li system at the four ^{6}Li beam energies and at the three average detecting polar angles are shown in fig. 3. The plotted points correspond to the centroid of the peaks in fig. 2. The absolute scale has been fixed by requesting that the integral of each curve is equal to the total $\alpha+d$ breakup cross-section measured [9]; this procedure is justified by the fact that the angular distributions of the $\alpha + d$ coincident events are relatively flat [9]. All the excitation curves are peaked at around 1 MeV above the threshold without evidence of any resonance, within the limited energy resolution of the set-up. The fact that the excitation energies look very similar at all angles and beam energies points out that we are dealing with a threshold, direct breakup process, as previously observed [10–14] at much higher beam energies with light-unstable-halo projectiles. For a comparison with theoretical calculations presented in the following we have averaged at each energy the data in fig. 3, measured at the three different angles; these average values are shown in fig. 4.

The present experimental data have been compared with two complementary theoretical approaches. The first

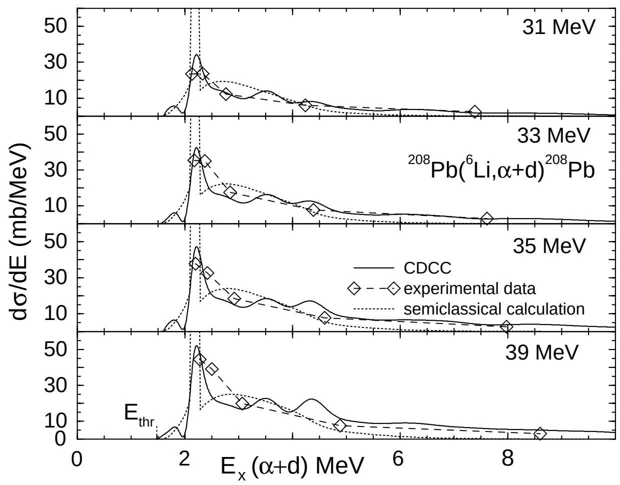

Fig. 4. Average $\alpha + d/^6$Li system excitation energies. The continuous (dotted) line is the calculation via CDCC (semi-classical Coupled-Channel) approach. The maximum of the peaks of the the semi-classical calculation, which is out of panels, has the following values: 177.0 mb/MeV, 241.7 mb/MeV, 276.2 mb/MeV and 285.4 mb/MeV at 31, 33, 35 and 39 MeV, respectively.

based on a full quantum-mechanical coupled-channels framework has already been extensively presented in ref. [9]. Summarizing, the calculations were done in the Continuum-Discretized Coupled-Channel (CDCC) approach with the code FRESCO [18]; for the ^{6}Li ground and continuum states, an $\alpha + d$ cluster structure was assumed. Calculations include coupling to discretized-continuum states up to 11.5 MeV excitation and continuum-to-continuum coupling as well, with excitation via both nuclear and Coulomb interaction. In this approach all the parameters are deduced from basic theory or experimental data: *i.e.* there are no free parameters. The results of the CDCC calculations are shown in fig. 4 (continuous curves) for the various beam energies. There is a rather good overall agreement between the experimental results and the theory. The resonant ^{6}Li levels at 2.19 MeV, $J^\pi = 3^+$, and at 4.31 MeV, $J^\pi = 2^+$, originating from the coupling of the deuteron, $J^\pi = 1^+$, to a d-wave cluster state, are not evident experimentally due to the limited experimental energy resolution. The $J^\pi = 3^+$ resonance is however well evidenced in the previous experimental results at ^{6}Li beam energies of 60 MeV [15] and 156 MeV [16].

The second set of calculations has been performed within a simpler approach. This retains the basic physical idea of the description of ^{6}Li as a dicluster $(\alpha + d)$ nucleus, as well as the construction of inelastic form factors connecting the initial bound state and the final states in the continuum. At variance with the fully quantum-mechanical CDCC approach, the relative motion is here treated classically, and along the classical trajectory one solves the semi-classical coupled equations for the amplitudes in the different channels [19]. Continuum-continuum couplings are not included in this approach. Both features make the calculation simpler than CDCC, allowing then for a much finer subdivision of the continuum (we have done the calculations with energy bins of 0.1 MeV). This is a crucial point, since one is dealing with the interplay of the non-resonant smooth continuum with the contributions from the resonant states. In particular, while the non-resonant continuum is strong enough to smear the 2^+ resonance, the low-energy region, corresponding to the 3^+ resonance, displays a narrow and strong peak. The most important qualitative differences are in the details of the energy distribution and may arise from the different way of subdivision of the continuum into energy bins. One advantage of this second approach is its simplicity which requires nearly two orders of magnitude less CPU time.

Table 1. Comparison between ^{6}Li breakup cross-section evaluated by semi-classical calculation and CDCC, and experimental data. All cross-sections are in mb.

Beam energy	Semi-classical calculation	CDCC	Experimental data
31 MeV	54.9	48.76	41.3(0.7)
33 MeV	69.3	65.43	59.2(1.2)
35 MeV	77.9	80.91	63.0(2.6)
39 MeV	84.5	102.32	76.5(5.3)

The results for the cross-section and excitation energy distribution shown in fig. 4 are similar to the one obtained with the first method. The high peak at $E_x \sim 2.1$ MeV, which is cut for plotting purposes, is much sharper than the one from CDCC calculation; however, what is relevant is the total calculated cross-section. In table 1 we compare the $\alpha + d$ cross-sections obtained by this method, the CDCC approach and the experimental ones. Both theoretical approaches slightly overestimate the experimental cross-sections.

In conclusion, the distribution of the excitation energies of the $\alpha + d/^6$Li system after the interaction with a ^{208}Pb target has been measured at four different beam energies around the Coulomb barrier in a large energy range, up to ~ 8 MeV excitation, with an energy resolution ranging from 0.4 to 1.7 MeV. The distributions resulted very similar at all beam energies. This supports an interpretation of a breakup process originating from a threshold effect as observed also with some light unstable/halo nuclei at much higher bombarding energies [10–14]. Resonances are also present as evidenced in previous experimental work [15,16] done with higher energy resolution but in a limited energy range, up to ~ 1 MeV, above the breakup threshold. Two different theoretical approaches with no free parameters, based the former onto the Continuum-Discretized Coupled-Channel approach and the latter onto a semi-classical Coupled-Channel description, reproduce quite well average experimental energy distributions and predict as well the resonances at 2.19 and 4.31 MeV. These results give a clear indication on how the breakup process develops experimentally and can be properly handled theoretically. They are therefore also relevant in the perspective of future studies with loosely-bound halo radioactive beams, where breakup phenomena could be even stronger.

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