Pb(^{6}Li,αd)Pb Breakup Experiment to Test Feasibility of Extracting the Astrophysically Relevant $\alpha+d$ Capture Cross Section

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The $(\alpha+d)$ breakup of 60 MeV ^{6}Li scattered from ^{208}Pb has been measured inside the grazing angle for c.m. energies of the fragments between 100 keV and 1.5 MeV. We find the integrated cross sections to be in agreement with Coulomb excitation theory, but the angular correlations of nonresonant breakup exhibit significant deviations from this theory. This shows that the measured breakup cross section cannot be related by first-order Coulomb excitation theory to the astrophysically relevant ^{4}He$(d,\gamma)^6$Li capture reaction.

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In the radiative capture reaction $x(y,\gamma)z$ the incident projectile y is absorbed by the nucleus x followed by the emission of γ radiation from the compound nucleus z. This process is one of the most important reactions for the formation of elements in the Universe [1]. Many astrophysical problems depend strongly on reliable measurements of the radiative capture cross sections involved [2,3]. Examples of astrophysical interest are the reactions ^{12}C$(\alpha,\gamma)^{16}$O important for the nucleosynthesis in red giants, ^{3}He$(\alpha,\gamma)^7$Be involved in the solar neutrino problem, and $\alpha(d,\gamma)^6$Li which could provide a consistency check for the standard big-bang model [4]. The direct measurement of such cross sections at astrophysically relevant energies, typically well below 100 keV, is rather difficult. Thus most cross sections could not yet be measured at sufficiently low energy.

In 1985, it was proposed to study photodisintegration processes $A(z,xy)A$ of a projectile z in the Coulomb field of a nucleus A in order to extract cross sections for the corresponding radiative capture reaction [5]. Using this indirect approach the following advantages are quoted: (i) Even at very low center-of-mass energies of the fragments a reliable detection of the fragments is possible due to their high velocities in the laboratory frame. (ii) Coulomb breakup experiments at sufficiently high projectile energies often produce higher reaction rates than capture experiments.

In order to extract reliable capture cross sections from Coulomb breakup data a good understanding of the breakup process is required. Especially, one has to know the contribution of nuclear interaction to the cross section and the influence of higher-order Coulomb effects, e.g., "postacceleration." At the moment, it is not clear whether these effects must be taken into account and how this might be done. To get experimental information on these questions we measured the breakup ^{208}Pb(^{6}Li,αd)^{208}Pb below the grazing angle. ^{6}Li should be well suited for the proposed indirect method, due to its low breakup threshold and due to the similar charge-to-mass ratio of projectile and fragments, which minimizes postacceleration effects.

Our experiment was performed by bombarding a 7.6-mg/cm^2-thick ^{208}Pb target (99% enriched) with a ^{6}Li beam of 60 MeV provided by the Heidelberg boosted MP tandem. The experimental setup is shown in Fig. 1. Coincident α-d events were measured by two semiconductor telescopes. The α telescope (telescope 1 in Fig. 1) consisted of a 200-μm ΔE counter and a 1.5-mm E counter covering a solid angle of 0.33 msr. The ΔE_1-ΔE_2-E telescope for the deuterons (telescope 2) had two 250-μm-thick crossed strip detectors $S_{1,2}$ as ΔE counters, and a 1.5-mm E detector combining good angular resolution ($\Delta\theta=0.5°$) with a large total solid angle of 8 msr. It was protected against the huge number of elastically scattered ^{6}Li projectiles by an aluminum foil 500 μm thick. Figure 2 shows the kinematic conditions of the breakup and defines the relevant physical quantities. In contrast to previous experiments, we measured at various detector arrangements in order to cover a large fraction of the decay cone in which the fragments were emitted. In the laboratory system, our measurements covered relative angles between α particle and deuteron from 3° to 13°. We took data at various angles ϕ_a between the scattering

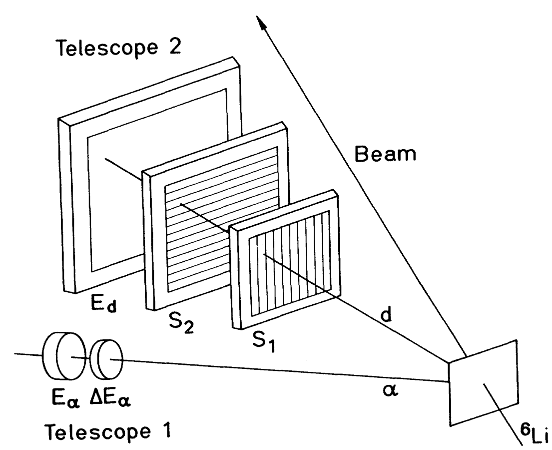

FIG. 1. The schematic view of the detector arrangement.

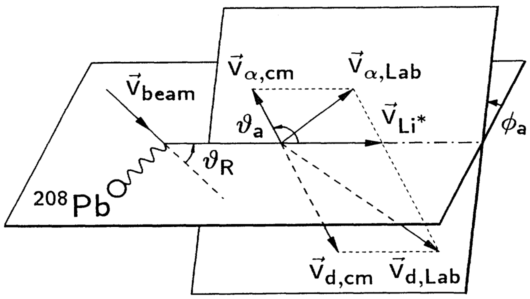

FIG. 2. Kinematics of the breakup process. The scattering plane is defined by the velocity vector of the incoming beam $\mathbf{v}_{beam}$ and the center-of-mass (c.m.) velocity $\mathbf{v}_{Li^*}$ of the outgoing fragments. The breakup plane is defined by the velocity vectors of the fragments $\mathbf{v}_{\alpha,lab}, \mathbf{v}_{d,lab}$. The center-of-mass system of incoming ^{6}Li is nearly equivalent to the laboratory system. The c.m. energy $E_{\alpha d}$ is related to the shown quantities: $E_{\alpha d} = \frac{1}{2} m_\alpha v_\alpha^2 + \frac{1}{2} m_d v_d^2$.

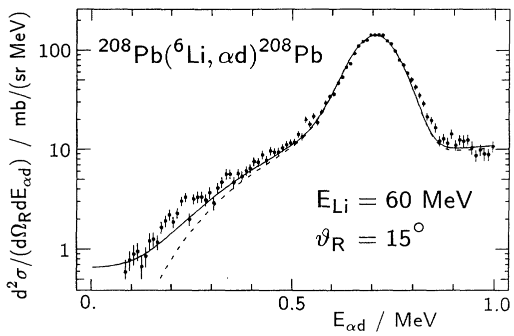

FIG. 3. The ^{208}Pb(^{6}Li,αd)^{208}Pb breakup cross section as a function of the fragments' energy $E_{\alpha d}$ in their center-of-mass system. The measurements have been performed at the beam energy $E_{Li} = 60$ MeV and at the scattering angle $\vartheta_R = 15°$. The dashed curve shows the result of a first-order Coulomb excitation calculation. The solid curve was calculated including an experimental background of 0.7 mb/MeV sr.

plane and the breakup plane between 0° and 180° in steps of 45°. We measured at scattering angles ϑ_R for the excited ^{6}Li* of 15°, 20°, and 25°. The grazing angle at our beam energy is $\approx 30°$. The Coulomb parameter ($\eta = 12$) justifies a semiclassical approach.

Figure 3 shows the measured double differential cross section $d^2\sigma/d\Omega_R dE$ as a function of the center-of-mass energy $E_{\alpha d}$. The data points result from measurements mapping out about 60% of the decay half cone in and above the scattering plane ($0° \leq \phi_a \leq 180°$) which is a symmetry plane of the problem. Breakup processes were reconstructed event by event using the energy measured in telescope 1, the position in telescope 2, and the energy of the beam assuming two-body kinematics for scattering and decay. Detector geometry was taken into account by a Monte Carlo simulation. By taking data in a large part of the breakup cone, we avoided making assumptions on the breakup's angular correlation. Background was suppressed by particle identification in telescope 1 and telescope 2 and a cut on the total energy. Because of a poor energy resolution near the edges of telescope 2 a complete background suppression, however, was not possible. By comparing events hitting the center and the edges of telescope 2 the remaining background was estimated to be ~1 mb/sr MeV. Throughout this paper error bars indicate the statistical errors only. Additionally, there is a systematic error of about 15%. The peak at $E_{\alpha d} = 0.71$ MeV indicates resonant breakup via the 2.18-MeV continuum state ($J^\pi = 3^+$) of ^{6}Li, while all other yield can be interpreted as nonresonant breakup [6]. The solid curve shows the result of a first-order Coulomb excitation calculation [5,7] using the $B(E2)$ values of Langanke's microscopic potential model calculations [8] for nonresonant breakup and $B(E2)$ from (e,e') experiments [9] for resonant breakup. Excitation and decay were treated as successive processes ("sequential breakup"). This might be justified because effective separation of the fragments consumes a significant amount of time due to their low relative energy $E_{\alpha d}$ [10–12]. In order to get an optimum fit to the data, the calculated curve was scaled by a factor $N \approx 0.8$ and a constant background of 0.7 mb/MeV sr was added. The curve was folded with a Gaussian [FWHM($E_{\alpha d}$) = 120 keV] taking into account the experimental energy and angular resolution. There is a surprisingly good agreement between our measurements and Coulomb excitation theory with respect to both absolute cross-section value and energy dependence. Even better agreement in absolute cross section ($N \approx 0.9$) is obtained if dipole polarization, the dominant higher-order effect [13], is taken into account [7,Vol.7].

Of course, the angular correlations contain much more detailed information on the breakup process itself; for example, their patterns might either establish Coulomb breakup and the contributing multipolarities or, by sensitive interference effects, reveal the presence of additional non-Coulomb breakup amplitudes. The left-hand part of Fig. 4 shows the angular correlation of events with 0.6 MeV $< E_{\alpha d} <$ 0.8 MeV where resonant breakup dominates. The solid curves show the result of a first-order Coulomb excitation calculation assuming sequential breakup, using Langanke's $B(E2)$ values. Agreement of measurement and calculation is satisfactory, which could be expected from earlier experiments measuring angular correlations at $\phi_a = 0°, 180°$ [14].

The right-hand part of Fig. 4 shows the angular correlations of events with 0.3 MeV $< E_{\alpha d} <$ 0.5 MeV where nonresonant breakup dominates. Again the calculations [7,15] use Langanke's $B(E2)$ values. The relative phases for final states with different orbital angular momenta are adjusted to get an optimum fit to the data. Here, data and calculations show significant deviations. The most prominent feature is a pronounced forward-backward asymmetry in the "in-plane geometry" ($\phi_a = 0°, 180°$) which vanishes in "out-of-plane geometry," and has dif-

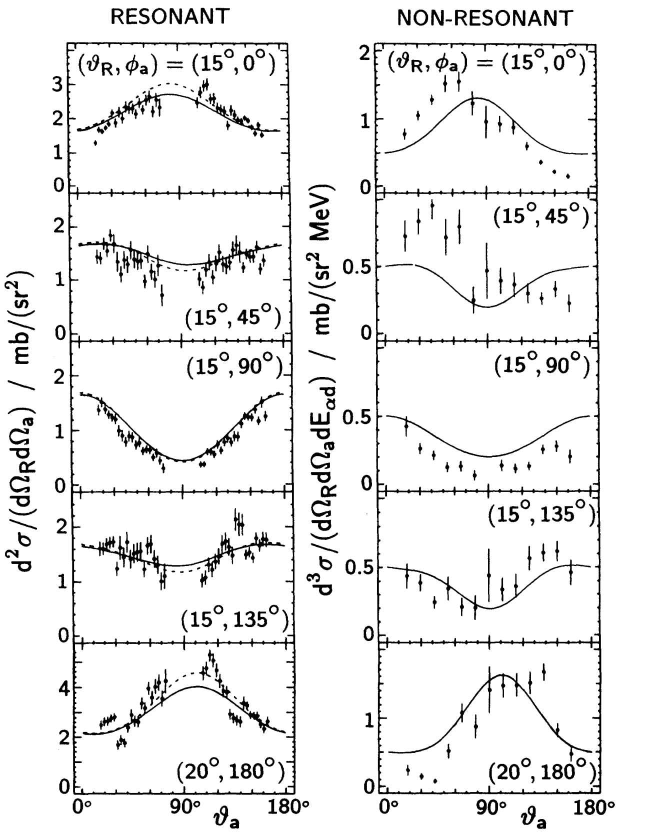

FIG. 4. The ^{208}Pb(^{6}Li,αd)^{208}Pb angular correlations for resonant (left) and nonresonant (right) breakup measured at indicated scattering angles ϑ_R and azimuthal angles ϕ_a (see Fig. 2). The data have been obtained at the incident energy of $E_{\rm Li}=60$ MeV. The solid curves show the result of a first-order Coulomb excitation calculation. The dashed curves were calculated assuming interference of resonant and nonresonant breakup amplitudes.

ferent signs for $\phi_a=0°$ and 180°. Because of the fact that data at different ϕ_a were taken with the same setup, by changing only the position of the detector a systematic error in experiment or data analysis could hardly explain this effect. The significance of the nonresonant data is confirmed by the fact that no such effects are seen in the resonant data measured simultaneously with the same experimental setup. Thus, first-order Coulomb breakup theory fails to describe the nonresonant breakup by a sequential approach. A more advanced theoretical study, which is valid also for nonsequential breakup, cannot explain the observed forward-backward asymmetry once again [16].

Measurements at a Rutherford scattering angle of $\vartheta_R \sim 20°$ agree with the results discussed so far. At a scattering angle of $\vartheta_R \sim 25°$ we observe deviations from Coulomb theory in both resonant and nonresonant breakup, indicating the increasing influence of the nuclear force near the grazing angle.

Our experimental results can be interpreted in the following way. Because of the long lifetime of the 2.18-MeV ^{6}Li state its decay following resonant excitation takes place far from the "catalyst" nucleus and there is no perturbation by its Coulomb field. First-order Coulomb excitation theory and the assumption of sequential decay are valid.

The present angular correlation measurements confirm, however, our earlier result [17] that nonresonant breakup cannot be described by these simple assumptions, at least at present limits. This might be explained by a non-negligible influence of the final-state interaction of fragments and target nucleus or by a significant contribution of nuclear interaction of projectile and target. Since our experiments are performed well below the grazing angle in a regime where Coulomb excitation is expected to dominate [6,10,18], and since the resonant breakup data do not show any evidence for nuclear interaction, we assume that nuclear interaction gives no obvious explanation of our results. The final-state interaction, however, could be a possible explanation. It should be more important in nonresonant breakup than in resonant breakup, because the effective separation of the fragments occurs much closer to the nucleus in the first case [10-12].

Recent ^{6}Li breakup experiments of a Karlsruhe group show no deviation from Coulomb theory in the nonresonant case [19]. They were performed at a beam energy $E_{\rm Li}$ of 156 MeV and a Rutherford scattering angle ϑ_R of about 3°. Using a magnetic spectrometer the measurements covered only a small part of the angular correlation, where the velocities of projectile and fragments are almost collinear. With our detector setup we cannot measure this kinematical situation, but extrapolation of our data to $\vartheta_a=0°$, 180° indicates also an agreement of Coulomb theory and measurements at just these kinematic conditions. For this reason the Karlsruhe results do not necessarily contradict ours.

In the case of ^{7}Li there is a similar situation. Measurements, where velocities of projectile and fragments are almost collinear, show less evidence for the final-state interaction [20] than measurements performed at $\vartheta_a \sim 90°$ [21].

With regard to astrophysical application of Coulomb breakup measurements it can be concluded that, in general, Coulomb breakup measurements cannot be correlated in a straightforward manner to astrophysically relevant capture reactions. But there might be special kinematical situations (e.g., collinear breakup, higher beam energy, smaller Rutherford scattering angle) where interpretable and reliable data can be taken. To establish the limits for these situations must be the aim of further investigations. The present work has demonstrated that considering the breakup cross section only is, in general, not sufficient for this purpose and that the thorough examination of the completely measured breakup correlations will be crucial.

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