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Coulomb Breakup of ^{6}Li

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Measurements of the Coulomb breakup of ^{6}Li have been performed in the energy range of the incident particle from 19–26 MeV. From the analysis of the deuteron component only, an almost constant $B(E2)$ value about 55 $e^2\,\mathrm{fm}^4$ has been deduced.

1. INTRODUCTION

It has been known for some time that a significant fraction of the total (^{6}Li, d) cross section arises from the breakup of the incident ^{6}Li in the nucleus. The breakup of ^{6}Li has been studied several times[1-5] at various bombarding energies above, around, and below the Coulomb barrier. First analyses of this phenomenon (which treated data taken above the barrier) already assumed a dominant Coulomb effect.[6] Only Coulomb effects, however, should contribute to the breakup at incident energies below the Coulomb barrier. Experimental studies of the Coulomb breakup of ^{6}Li on ^{208}Pb at 24 and 26 MeV have recently been performed at this laboratory.[5] The present note concerns data taken in connection with this experiment, but previously unreported, as well as extension of the measurements to lower energies.

For the comparison of experimental and theoretical cross sections for the Coulomb breakup of ^{6}Li one assumes[7] that this process proceeds via the excitation of the 2.18-MeV level by pure Coulomb interaction. The breakup of this level should therefore yield equal numbers of α particles and deuterons. On the basis of these assumptions we found that our recent results have been, to some extent, in disagreement with theoretical[7,8] and other experimental results[9] as follows:

(i) The experimental angular distributions of the α particles cannot be described by the theory of Coulomb excitation.[8]

(ii) The experimental value of the reduced matrix element $B(E2)$ for quadrupole excitation of the 2.18-MeV level in ^{6}Li deduced from the integrated α-particle cross section is energy-dependent and does not agree with the value obtained from inelastic electron scattering.[9] Even below the Coulomb barrier we found a larger integrated cross section for α particles than for deuterons. Hence, we also investigated the proton channel to study processes which could compete with the two-step breakup.

2. EXPERIMENTAL PROCEDURE AND RESULTS

The experiments were performed with the Li beam[10] of the EN tandem accelerator of the Max-Planck-Institut für Kernphysik at Heidelberg.

Simultaneously with the α particles, deuterons and protons were also detected in the measurements on ^{208}Pb (target thickness about 1 mg/cm^2) at six energies between 19 and 26 MeV. The deuteron and proton data were previously not published because they seemed of lesser importance. Figure 1 shows spectra of deuterons and α particles taken at bombarding energies of 24 and 26 MeV. From an examination of these spectra it was concluded that both are well described within the framework of a two-step process. Thus the previous analysis was only carried out for the α particles.[5]

Figure 2 shows proton spectra at 19-MeV incident energy as an example. The proton spectra at all bombarding energies and all measured angles increase with decreasing proton energies as low as these energies could be measured. Since these spectra do not exhibit maxima the yield at low proton energies is completely undetermined. We therefore could only extract upper limits for the proton cross sections. A proton peak is marked which shows the 8.46-MeV state in ^{17}O from the reaction ^{12}C(^{6}Li, p)^{17}O. The breakup spectrum on heavy target nuclei, e.g. ^{208}Pb, is free of contributions from breakup on lighter target nuclei (which may be present as impurities on the target) only at large angles, because of the kinematical shift. Most of the impurity breakup contributions appear in the lower half of the spectrum. Therefore the total deuteron counting rate at each angle has been obtained by duplicating the upper half of the deuteron spectrum. Contributions from reactions on ^{12}C and ^{16}O have been subtracted, since the level structure of the residual nuclei is known. Some reaction cross sections on ^{12}C are also available.[11]

Figures 3 and 4 show the deuteron angular dis-

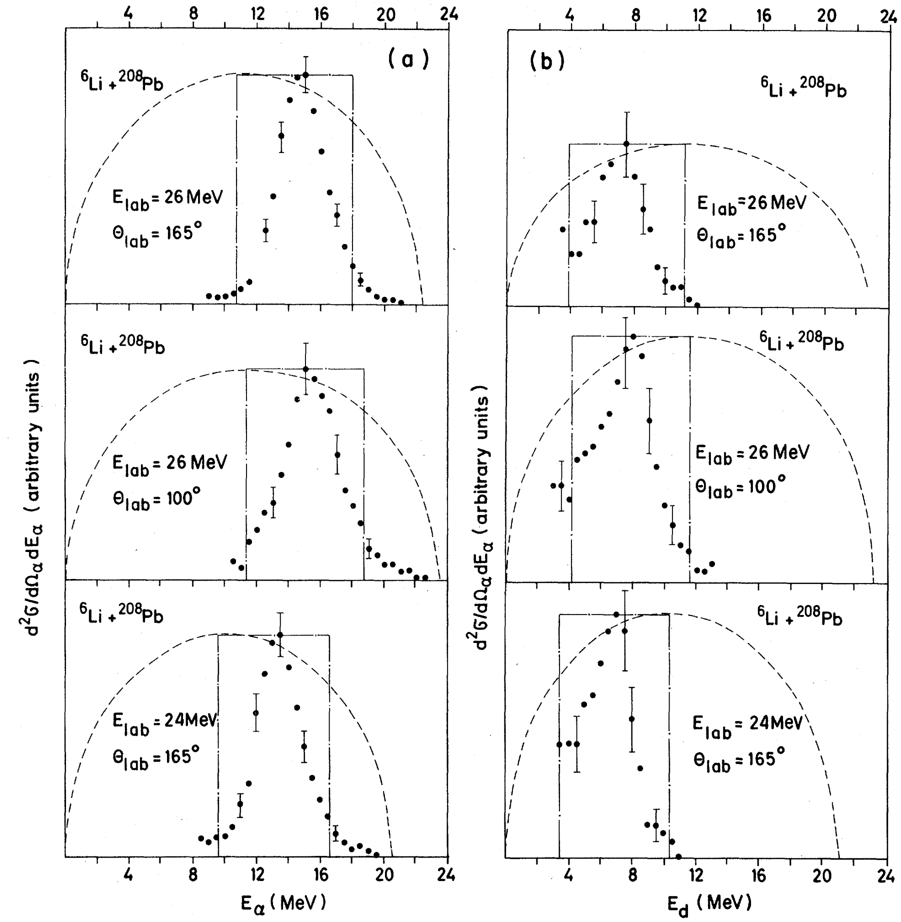

FIG. 1. Spectra of α particles (a) and deuterons (b) from the breakup reaction at 26 and 24 MeV. The rectangular shapes correspond to the two-step process assuming isotropic α-d decay, and the semiellipse represents the phase-space factor for the simultaneous decay into the α-d continuum (Ref. 12). The calculated curves are normalized to the experimental peak height.

tributions, and in addition Fig. 4 shows some of the corresponding α-particle angular distributions. The integrated cross sections are listed in the Table I. The largest cross sections have been measured for α particles, whereas the sum of the proton and deuteron cross sections approximately equals the integrated α cross sections (see Table I).

3. DISCUSSION

A. Deuterons

The best information on the breakup process is contained in the deuteron cross sections. The measured spectra are extremely well confined within the energy boundaries given by the two-step kinematics.[12]

The angular distributions shown in Fig. 3 as

TABLE I. Integrated cross sections of α particles, deuterons, and protons from ^{6}Li breakup on ^{208}Pb. The large errors of the deuteron cross section are due to the uncertainty of the behavior of the angular distributions at forward angles. As the proton spectra did not show any distinct peak, only upper limits can be given. The theoretical values are calculated with $B(E2)=26\ e^2\,fm^4$ from Ref. 9.

E (MeV)	σ_α (mb)	σ_d (mb)	σ_p (mb)	σ_d theoret. (mb)	$B(E2)$ $e^2\,fm^4$
26	52 ± 15%	18 ± 40%	≤25	10.5	52
24	20 ± 15%	11 ± 40%	≤12	5.5	55
22		5.6 ± 40%		2.3	55
21	4 ± 30%			1.9	
20	3.2 ± 40%	2.2 ± 40%		0.9	61
19	0.9 ± 40%	0.58 ± 40%		0.26	55

well as the integrated cross sections approximate the theoretical predictions much better than the corresponding α-particle cross sections. From the analysis of the angular distributions the reduced matrix element $B(E2, 1^+ \rightarrow 3^+)$ has been extracted.[5] In the energy range between 19 and 26 MeV this value is constant at about 55 $e^2\,\mathrm{fm}^4$, which is about a factor of 2 too large compared to the value extracted from the electron scattering experiment.[9] Taking, however, the large errors into account, the lower limit approaches the experimental value.

From the present theory[7,8] it is claimed that excitation of higher-lying resonant states in ^{6}Li and their direct disintegration into $\alpha + d$ via quadrupole continuum excitation, as well as higher-order effects,[7,13] are small, assuming a pure Coulomb interaction. Direct disintegration into $\alpha + d$ via the dipole continuum transition is not possible, because of the selection rules.[8] The constancy of the $B(E2, 1^+ \rightarrow 3^+)$ value in the energy range covered here convinces us that we are observing the same process, which is most probably a Coulomb process. Contributions to the deuteron cross section with an origin other than breakup should show an energy dependence if these effects are caused by nuclear forces because they become strong if the Coulomb barrier is approached.

The discrepancy between our results and the values given in a recent publication by Disdier *et al.*[14] cannot be explained. A large contribution from a polarization effect in ^{6}Li Coulomb excitation can therefore not be deduced from our data.

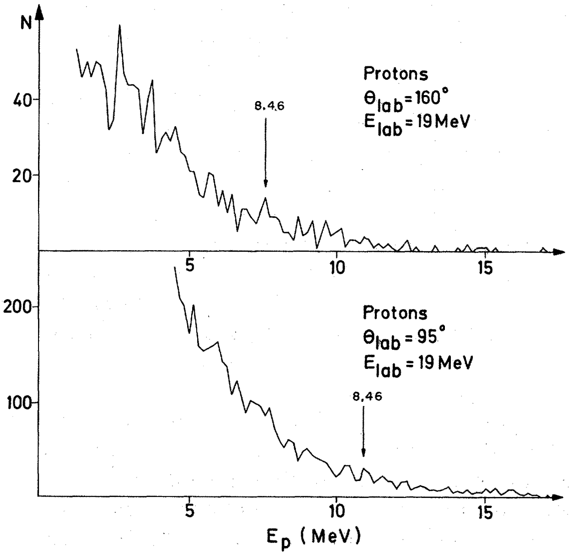

FIG. 2. Proton spectrum at 19-MeV incident ^{6}Li energy. The arrows indicate the position of the 8.46-MeV level of ^{17}O from the reaction ^{12}C(^{6}Li,p)^{17}O.

Since this effect is estimated by Winther[15] to be about 15% of the normal Coulomb excitation, it is not possible to observe this effect within the large error range of our data.

B. α Particles

The measured α-particle spectra are reasonably well confined within the kinematical boundaries; however, larger fractions of the cross sections are found outside these limits than in the deuteron spectra. In the breakup studies with lower-Z-target nuclei[12] (^{58}Ni, ^{118}Sn) it has been found that sub-Coulomb transfer processes have to be considered. The shape of the α-particle spectra from processes with higher Q values than the breakup are spread over a larger energy range than those for the breakup process. An inspection of the spectra measured on ^{208}Pb shows that these spectra are quite narrow, which indicates that sub-Coulomb neutron- or proton-transfer reactions leading to α-unstable ^{5}Li or ^{5}He may not contribute considerably.

The very large absolute cross sections for the

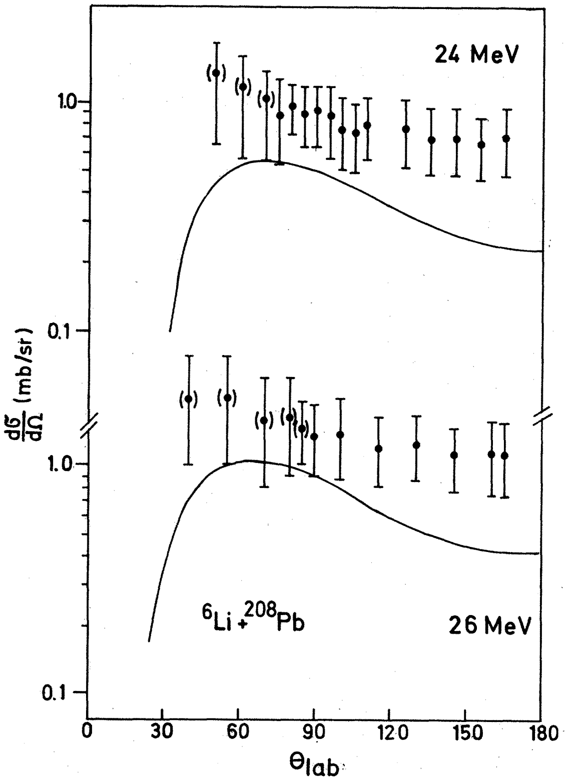

FIG. 3. Deuteron angular distributions at 24 and 26 MeV. The points in parentheses have large uncertainties due to the method of analysis described in the text. The solid lines are theoretical curves calculated by using a cross-section function from Ref. 8.

α particles, however, indicate that other processes contribute to the α channel but not to the deuteron channel. One possible effect is the direct dipole excitation into the continuum which produces $\alpha + p + n$. This process may contribute considerably even assuming a pure Coulomb interaction. Unfortunately it has not been calculated so far.

Another possible process proceeds via two steps. First the ^{6}Li projectile is dissociated into $\alpha + d$, and subsequently the deuteron is captured by the target nucleus, forming a compound system. Since the Coulomb barrier for capturing a deuteron into the target nucleus is lower than that for the α particle, such processes would contribute a larger α-particle yield than deuteron yield. Similar processes have been discussed for ^{7}Li projectiles.[16, 17]

The angular distributions for the α particles [Fig. 4(b) and Fig. 2 from Ref. 5] deviate completely at backward angles from those calculated for a pure Coulomb effect. This indicates that additional non-Coulomb processes have to be taken into account in the analysis of the α-particle spectra. Therefore a much too large matrix element had been extracted from these data previously.[5]

Wittern[18] has already shown that nuclear contributions have to be considered. Since a distinction between a Coulomb breakup and nuclear processes cannot currently be made, the α-particle data cannot be used for the analysis of the breakup process below the Coulomb barrier.

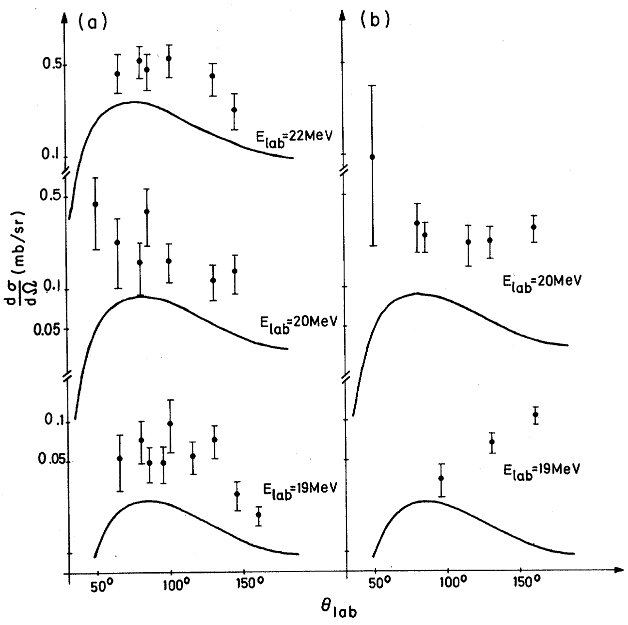

FIG. 4. (a) Deuteron angular distributions at 19, 20, and 22 MeV. (b) α-particle angular distributions at 19 and 20 MeV. The units on both vertical axes are the same.

C. Protons

From any reaction with more than two particles in the exit channel, one expects a continuous spectrum with a maximum at a certain energy. Under the assumption that the protons originate from such a process we expect a continuous spectrum for the protons also.

Our proton spectra, however, do not show a maximum in the energy range covered which can either be due to the experimental limitation that the measurements could not be extended to very low energies, or the process from which the protons originate may be responsible.

If it is assumed that the Coulomb breakup of ^{6}Li proceeds only via the 2.18-MeV level, protons should not be present at all because:
(i) They cannot be formed directly $(\alpha + p + n)$ because the resonance process requires an excitation in ^{6}Li of 3.7 MeV (>2.18 MeV).
(ii) Protons cannot originate from a secondary distintegration of the deuterons. Because the lifetime of ^{6}Li* is about 2×10^{-20} sec, this nucleus is too far from the interaction potential (several 100 fm) before disintegrating.

Hence, the presence of protons in breakup studies requires the assumption of additional reaction mechanisms.

The direct dipole excitation into the continuum has already been mentioned in the discussion of the α particles. Also, the second process mentioned in the previous section, the breakup and subsequent capture of the deuterons forming the compound nucleus ^{210}Bi, can contribute to the proton yield because the states of that compound nucleus are particle-unstable. Furthermore, the possibility cannot be excluded that some of the protons are caused by impurities contained in the lead targets. It has been shown[11] that the cross section for the reaction ^{12}C(^{6}Li, p)^{17}O is quite large. However, it was not possible to identify more states in ^{17}O uniquely despite the 8.46-MeV state which is most strongly excited. Cross sections for the reaction ^{16}O(^{6}Li, p)^{21}Ne are not known.

It is, however, unlikely that protons are only due to impurity reactions because the sum of the deuteron and proton cross sections equals the α cross sections quite well. A clear decision on the origin of the protons and on the nature of the mechanism has to be postponed until correlation measurements, e.g. between α particles and protons, have been performed.

4. CONCLUSION

The present discussion was intended to show that the only information on the ^{6}Li breakup is contained in the deuteron cross sections and angular distributions, and that for the quantitative analysis of the α-particle cross sections, more and complicated processes have to be assumed. It also indicates, unfortunately, that only limited information can be obtained from incomplete kinematical experiments. In particular, the origin of the protons has to be investigated carefully.

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^{18}O + ^{16}O Elastic Scattering in the Energy Range $E_{\rm c.m.}$ = 13–33 MeV[†]

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The elastic scattering of ^{16}O from ^{18}O has been measured in the c.m. energy range 13–33 MeV. The measurements include angular distributions at $E_{\rm c.m.}$ = 21.1, 23.7, 26.4, and 29.0 MeV and excitation functions at $\theta_{\rm c.m.}$ = 50, 60, 70, 80, 90, and 100°. Data have been analyzed with the conventional optical model with the aid of both strongly and weakly absorbing potentials as well as an absorptive potential obtained from the matter distribution of the colliding ions. The principal result is that the potential must be transparent (weakly absorbing) for surface partial waves. The detailed behavior for the low-l partial waves is not well defined.

I. INTRODUCTION

The observation of pronounced and unexpected gross structure in the excitation functions of the ^{16}O + ^{16}O scattering[1] led to much renewed interest in the heavy-ion–nucleus interaction. Similar, though less pronounced, gross structure in the excitation functions has since been observed in the scattering for many other systems of identical and nonidentical particles in extensive studies[2-7] in this and in other laboratories. It was shown recently[6] that the picture emerging from these studies (of which the present ^{16}O + ^{18}O investigation is a part) is that the heavy-ion–nucleus interaction is strongly absorbing ("black") for the low-l partial waves but very "transparent" (i.e., weakly ab-