Search for ^{7}Li Breakup in ^{7}Li + ^{197}Au near Grazing Incidence

J. L. Québert, B. Frois, L. Marquez, and G. Sousbie
Centre d'Etudes Nucléaires de Bordeaux-Gradignan, Institut National de Physique Nucléaire et de Physique des Particules, 33170 Gradignan, France

and

R. Ost, K. Bethge, and G. Gruber
Zweites Physikalisches Institut der Universität Heidelberg, Heidelberg, Germany
(Received 12 November 1973)

Coincidence measurements of charged particles emitted in a narrow cone in ^{7}Li + ^{197}Au, near grazing incidence, show that the two-step breakup via the $\frac{7}{2}^-$ (4.63 MeV) state in the $\alpha + t$ channel is very weak, in agreement with the predictions of the corresponding inelastic process ($\sigma_{tot} = 350$ μb). An important α-d coincidence yield comes from the following mechanism: ^{197}Au(^{7}Li, ^{6}Li*(2.18 MeV))^{198}Au, ^{6}Li*(2.18 MeV) $\rightarrow \alpha + d$; $\sigma_{tot} \leq 9 \pm 2$ mb. The experimental optimum Q value of the first step of this process is $Q_{opt} = -1.8 \pm 0.1$ MeV.

Recent experiments have shown that the nature of the projectile must be taken into account in understanding heavy-ion scattering. For instance, the so-called second-order processes such as reorientation effects or virtual excitations may not be negligible for the projectile.

We present here a study of another process which may occur in inelastic scattering or transfer reactions, i.e., the breakup of the projectile via a real or virtual excitation above a particle threshold. The study of such a two-step process may be a help in the understanding of transfer form factors and a probe for the best configuration to choose in the projectile wave function. From the experimental point of view, it is attractive to attempt to record the particle components by a coincidence method which is very sensitive to the prior excitation energy in the projectile and therefore to the state involved in the two-step process.

In this work, we study the possibility of a two-step breakup of ^{7}Li when it is scattered by a heavy target (^{197}Au in this case). For example, we can expect an $\alpha + t$ dissociation when considering the transition from the $\frac{3}{2}^-$ ground state to the $\frac{7}{2}^-$, 4.63-MeV state which lies above the $\alpha + t$ threshold. Let us now define what seem to be the best conditions to study this process.

First, it seems reasonable to link this mechanism to the behavior of inelastic Coulomb plus nuclear scattering. However, destructive interferences between Coulomb and nuclear perturbations may occur in the grazing-incidence region and have to be avoided.

Second, when the breakup occurs very close to the target, one of the clusters may be transferred to it and the phenomenon may be intermingled with a multinucleon transfer. The only region which seems to favor a simultaneous emission is at the maximum of the Coulomb effect.

Third, the two clusters have to be detected in coincidence in the right cone of emission. The aperture of this cone depends on the state which is involved and on the kinematics.

In the scattering of ^{7}Li on different targets,[1,2] many α particles and tritons are seen in singles spectra. Though not shown, all particle spectra have similar symmetrical shapes. They also have the same mean energy for each kind of isotope. The following table gives the absolute total cross sections for all particles identified in the reaction under the same kinematic conditions and taking into account the experimental angular distributions:

σ_{tot} (mb)	Particle
11 ± 3	p
9 ± 2	d
19 ± 3	t
220 ± 10	α
9 ± 3	^{6}He

In previous work[1], we showed that we actually recorded the remaining particle (α/t) connected with a (t/α) transfer to the target. This gave a qualitative explanation of the different yields of emitted particles. We analyzed quantitatively the behavior of the mean energies against the incident energy. These quantities are not increasing very fast with the incident energy, and are in fact in very good agreement with calculations of the optimum Q value for transfer reactions, using the kinematic conditions and including recoil effects.[3-5] Thus, the symmetrical shapes for each spectrum reflect the behavior of the Q effect for each kind of transfer to the target. These shapes are not rectangular as would result from a breakup in flight via some level in ^{7}Li.

In order to clarify whether an $\alpha + t$ breakup via the $\frac{7}{2}^-$ state really occurs or not, we performed a coincidence experiment for $^7\mathrm{Li} + {}^{197}\mathrm{Au}$, using the Heidelberg Emperor accelerator. Our purpose was to record coincidences of charged particles identified by a telescope triggered by the correlated particle impinging on a single solid-state detector. Both detectors were set up in a plane normal to the beam direction at the target center. The two axes of symmetry of the detectors cross the target center and define an angle φ_{12} which corresponds to the relative cone of emission of each fragment.

The experimental conditions have been chosen so that (a) φ_{12} lies between 0 and 25° in order to observe the possible breakup via the 4.63-MeV state, and (b) $d\sigma_{\mathrm{elastic}}/d\sigma_{\mathrm{Rutherford}}$ begins to deviate from unity. The coincidence counts are obtained by gating on true events in the time spectrum and by choosing a type of particle recorded by the telescope. The corresponding density $N(E_1, E_2)$ is shown in Fig. 1.

The main result of this experiment is that no appreciable counting rate of an α-t type comes through the identification gating at any angle φ_{12} (0–25°), so no strong breakup comes from the $\frac{7}{2}^-$ level at this energy. The experimental upper limit of this process at 90° does not exceed the theoretical predictions of a Coulomb excitation of $^7\mathrm{Li}(\frac{7}{2}^-)$. We used for that the de Boer-Winther program[6] in which the role of the target is played by ^{7}Li with appropriate kinematic conditions. By using the matrix element

$$\langle\tfrac{3}{2}^- \| \mathfrak{M}(E2) \| \tfrac{7}{2}^-\rangle = \pm\left[(2\times\tfrac{3}{2}+1)B(E2;\tfrac{3}{2}^- \to \tfrac{7}{2}^-)\right]^{1/2} = \pm 0.07899e\ \mathrm{b},$$

we found $\sigma_{\mathrm{tot}}(\frac{7}{2}^-) = 0.35$ mb and $(d\sigma/d\omega)$(breakup; 90°) ≤ 40 μb/sr. The only important counting rate is of an α-d type and may be explained by considering a neutron transfer to the target and a core excitation of ^{6}Li:

$$^{197}\mathrm{Au}(^7\mathrm{Li}, {}^6\mathrm{Li}^*(2.18\ \mathrm{MeV}))^{198}\mathrm{Au},$$

$$^6\mathrm{Li}^*(2.18\ \mathrm{MeV}) \to \alpha + d.$$

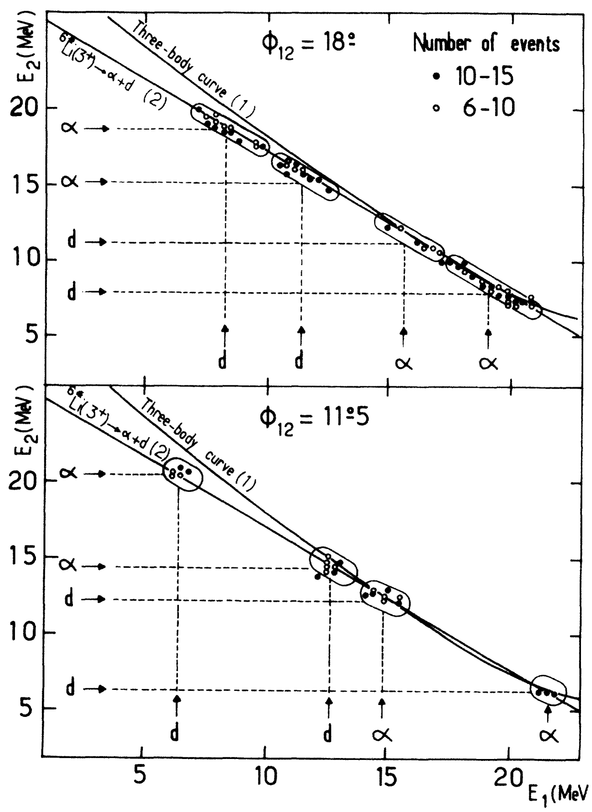

FIG. 1. Correlated events of the α-d type. Four zones can be distinguished but only one side of the plot, relative to the $E_1 = E_2$ line, has to be considered because of the symmetry in the detector locations. Each zone corresponds to the double condition $^7\mathrm{Li} + {}^{197}\mathrm{Au} \to \alpha + d + {}^{198}\mathrm{Au}$ (kinematic line 1, overbent for the drawing) and $^6\mathrm{Li}^*(3^+) \to \alpha + d$ (kinematic line 2).

This reaction can be studied in the framework of three-body reactions in which we define a projected spectrum[7]:

$$S_i = \left(\frac{m_i m_k P_i P_j}{1 + m_k/m_j + P_i \cos(\varphi_{12})/P_j}\right)|A|^2; \qquad (1)$$

$m_{i,j,k}$ $(i, j, k = 1, 2, 3)$ are the masses of the particles involved, with scalar momenta $P_{i,j,k}$ in the lab system. The matrix element A accounts for the neutron transfer and the breakup of ^{6}Li.

The projected spectrum depends mainly on the form factor in A which refers to the breakup of $^6\mathrm{Li}(3^+$, 2.18 MeV) to a free α particle plus a free deuteron. We write it as

$$f_{\mathrm{brkup}} = \gamma_{^6\mathrm{Li}} \cdot \gamma_{\alpha\text{-}d}/(\epsilon_{ij} - \epsilon_r + \tfrac{1}{2} i\Gamma); \qquad (2)$$

γ stands for the reduced width in each subscripted channel, ϵ_r and Γ define the 3^+ state, and ϵ_{ij} is the available energy in the two-body system α

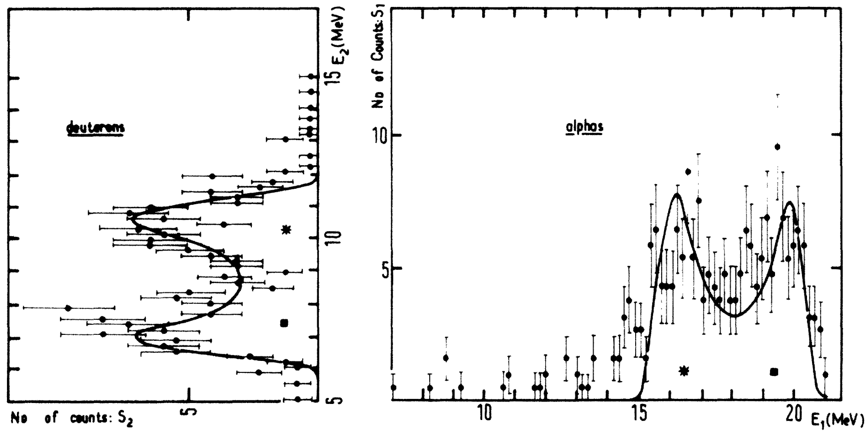

FIG. 2. Projections of the coincidence density for $\varphi_{12}=18°$. Solid curves are the best-fit results of the calculation with expressions (1) and (2) and a residual energy of 1 MeV in the three-body system. The peaks are correlated by the squares and asterisks. The finite sizes of the detectors have been taken into account.

$+d$. We show a part of theoretical calculations in Fig. 2. To fit the data, we need to assume a residual energy E of about 1 MeV in the three-body system ($\alpha+d+{}^{198}$Au). This means that the experimental optimum Q value for the neutron transfer is

$$Q=\Delta({}^7\mathrm{Li}+{}^{197}\mathrm{Au})-\Delta({}^6\mathrm{Li}^*+{}^{198}\mathrm{Au})-E$$
$$=-1.8\pm0.1\ \mathrm{MeV}.$$

This result leads to a virtual energy of 10.4 MeV in ^{7}Li prior to the neutron capture.

The absolute value of the total α-d breakup is not easy to get from the coincidence experiment. The upper limit is however contained in the total deuteron yield, $\sigma_{\mathrm{tot}}\leqslant 9\pm2$ mb. If we consider the Coulomb inelastic process ^{198}Au + ^{6}Li(1^+) $\rightarrow$ ^{198}Au + ^{6}Li(3^+) with a relative c.m. energy corresponding to the total available energy [E(^{7}Li) = 32 MeV; E(^{6}Li) $\simeq \frac{6}{7}E$(^{7}Li)], and use $B(E2;\ 1^+\rightarrow3^+)^8=26e^2\ \mathrm{fm}^4$, we find a total cross section $\sigma_{3^+}=5.15$ mb. This value does not seem to be too far from the estimated upper limit of the breakup. Another point of comparison is the result of a rough integration on the three-body parameters of the coincidence yield, obtained in the experiment at 90°, with the theoretical inelastic differential cross section. We found

$$(d\sigma/d\omega)_{3^+}(90°)\simeq0.5\ \mathrm{mb/sr},$$

and

$$(d\sigma/d\omega)_{\mathrm{brkup}}(90°)=1.0\pm0.3\ \mathrm{mb/sr}.$$

These results show that a Coulomb excitation of the ^{6}Li core in the total reaction is not out of consideration.

In conclusion, the search for a real two-step process, involving the excitation of the 4.63-MeV state in ^{7}Li, has shown that this mechanism is negligible ($\sigma_{\alpha+t}\leqslant350\ \mu$b). However, the experiment has shown a strong selectivity of the ^{6}Li(3^+) $+n$ configuration in ^{7}Li. In this case the excited core is far enough from the residual nucleus so that it breaks into a free α particle and a free deuteron without absorption by the residual nucleus. The process is optimum for virtual excitation energy of 10.4 MeV in the projectile + target system. This experiment shows the effect of the projectile structure and the importance of coupled-channel effects in the transfer process.

One of us (J.L.Q.) acknowledges valuable discussions with Dr. R. M. Diamond, Dr. F. S. Stephens, and Dr. K. Nakai. He also thanks Mrs. R. Garret for her help in the initial data processing at Berkeley. We also thank Dr. Van Staden, Dr. P. Gil, and Dr. H. Sztark for their help during the last experiments in Heidelberg.

[1]J. L. Québert and H. Sztark, J. Phys. (Paris), Colloq. 32, C6-255 (1971).

[2]K. O. Pfeiffer, E. Speth, and K. Bethge, Nucl. Phys. A206, 545 (1973).

[3]P. J. A. Buttle and L. J. B. Goldfarb, Nucl. Phys. A176, 299 (1971).

[4]P. J. Siemens, J. P. Bondorf, D. M. E. Gross, and F. Dickmann, Phys. Lett. 36B, 24 (1971).

[5]
$$Q=(\epsilon_i-U_T)\left(\frac{bA}{aB-1}\right)+\frac{2\epsilon_i}{1+1/\sin(\theta_i/2)}\left(1-\frac{\rho}{R_T}\frac{z_fZ_f}{z_iZ_i}-1\right);$$

ϵ_i is the total energy in the entrance channel of the reaction $a(b+n)+A=b+B(A+n)$, $U_T(R_T)$ is the total Coulomb plus nuclear potential at which the transfer takes places and is roughly a constant, R_T is the distance of closest approach, $\rho=nR_a/a$ is the recoil effect with R_a the radius of a, and θ_i is the c.m. scattering angle.

[6]A. Winther and J. de Boer, in *Coulomb Excitation*, edited by K. Alder and A. Winther (Academic, New York, 1966).

[7]J. L. Quêbert and L. Marquez, Nucl. Phys. A126, 646 (1969).

[8]F. Eigenbrod, Z. Phys. 228, 337 (1969).

Quantum Electrodynamics in a Photon Sea

E. P. Tryon
Department of Physics and Astronomy, Hunter College of The City University of New York, New York, New York 10021

(Received 18 March 1974)

Thermal photons are present in every initial state, and nonthermal photons are present in many systems of interest. Furthermore, stimulated emission promotes the infrared divergence of quantum electrodynamics from logarithmic to an inverse power in a Planck distribution. I have calculated to order e^2 the background-photon corrections to the cross section for scattering a charged particle off an external Coulomb potential. I demonstrate the cancelation of infrared divergences, and derive a formal shift in the masses of charged particles. I interpret this shift, and discuss atomic spectra.

Standard treatments of quantum electrodynamics (QED) involve an important unphysical assumption—namely, that reactions take place in a vacuum. In reality, thermal photons are present in every initial state, and nonthermal photons are also present in many systems of interest.

For a Planck distribution, the photon-mode occupation number diverges like kT/ω as $\omega\to 0$ (where k denotes Boltzmann's constant, T the absolute temperature, and ω the angular frequency). This divergent behavior of the occupation number promotes from logarithmic to an inverse power the infrared divergence of photon-emission cross sections, thereby posing a new challenge to the finiteness of the theory. In addition to obvious academic questions, the possibility of new phenomena must be considered.

In this Letter, I analyze a simple example of QED in a photon sea. Specifically, I calculate to order e^2 the background-photon corrections to the cross section for scattering a charged particle off an external Coulomb potential. I demonstrate the cancelation of divergences in the total cross section, and derive a formal shift in the masses of charged particles. I interpret this shift, and discuss atomic spectra.

Let us begin by reviewing some elementary facts. When a boson creation operator $a^\dagger(q)$ [or annihilation operator $a(q)$] acts on a state with n bosons of momentum q, the effect is

$$a^\dagger(q)|nq\rangle=(n+1)^{1/2}|(n+1)q\rangle, \tag{1a}$$

$$a(q)|nq\rangle=n^{1/2}|(n-1)q\rangle. \tag{1b}$$

We shall render the photon modes discrete by quantizing in a box. The continuum limit is obtained by letting the volume V go to ∞, in which case a mode becomes a unit cell $(d^3x)(d^3q)=h^3$.

For a Planck distribution, the number of positive- or negative-helicity photons in a mode is given (with $\hbar=c=1$) by

$$\begin{aligned} n_\pm(q) &= [\exp(\omega/kT)-1]^{-1} \\ &\cong kT/\omega \text{ for } \omega\ll kT. \end{aligned} \tag{2}$$

Throughout this work, we assume the radiation field to be an eigenstate of the occupation numbers $n_\pm(q)$. Such a field is incoherent, with $\langle\vec{E}(\vec{x},t)\rangle=0$. The results should have qualitative validity, however, for coherent fields as well.

Now consider the scattering of a spin-zero charged meson off an external Coulomb potential. (The scattering of a Dirac particle will be discussed later.) We denote the meson mass by m, and its initial and final momenta by p and p', respectively, with $p^2=p'^2=m^2$. We denote the lowest-order S-matrix element by S_0, which yields an elastic cross section of order $Z^2\alpha^2$ for scattering a charge e off a static charge Ze (where α