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Observation of the α-Particle Breakup Process at $E_\alpha{}^{\mathrm{lab}} = 172.5$ MeV

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Double-differential cross sections $d^2\sigma/d\Omega\, dE$ have been measured for the $(\alpha, {}^3\mathrm{He})$ reaction on Ni isotopes at $E_\alpha{}^{\mathrm{lab}} = 172.5$ MeV. A distinct peak was found, having a half-width of ~ 40 MeV and a strongly decreasing intensity with increasing reaction angle. Theoretical evidence is provided to attribute this peak to the $(\alpha, {}^3\mathrm{He})$ stripping process into the continuum.

In connection with preequilibrium reaction theories, there has been growing interest in the study of continuous spectra of particles emitted in nuclear reactions. In the present investigation spectra of ^{3}He particles emitted in reactions induced by 172.5-MeV α particles on ^{58,60,62,64}Ni targets have been studied in the energy range from 50 to 160 MeV (lab). The experiment has been performed at the Jülich isochronous cyclotron JULIC in a 100-cm-diam scattering chamber. Two ΔE-E semiconductor telescopes were used, each consisting of a 1000-μm-thick commercial Si surface-barrier ΔE transmission detector and a Li-drifted Ge E detector of the side-entry type developed in the detector laboratory of the institute.[1]

In addition to the peaks corresponding to stripping to bound states (neutron transfer), the ^{3}He spectra show at forward angles a broad peak with a half-width of $\simeq 40$ MeV and which is centered around $E_{{}^3\mathrm{He}}{}^{\mathrm{c.m.}} = 122$ MeV (Fig. 1). Its intensity decreases by orders of magnitude with increasing

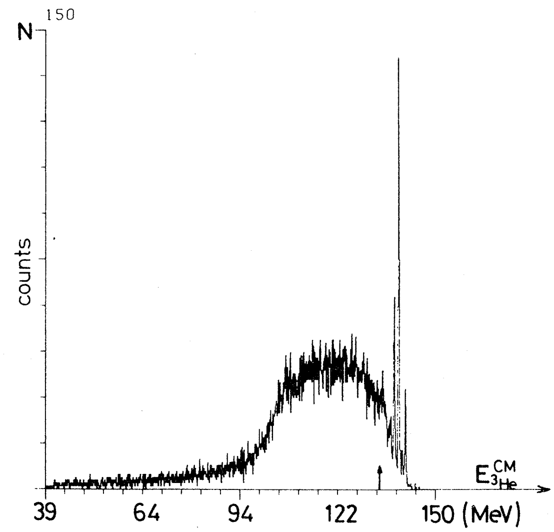

FIG. 1. ^{3}He spectrum from the ^{60}Ni(α, ^{3}He) reaction at $\theta_{lab} = 4.5^0$. The arrow indicates the three-body threshold.

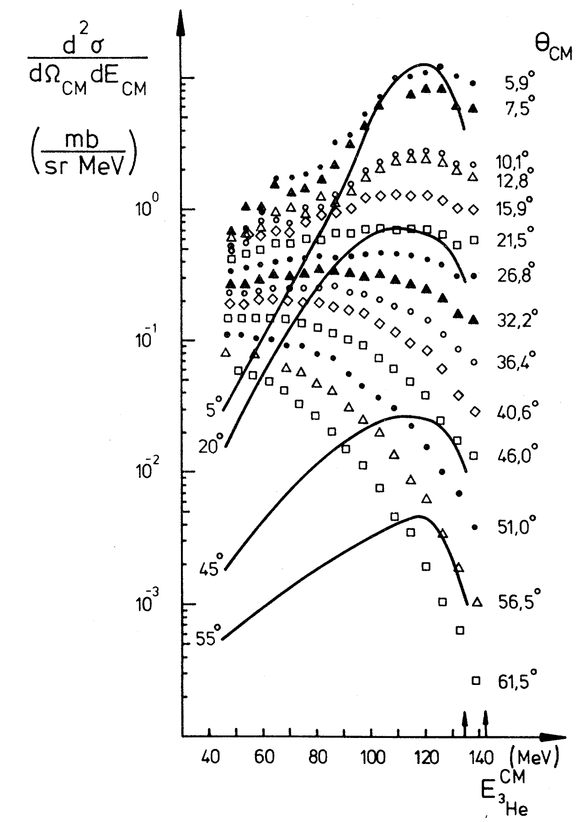

FIG. 2. Double-differential cross sections for the ^{62}Ni(α, ^{3}He) reaction. Full lines indicate theoretical calculations described in the text. The energies corresponding to the ground-state transition and to the three-body threshold are indicated by arrows. (The c.m. angles given for the experimental points depend slightly on the ^{3}He energy; however, the deviations are less than 1°, and therefore negligible for our purposes).

reaction angle. The energy of this peak is much higher than that expected for evaporation ($E_{^3He}^{c.m.} \simeq 15$ MeV). It is natural to assume that this broad peak is connected with some fast one-step process, namely the breakup of the α particle into a neutron and a ^{3}He particle on the edge of the nuclear potential.

Figure 1 shows the ^{3}He spectrum obtained from a ^{60}Ni target. The three distinct sharp lines on the high-energy side of the spectrum correspond to 0.068-MeV $1f_{5/2}$, 2.13-MeV $1g_{9/2}$, and 3.5-MeV $1g_{9/2}$ single-neutron states in ^{61}Ni. The strong intensity of these peaks can be explained by the angular momentum matching at the nuclear surface which favors $l_n = 4$ transfer: $l_n = L_\alpha - L_{^3He} \approx (k_\alpha - k_{^3He})R \approx 4$, where l_n, L_α, and $L_{^3He}$ are the angular momenta of the transferred neutron, the incoming α particle, and the outgoing helion at the nuclear surface, respectively. The radius of the target nucleus is R and k_α and $k_{^3He}$ are the corresponding wave numbers. The arrow in Fig. 1 indicates the upper energy limit for the stripping into the continuum. Below this limit the spectrum exhibits one characteristic broad maximum which we shall ascribe to the α breakup process. Similar ^{3}He spectra have been obtained for the other Ni isotopes.

In Fig. 2 the double-differential cross section $d^2\sigma/d\Omega_{c.m.}dE_{c.m.}{}^{^3He}$ for the ^{62}Ni(α, ^{3}He) reaction is shown. These cross sections were obtained by integrating the ^{3}He spectra in 6-MeV bins so that the discrete structures are averaged out.

The arrows indicate the energies corresponding to the ground-state transition and to the threshold of the free breakup process, respectively. As can be seen the breakup peak merges into the low-energy background at around 20°. We also notice that the cross section corresponding to large energy transfer falls off with increasing reaction angle less rapidly than that for small energy transfer. This may indicate the growing importance of multistep processes for ^{3}He particles emerging with lower energies. A similar behavior was observed for the cross sections of the ^{90}Zr(α, t) reactions at $E_\alpha = 140$ MeV for angles larger than 20° by Wu, Chang, and Holmgren.[2] These authors have also quite recently observed the breakup effect experimentally[3] and performed an analysis with the Serber model.[4]

It should be pointed out that the simple spectator-particle model[5] (only the neutron interacts with the target nucleus, and the corresponding off-shell T-matrix element is put constant) predicts the energy of the breakup peak at $E_{^3\mathrm{He}}{}^{\mathrm{c.m.}} = 104$ MeV. In this simplified spectator model, the width of the peak reflects the momentum distribution of the neutron bound in the α particle. It comes out at the right value, $\Gamma = 40$ MeV, when harmonic-oscillator wave functions are used for the α-particle internal state. The 20-MeV shift of the calculated peak position relative to the observed value can be partly explained by the influence of the Coulomb barrier, which increases the ^{3}He energy by about 13 MeV. Because of the strong binding energy of the neutron in the α particle ($Q = -20.6$ MeV) the breakup can occur only in the nuclear surface of the target nucleus where the gradient of the potential is large, at least of the order of (20.6 MeV)/R_α ($R_\alpha = 1.6$ fm is the radius of the α particle). This means that the distortion effects should be rather strong.

In order to treat distortion effects in the α and ^{3}He motion properly, distorted-wave Born-approximation calculations for breakup were performed. These include the "elastic" breakup process[6] of the type $\alpha + \mathrm{Ni} \to {}^3\mathrm{He} + n + \mathrm{Ni}_{\mathrm{g.s.}}$ and also "inelastic" breakup processes. The later arise from any inelastic process which the neutron and the target nucleus may produce in the final state. Thus the inclusive (α,^{3}He) cross section is written in the form[7]

$$\frac{d^2\sigma}{d\Omega_{\mathrm{c.m.}}\, dE_{\mathrm{c.m.}}{}^{^3\mathrm{He}}} = \frac{2\pi}{\hbar v}\rho(\mathrm{phase}) \sum_{l_n m_n} \left(|T_{l_n m_n}|^2 + \frac{\sigma_{l_n}{}^{\mathrm{reac}}}{\sigma_{l_n}{}^{\mathrm{el}}} |T_{l_n m_n} - T_{l_n m_n}{}^0|^2 \right), \tag{1}$$

where ν is the relative velocity in the initial state, ρ(phase) the phase-space factor, and $\sigma_{l_n}{}^{\mathrm{el}}$ and $\sigma_{l_n}{}^{\mathrm{reac}}$ the total neutron-target elastic and reaction cross sections in the l_nth partial wave, respectively. The matrix elements $T_{l_n m_n}$ which describe the elastic breakup are

$$T_{l_n m_n} = D_0 \int \chi_{^3\mathrm{He}}{}^{(-)*} f_{l_n}(R) Y_{l_n m_n}(\hat{R}) \chi_\alpha{}^{(+)} \Lambda(\boldsymbol{R})\, d^3\boldsymbol{R}. \tag{2}$$

Here f_{l_n} denotes the radial wave function of the neutron in the optical-model potential. The quantity $T_{l_n m_n}{}^0$ is a corresponding matrix element with f_{l_n} replaced by the spherical Bessel function j_{l_n}. It describes the breakup process in the absence of a neutron-target interaction. We take finite-range effects into account by means of the local energy approximation[6] in the factor $\Lambda(R)$. D_0 denotes the strength constant. We use a value consistent with those given by Shepard, Zimmerman, and Kraushar,[8] i.e., $D_0 = 390$ MeV fm$^{3/2}$, who systematically studied the (^{3}He,α) reaction. They found for bound states that the local energy approximation takes the finite-range effects into account in a reliable way.

The results of our calculations are shown in Fig. 2. The α-Ni optical-model potential parameters were obtained by fitting the elastic cross sections, measured simultaneously[9] with the (α,^{3}He) spectra ($V = 108.6$ MeV; $r_v = 1.23$ fm; $a_v = 0.85$ fm; $W_v = 20.73$ MeV; $r_w = 1.56$ fm; $a_w = 0.766$ fm). For the ^{3}He-Ni potential, the energy-independent parameter set of Fulmer, Hafele, and Foster[10] was used, while for n-Ni we took the Becchetti-Greenlees[11] potential. Other choices for the ^{3}He and n potentials gave similar results. We interpret these calculations (Fig. 2) in the following way. In the energy region of the broad peak, cross sections calculated with commonly accepted parameters are in reasonable agreement with experiment. The strong decrease in the angular distribution over three orders of magnitude is well reproduced. This supports the direction nature of the process and the applicability of our theoretical model.

In the deep-inelastic region $E_{^3\mathrm{He}} \leq 90$ MeV our calculations underestimate the (α,^{3}He) cross section by at least one order of magnitude. This is expected, since the calculation did not include multistep processes. These become more important for lower ^{3}He energies. For these processes a multistep direct[12] or a precompound analysis[13] using statistical concepts seems most appropriate.

Because only ^{3}He is observed, various partial waves of the neutron add up incoherently. In Fig. 3 the contributions of different l_n values to the breakup peak at $\theta_{\mathrm{c.m.}} = 5°$ are shown separately. It is seen that higher l_n values dominate the peak with decreasing ^{3}He energy. Thus the reaction selectively excites favored l_n values. This selectivity is due to the so-called stripping l-enhancement factor[14] and makes the (α,^{3}He) reaction a useful tool for extending studies of the single-neutron strength distribution in nuclei made so far by means of the (d,p) reaction[15] towards high-

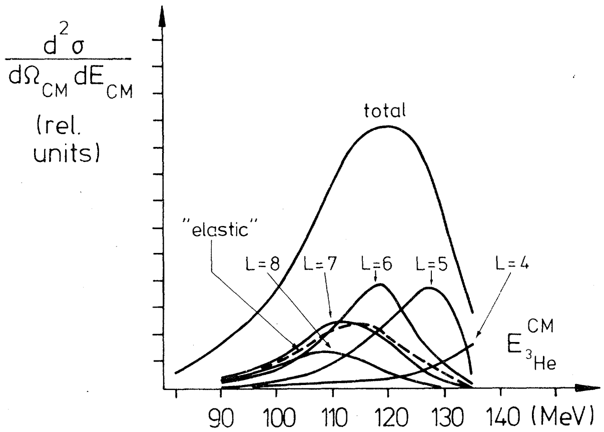

FIG. 3. Calculated contributions of various neutron partial waves to the total cross section for the breakup process (full lines). The elastic break-up contribution (leaving the target nucleus in its ground state) is indicated by the dashed line. $\theta_{c.m.} = 5°$.

er l_n values. We note also from Fig. 3 that the elastic breakup accounts only for about 25% of the total inclusive cross section.

Another interesting aspect of this reaction is connected with studies of the transition region between stripping to bound and unbound states.[14] In the present work the transition region is far away from the energy region where compound or complicated pre-equilibrium processes dominates so that direct reaction theories are applicable. As can be seen from Fig. 2 the calculated cross sections are somewhat lower than the experimental ones in the vicinity of the three-body threshold. This discrepancy is probably due to the poor knowledge of the $l_n = 4$ and $l_n = 5$ single-neutron strenght distribution around $E_n = 0$. The present calculations use a neutron potential[11] which was determined from elastic and total reaction cross sections. These latter data, however, are insensitive to details of the neutron potential for higher l_n values when the neutron energy approaches zero. If the neutron optical model includes absorption at $E_n = 0$, it can be seen that the inclusive cross section, Eq. (1), tends to a constant limit, generally different from zero.

In conclusion we stress that our calculations with commonly accepted parameters give the correct absolute value of the cross section at the observed peak. This supports the breakup mechanism as an explanation of the observed peak.

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