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Dissociation of 15-MeV/nucleon ^{20}Ne in collisions with ^{197}Au: Direct reactions leading to particle-emitting states

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Energy and angular correlations between α particles and quasielastic projectilelike fragments produced in the $^{20}\mathrm{Ne}+^{197}\mathrm{Au}$ reaction at 290 MeV show that the α particles are sequentially emitted from long-living states of primary fragments populated in direct reactions such as inelastic scattering and few-nucleon transfer. An analysis of the energy-integrated angular correlation leaves no notable cross section for a direct breakup or uncorrelated particle emission.

[NUCLEAR REACTIONS $^{20}\mathrm{Ne}+^{197}\mathrm{Au}$, $E_{\mathrm{Ne}}=290$ MeV, measured energy and angular correlations of α particles in coincidence with ^{15}N, ^{16}O. Deduced reaction mechanism of quasielastic projectile dissociation.]

Nuclear reactions involving excited states of the reaction fragments can generally be subdivided into the primary process and the subsequent γ decay or light-particle emission. If the lifetime of the primary fragments becomes comparable to their interaction time—the extreme being the direct fragmentation into the continuum—the fragmentation products may suffer final-state interaction. This will deteriorate the clean energy and angular correlation of coincident events characterizing a sequential process. With heavy-ion reactions on light target nuclei the importance of sequential emission of fast α particles has been shown.[1] However, it has been demonstrated in a recent study of the dissociation of ^{7}Li into α particles and tritons at 10-MeV/nucleon bombarding energy that direct breakup processes are effective on heavy target nuclei.[2] With heavier projectiles, ^{14}N, ^{16}O, ^{20}Ne, at comparable or higher bombarding energy on medium to heavy target nuclei, contradictory interpretations of measured energy and angular correlations are reported. While some claim to have observed evidence for direct breakup[3] and uncorrelated emission[4,5] others find similar data to be consistent with the assumption of a sequential decay.[6,7] This obvious discrepancy is at least partially due to experimental difficulties: With the limited energy resolution, long-lived excited states are not easy to identify if the primary process is not very selective. Furthermore, both reaction types may not be distinguished because of similar kinematic conditions. Last but not least, very small target contaminants cause severe background problems, especially at correlation angles opposite to the beam axis. Therefore, in order to check the relative importance of the different dissociation phenomena we had to endeavor to perform a careful experiment, characterized by good energy and angular resolution, large angular range, a clean heavy target, ^{197}Au, and an appropriate projectile, ^{20}Ne. The cluster structure of the ^{20}Ne ground state may, similar to the case of ^{7}Li, favor its direct breakup into α particles and ^{16}O.

The experiment was carried out using the 290-MeV ^{20}Ne beam of the VICKSI accelerator at the Hahn-Meitner-Institut, Berlin. Light and heavy fragments were detected by ΔE-E solid-state detector telescopes. Inclusive light- and heavy-ion cross sections were measured over the angular range from 8° to 50° yielding a total cross section for fast α particles ($E_\alpha \geq 25$ MeV) of (1 ± 0.1) b and (950 ± 100) mb for projectilelike fragments (F through Li isotopes). Coincident data were taken between heavy ions around the grazing angle of 25° at $\theta_{\mathrm{HI}}=15°$, 21°, 27°, and 34° and α particles in the forward hemisphere. Precise correlations around the axis of the heavy

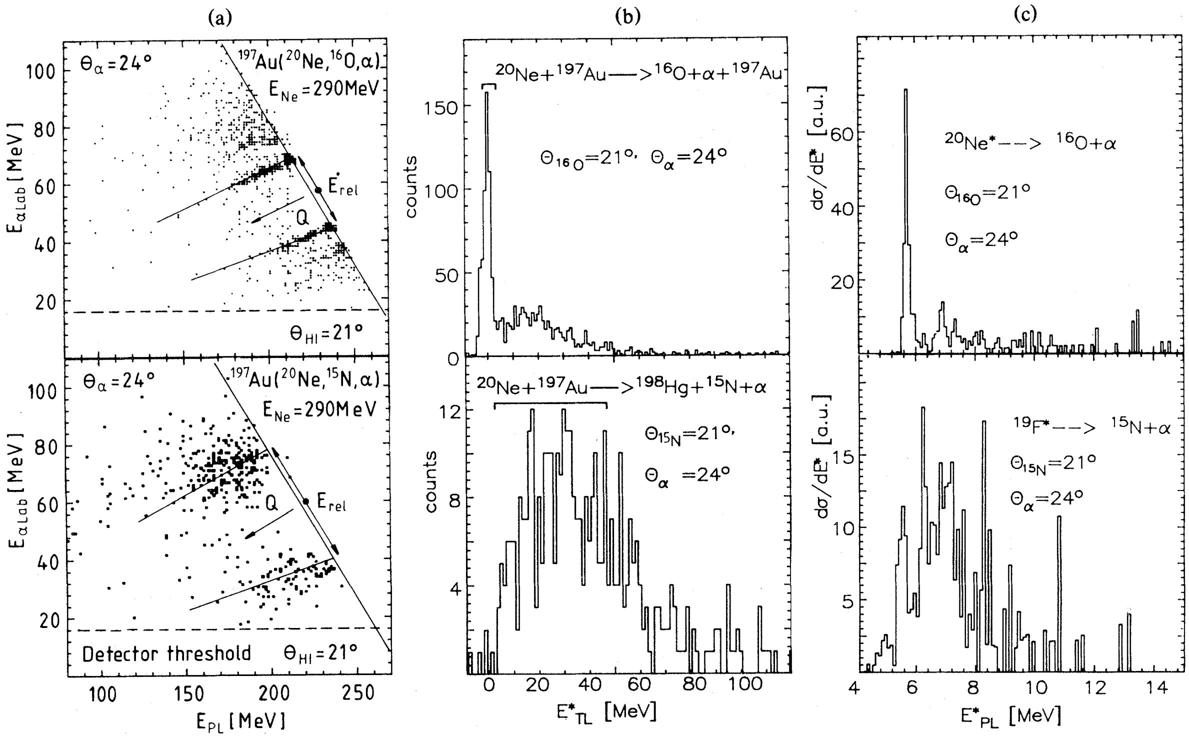

FIG. 1. Distribution of events in the $E_{\rm HI}$-E_α plane. Solid lines mark the border given by the total reaction Q value and loci of constant relative energies between α particles and heavy ions (a). Excitation energy spectra of the targetlike (b) and projectilelike fragments (c). The latter were obtained from the spectra of relative energies in the range of $E^*_{\rm Tl}$ indicated by bars in (b) taking the Jacobian $\partial(E_\alpha, E_{\rm HI}, \Omega_\alpha, \Omega_{\rm HI})/\partial(E^*_{\rm Tl}, E^*_{\rm Pl}, \Omega_{\rm Pl}, \Omega_{\rm HI\text{-}\alpha})$ into account.

fragment were measured with three heavy-ion counters and two α-particle counters with apertures between 0.2° to 1.0° alternatively mounted on a detector bank in angular intervals of 3° to 3.5°. Additional α-particle counters could be moved independently in the reaction plane. Strong coincident cross sections were observed for all projectilelike fragments with $X \leq 8$. Detailed analyses are presented for the isotopes ^{16}O and ^{15}N which have the advantage that their first excited states (above 5 MeV) cannot be populated via sequential decay except for rather high excitations of the primary fragments. This eliminates the complication of complex or quasicontinuous decay spectra. From their representation in the E_α-$E_{\rm HI}$ plane at small relative angles [Fig. 1(a)] it can be recognized that the coincident events are concentrated at discrete relative energies between α particles and the heavy fragments in their ground states, i.e., at discrete excitation energies $E^*_{\rm Pl}$ [Fig. 1(c)] of the composite heavy-ion—α-particle systems ^{20}Ne* and ^{19}F*. This allows us to attribute the total reaction Q value to the excitation energies of the targetlike fragments $E^*_{\rm Tl}$ as shown in Fig. 1(b). For ^{16}O-α events roughly one-half of the strength is concentrated in a sharp peak which is, within the experimental resolution, consistent with zero energy transfer to the target nucleus. The one-half is spread out over a broad bump peaking around 20 MeV excitation. For ^{15}N-α events, the distribution of energy transfer to the targetlike nucleus is broader, peaking around 25 MeV. The relative-energy spectra in terms of excitation energies of ^{19}F* and ^{20}Ne* for energy transfers to the targetlike fragments marked by bars in Fig. 1(b), show a pronounced structure indicating that the α particles are emitted from distinct states or groups of states populated in the first step of the reaction. They are also the source of emission for all α-particle angles measured as shown by the concentration of events on ellipses around the velocity vectors of the ^{16}O and ^{15}N if the coincident cross section is displayed in the plane spanned by the velocity components of the α particles parallel and perpendicular to the beam axis [Fig. 2(a)]. The broader distribution for the ^{15}N arises from the integration over a broader range of excitation of the targetlike recoil. The same behavior is found for events at higher excitation of the target nucleus in the case of ^{16}O $+\alpha$ (not shown).

Energy-integrated angular correlations expected from the decay of the states observed in the narrow detector geometry [Fig. 1(c)] can, in principle, be calculated: For the case of pure sequential emission the

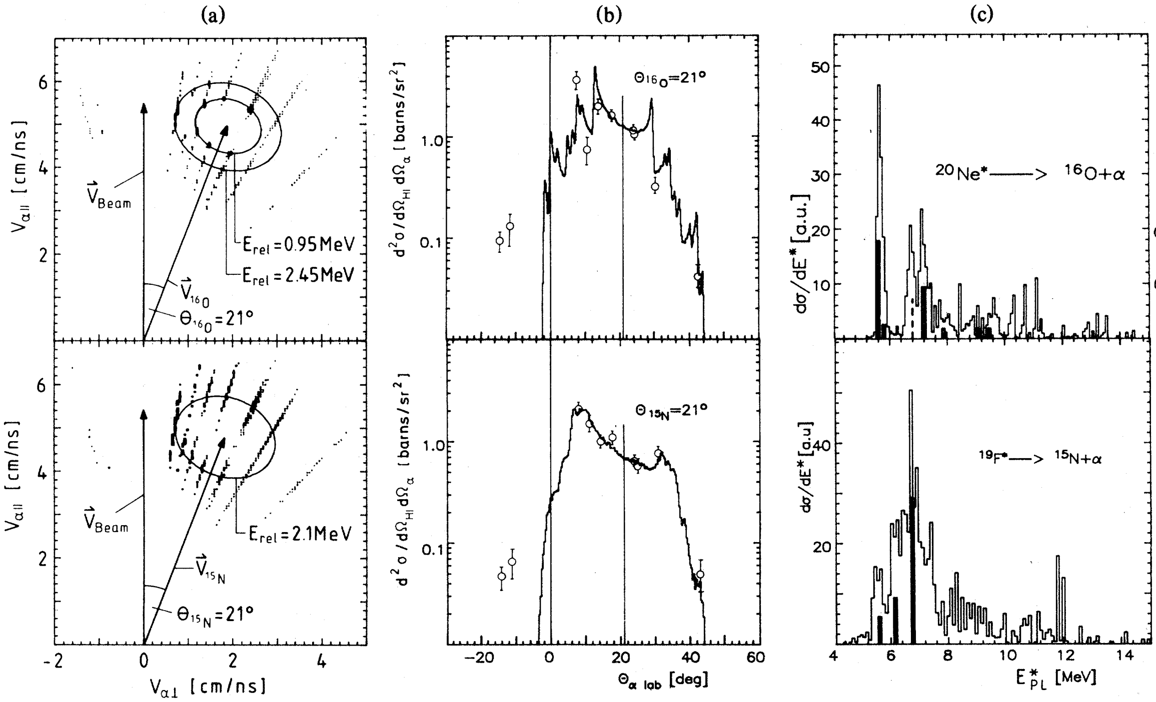

FIG. 2. Velocity distributions of α particles for fixed heavy-ion angles. Ellipses correspond to loci of constant relative energies (a). Energy-integrated double differential cross sections. Histograms show the predictions of the Monte Carlo calculations (b). Excitation energy spectra for ^{20}Ne* and ^{19}F* obtained from summation of all angles on the right-hand side of the beam axis taking the corresponding Jacobian into account, in comparison with results from light-ion induced reactions (c). Bars indicate the strengths $\beta_L{}^2$ from ^{20}Ne(p,p') and C^2S from ^{20}Ne$(d,{}^3$He$)^{19}$F (Refs. 9 and 10). The dashed line marks the O$^+$ state at 6.72 MeV which is also strongly excited in ^{20}Ne(p,p'). In all figures the same gates on $E^*_{\rm Tl}$ [Fig. 1(b)] were applied.

angular correlation in the laboratory system, $d^2\sigma/d\Omega_{\rm HI}\,d\Omega_\alpha$, for a fixed heavy-ion angle is given by the integral of the cross section of the primary fragments for various excitation energies $E^*_{\rm Tl}$ and $E^*_{\rm Pl}$, multiplied with the in-plane angular correlation $W(\Phi_{\alpha-\rm HI})$ in the center-of-mass system of the primary fragment contributing to a fixed heavy-ion angle. For the sake of simplicity the calculations were performed using a Monte Carlo code with the following approximations: (i) Excitation energies $E^*_{\rm Pl}$ and $E^*_{\rm Tl}$ and their relative strengths are taken from the experiment at small relative angles. (ii) The variation with angle of the primary angular distribution $d\sigma/d\Omega_{\rm Pl}$ is independent of $E^*_{\rm Pl}$ and $E^*_{\rm Tl}$ and is modeled from the inclusive ^{19}F angular distribution. (iii) Correlations between $E^*_{\rm Pl}$ and $E^*_{\rm Tl}$ are neglected. (iv) The angular correlation $W(\Phi_{\alpha-\rm HI})$ is isotropic which is the classical limit if all transferred angular momenta are oriented perpendicular to the reaction plane.[8] The calculations normalized to the data at $\theta_\alpha=24°$ fully exhaust the measured angular correlations [Fig. 2(b)].

The small cross section opposite to the beam axis which is not reproduced could be considered as an upper limit of contributions of uncorrelated emission centered around the beam axis.[4,5] In terms of sequential emission it would correspond to weak but high excitations of the primary fragments (≈ 18 MeV) decaying into the ground states of the daughter nuclei. The detection of these events was beyond the count statistics and the stopping power of the detectors in the narrow geometry and thus could not be included in the calculations. A straightforward qualitative understanding of the primary process can be found from the comparison of the states of the projectilelike fragments populated strongly in this experiment with those seen predominantly in light-ion data of inelastic scattering[9] and proton pickup[10] from the projectile nucleus ^{20}Ne. They show a nice correspondence in selectivity and relative strengths as seen in Fig. 2(c). This indicates that the primary processes can be looked at as direct reactions such as inelastic scattering and few-nucleon transfer. For ^{20}Ne* in particular, the strength distribution differs from that in α transfer on ^{16}O which one would expect for the case of direct breakup with final-state interaction between the projectile fragments.[11]

Thus, from the representation of these data involving low (^{16}O) and high (^{15}N) excitation of the targetlike nucleus we could exclude notable contributions of exotic mechanisms, but rather show that the sequential α decay of states populated via direct reactions describe the observed energy and angular correlations. Qualitatively we find the same results for the other angles and other isotopes which leave the target with velocities slightly below the beam velocity. The very importance of these mechanisms is emphasized by an estimate of the α multiplicity which can be obtained if the width of the out-of-plane correlation (not measured) is known. With a half-width angle of $\approx 30°$ estimated from the classical limit[8] for the L values in question of $L \approx 2-4$ this yields a lower limit of the α multiplicities for ^{16}O and ^{15}N at 21° of 0.5 and 0.7, respectively. These numbers increase with larger heavy-ion angles and lower masses of the projectilelike fragments. This means that at least 60% of the total inclusive yields of quasielastic projectilelike fragments are secondary products. It also accounts for 60% of the total fast-α-particle cross section.

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[11]W. D. Rae *et al.*, Phys. Lett. 105B, 417 (1981). The arguments presented in this reference for the presence of direct (termed "incoherent") breakup are not stringent. The continuum of relative α-^{12}C energies observed (only) for more negative three-body Q values may also be due to sequential breakup, since the number of possible $^{16}O^* \rightarrow {}^{12}C^* + \alpha$ transitions strongly increases, and the selectivity decreases, for $Q_3 \leq -11.6$ MeV where the first 2+ state of the ^{12}C projectile fragment *or* target becomes accessible.