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Search for Fragment Emission from Nuclear Shock Waves*

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Energy spectra and angular distributions have been measured of ^{3}He and ^{4}He fragments emitted from Ag and U targets, bombarded with 2.7-GeV protons, and 1.05-GeV/nucleon α particles and ^{16}O ions. All cross sections increase dramatically with projectile mass. No narrow peaks are found in the angular distributions or in the energy spectra.

For central collisions of nuclei at relativistic energies, recent theoretical investigations[1-6] have focused on the question of how large amounts of energy and momentum are transferred from projectile to target nucleons, and on the early events in the evolution of hot, high-density regions as thermal equilibrium is approached. In particular, the formation of squirts of nuclear matter, or of nuclear shock waves[7] carrying large transverse momentum and compressional energy, has been predicted.[2-5] These would be formed in central collisions if the projectile velocity exceeds the nuclear sound velocity $\nu_0 \approx 0.2c$. The models are in disagreement about the angles in the lab system at which emission should occur, some predicting[3,4] a narrow peak at angles ranging from 25° to 45° depending systematically on the incident energy while others anticipate a broad range of forward angles for the fragments.[5] There is agreement, however, as to the expectation that such processes should have a high fragment multiplicity, with energies ranging far above the evaporative domain.

In an experiment with Lexan foil detectors, Crawford *et al.*[8] investigated fragments resulting from the interaction of a 2.1-GeV/nucleon ^{12}C beam with Au. Nonevaporative tails in the spectra were observed but angular distributions showed no significant peaks. Kullberg and Otterlund[9] have studied the emission of α particles produced in nuclear emulsions by heavy cosmic-ray nuclei. The angular distributions deviate markedly from evaporation-model predictions at angles around 45°. The authors observe that the high-energy α particles result primarily from high-multiplicity (star event) target fragmentations.[10]

The most provocative experiment thus far is a recent study of prong angular distributions of star events produced in AgCl crystals irradiated with 0.87-GeV/nucleon ^{16}O ions by Baumgardt *et al.*[3] They report the observation of narrow peaking in $d\sigma/d\theta$ at 40°, with an angular width of about 20° full width at half-maximum (FWHM). The prongs analyzed in that experiment are due to protons less than 28 MeV and He nuclei less than 200 MeV/nucleon, with no further discrimination with respect to energy and isotope. The peak is only pronounced when data with large prong multiplicity are selected.

We have therefore undertaken a study at the Bevalac of target-fragment energy spectra and angular distributions with a ΔE-E counter telescope that would identify He fragments with $15 \leq E \leq 150$ MeV/nucleon. The beams used were 2.7-GeV protons, 0.7- and 1.05-GeV/nucleon α particles, and 1.05-GeV/nucleon ^{16}O ions. Average particle fluxes were 10^8 particles per beam burst. Targets of natural silver and uranium, about 200 to 300 mg/cm^2 thick, were mounted in a scattering chamber equipped with a detector telescope consisting of a 1-mm-thick Si transmission counter as a ΔE detector, and a 5-cm-thick plastic scintillator (Pilot B) coupled to a 2.5-cm-diam phototube as an E detector. The telescope was mounted 25 cm from the target and subtended a solid angle of 5 msr.

The energy calibration of the spectra was obtained for each kind of particle from the ΔE signals in the surface-barrier detector by use of the known relation between energy loss in the ΔE counter and total kinetic energy. The overall energy resolution was better than 5%. The accessible energy range for ^3He and ^4He ions stopped in the second detector was 20 to 95 and 15 to 80 MeV/nucleon, respectively. However, because of the good separation of ^3He and ^4He branches in the ΔE-E plot, it was possible to identify ^3He particles that were not completely stopped, and to follow their spectra up to about 160 MeV/nucleon.

The beam intensities were monitored[11] with an ionization chamber, with the assumption that its output is proportional to Z^2. The relative cross sections from the proton, ^4He, and ^{16}O beams on the same target should be accurate to better than 20%. The overall normalization of the absolute-cross-section scale was determined within ± 50% by matching the present data to spectra obtained previously in the vicinity of the low-energy evaporation peaks.[12]

Spectra are shown in Fig. 1 for ^3He and ^4He emission at 20° in the lab system from a U target bombarded with several projectiles and energies. For energies above 50 MeV/nucleon, the cross sections increase by more than an order of magnitude as the projectile changes from p to ^4He, and from ^4He to ^{16}O. The ^3He spectrum from $^{16}O + U$ is remarkably flat, with cross sections above 1 mb/MeV sr even at 150 MeV/nucleon.

A comparison of ^3He and ^4He double-differential spectra from the $^{16}O + U$ interaction is shown in Fig. 2. The ^4He spectra decay much faster towards higher energies than do the ^3He spectra, with the latter showing higher cross sections above about 30 MeV/nucleon. It is obvious that the spectra cannot be understood by a simple evaporation process because the "nuclear temperatures" (60 MeV for ^3He, 38 MeV for ^4He) are far too high.

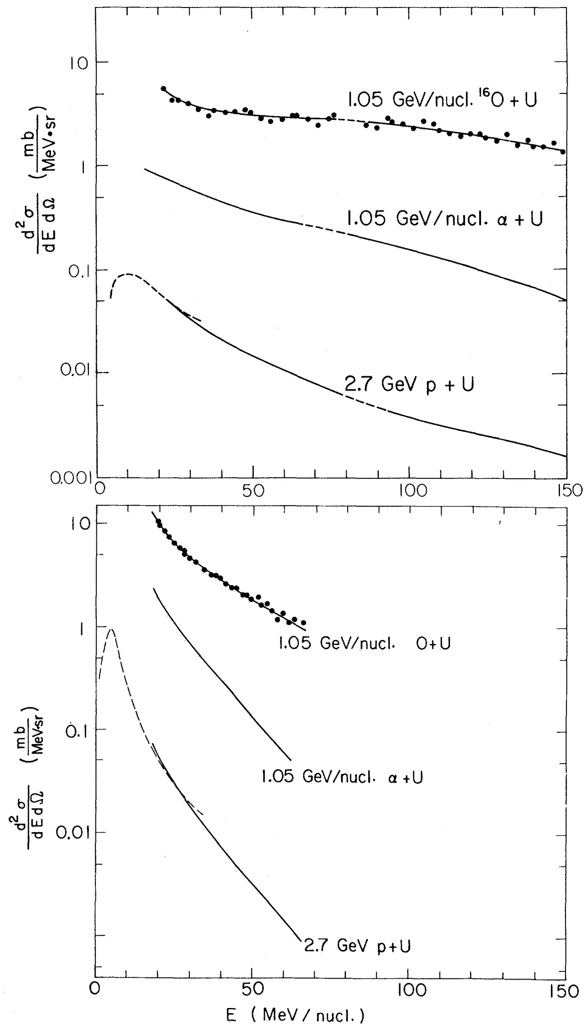

FIG. 1. Comparison of ^3He (upper part) and ^4He (lower part) spectra at 20° (lab) obtained upon bombardment of a uranium target with 2.7-GeV protons and with 1.05-GeV/nucleon α particles and ^{16}O ions. The data points are shown for the $^{16}O + U$ spectra. For $p + U$ dashed curves are shown for the low-energy evaporation spectra obtained previously (Ref. 12).

From Fig. 2 it is clear that the angular distributions do not show pronounced maxima. At about 20 MeV/nucleon the differential cross sec-

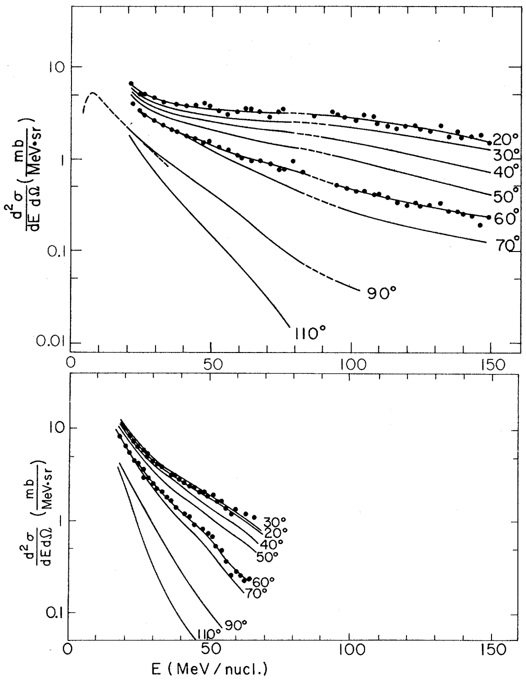

FIG. 2. Double-differential cross sections for ^{3}He (upper part) and ^{4}He (lower part) produced by 1.05-GeV/nucleon ^{16}O ions on uranium as a function of laboratory angle. Data points are shown at 20° and 60° to indicate the statistical quality of the data.

tions are only somewhat forward peaked, but at higher energies they are strongly forward peaked. For ^{3}He produced from ^{16}O + Ag, the angular distributions are shown in Fig. 3 for four successive bins of energy. We have plotted $d\sigma/d\theta = (d\sigma/d\Omega)\sin\theta$ here only in order to facilitate a comparison with the data of Baumgardt *et al.*[3] The peak in $d\sigma/d\theta$ has a width of about 60° FWHM; its position shifts from 58° in the low-energy bin to about 30° above 100 MeV/nucleon where the angular distributions show little further change in shape. The same behavior is observed for all other combinations of target, projectile, and reaction product. No narrow peaking comparable with the 20° width observed by Baumgardt *et al.* is found. If one assumes the correspondence reported by Kullberg and Otterlund[9] between high-energy He emission and high prong multiplicity, our data are in disagreement with those of Baumgardt *et al.* concerning the shape of the angular distributions. The angular distributions, as $d\sigma/d\Omega$, integrated over all energies detected in this experiment are given in Fig. 4. They showed forward peaking with leveling off towards angles $\theta \leq 40°$. The preliminary numerical calculations[5]

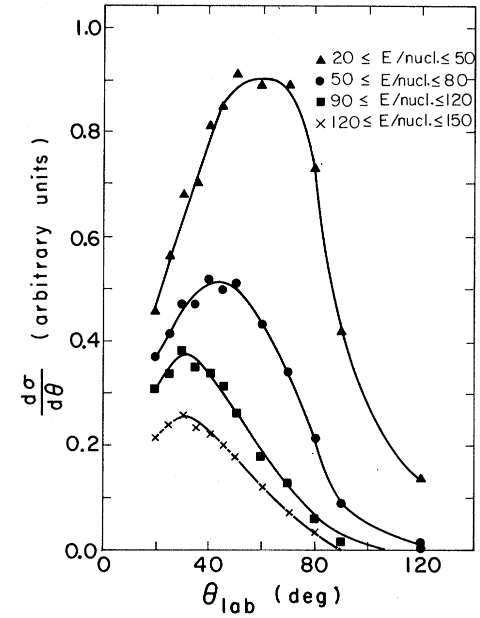

FIG. 3. Differential cross sections per unit angle, $d\sigma/d\theta$, of ^{3}He fragments emitted in various energy domains between 20 and 150 MeV/nucleon from ^{16}O + Ag at 1.05-GeV/nucleon incident energy.

of the two-dimensional relativistic hydrodynamics for the ^{16}O + Ag interaction are in qualitative agreement with these angular distributions, but the energy spectra do not agree.

Even though our data are not selected for high-multiplicity events we may still compare our absolute cross sections to those of Baumgardt *et al.* For their 20°-wide peak at 40° they report[13] $d\sigma/d\Omega = 0.7$ b/sr. It would be difficult to hide such a peak under the smooth curves in Fig. 4

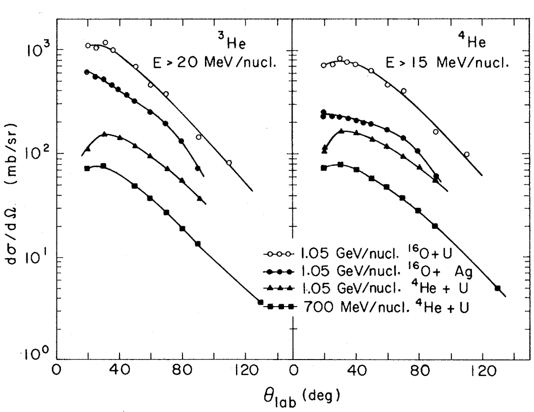

FIG. 4. Angular distributions of ^{3}He and ^{4}He fragments observed with ^{4}He and ^{16}O projectiles on Ag and U targets.

for 1-GeV/nucleon ^{16}O on Ag. In addition, if their cross section were spread uniformly over their observable energy range of 200 MeV/nucleon, $d^2\sigma/d\Omega\, dE$ would be about 1 mb/MeV sr. Our curves for the Ag target (like those in Fig. 2 but down by a factor of $2\frac{1}{2}$) are smooth in both energy and angle, and at 40° drop below this value at 35 and 60 MeV/nucleon for ^{4}He and ^{3}He, respectively. Thus we may conclude, without an any assumptions about high-multiplicity stars, that the events of Baumgardt *et al.* are not dominantly due to high-energy He nuclei.

In conclusion, our data present evidence for the nonevaporative emission of ^{3}He and, to a somewhat lesser extent, ^{4}He products in collisions between relativistic heavy ions. The cross sections for these high-energy products are two to three orders of magnitude higher than those found for proton-induced reactions at comparable incident velocity.[14] This points towards a cooperative mechanism that cannot be explained by geometrical considerations or by an independent superposition of nucleon-induced knockon cascades.

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Detection and Lifetime Measurement of Rb-He Quasibound Molecules*

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Quasibound Rb-He Van der Waals molecules have been observed through their influence on the electron spin relaxation of optically pumped Rb^{85} and Rb^{87}. The natural lifetime of the complex has been measured to be 6×10^{-10} sec.

Atomic-beam and optical-pumping experiments have yielded considerable information on the properties of bound Van der Waals molecules formed in three-body collisions of alkali-metal atoms with noble-gas atoms.[1-3] Two-body or three-body collisions of alkali-metal with noble-gas atoms also should lead at times to the formation of molecular complexes which are quasibound, that is, to molecular states which have energies that are positive but less than the centrifugal-barrier potential.[4-7] In this Letter we report the first observation of a Rb-He quasibound molecular complex, together with an experimental determination of its mean lifetime