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Target-A Dependence of Light-Ion Emission from Reactions Induced by 100-MeV/u ^{16}O

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The target-A dependence of cross sections for emission of energetic $Z = 1, 2$ particles from 100-MeV/u ^{16}O on Al, Ni, Sn, and Au targets is found to vary from an $A^{1/3}$ dependence at small angles to $\approx A^{2/3}$ at $\theta > 45°$, suggesting a smooth transition from peripheral to central collisions. The A dependence of ^{2}H and ^{3}H yields indicate that target neutrons contribute to the formation of these particles. Velocity and temperature parameters of a heated, moving source are given for projectile energies from 7.5 to 147 MeV/u.

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Recent studies[1] of light-ion emission at angles greater than 32° using 86-MeV/u ^{12}C projectiles on various target masses (A_T) indicated that the high-energy proton yields increased approximately as $A_T^{2/3}$. This is in sharp contrast to the much weaker target mass dependence reported at 8° and 20° using 13-MeV/u ^{16}O projectiles.[2] The present studies examine the question of target mass dependence over a broader angular range than was reported in Ref. 1.

The measurements were made with ^{16}O beams from the Lawrence Berkeley Laboratory Bevalac. Natural-abundance targets of aluminum (26 mg/cm^2), nickel (43 mg/cm^2), tin (57 mg/cm^2), and gold (55 mg/cm^2) were bombarded with 100-MeV/u projectiles. Spectra were also obtained, for selected targets, at 50- (Ni) and 147-MeV/u (Ni, Au) projectile energies as part of a systematic study of the beam-energy dependence. Particles with $Z = 1, 2$ were detected in telescopes consisting of 1000-μm Si (ΔE) and 12.7-cm-long NaI(Tl) (E) detectors placed at 6°, 12°, 18°, 24°, 45°, 85°, 115°, and 155° in the laboratory. The energy calibrations of the detectors were obtained by placing them directly into low-intensity beams of 200-MeV deuterons and 400-MeV alpha particles, using suitable absorbers to obtain several calibration points with each beam. These data were also used to obtain detector efficiency calibrations for deuterons and alpha particles. Published[3] efficiency corrections were used in analyzing the proton data.

Typical proton spectra, obtained at 12° and 85°, are displayed in Fig. 1. At small angles, the spectra are observed to peak near energies corresponding to the projectile velocity, while at larger angles an exponential falloff is obtained. At all angles studied, the spectral shapes are

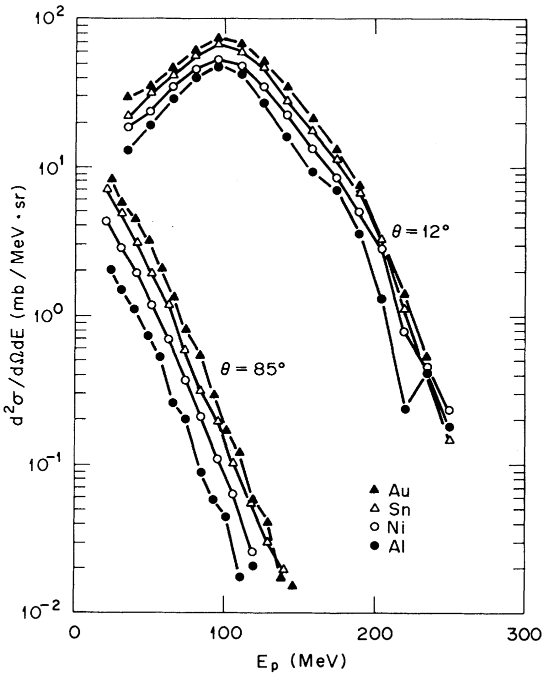

FIG. 1. Proton inclusive spectra from bombardment of various targets with 100-MeV/u ^{16}O projectiles.

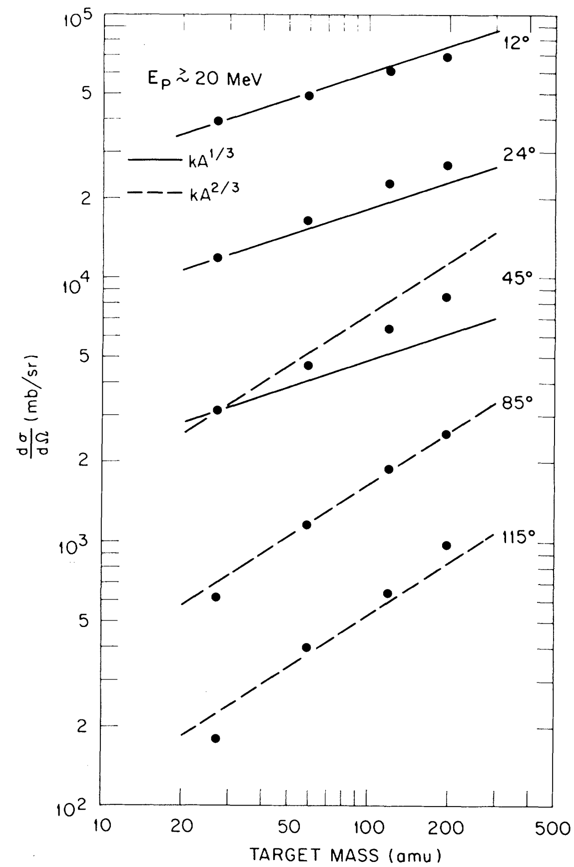

FIG. 2. Energy-integrated yields of protons produced in the bombardment of Al, Ni, Sn, and Au targets with 100-MeV/u ^{16}O projectiles. Solid and dashed lines display the slopes expected for $A^{1/3}$ and $A^{2/3}$ mass dependence, respectively.

virtually independent of the target mass. This is different from the results reported in Ref. 1 where proton spectra measured at 90° were reported to have steeper slopes for light (C, Al, Cu) than for heavy (Ag, Au) target nuclei.

The energy-integrated cross sections for protons having energies greater than the lower detection limit ($\approx$20 MeV) are plotted in Fig. 2. The cross section is observed to increase with target mass approximately as $A_T{}^x$ where x increases from $\approx\frac{1}{3}$ at small angles to $\approx\frac{2}{3}$ at angles of larger than 45°. This change in target mass dependence with increasing angle is found to be nearly independent of the lower-energy cutoff used in the cross-section integration. The cross sections for emission of composite light ions show similar target mass dependences, although the variation of the exponent with angle tends to be more rapid than for protons. In addition, the energy-integrated cross sections for deuterons and tritons increase more rapidly between Ni and Sn, with the discontinuity being less pronounced for high-energy (> 200 MeV) than for low-energy ($\approx$40–200 MeV) particles. This effect seems to be related to N/Z of the target and suggests that target neutrons make a substantial contribution to the formation of lower-energy deuterons and tritons produced in 100-MeV/u ^{16}O-induced reactions.

The observed behavior of light-particle emission with respect to the mass of the target nucleus is consistent with various models which have been suggested in the literature. The particles emitted at small angles, whose spectra peak at E/A near that of the projectile $[E/A \approx (E/A)_{\rm proj}\cos^2\theta]$, are probably due primarily to projectile fragmentation as suggested, for example, for ^4He and ^{20}Ne projectiles.[4] Such particles are emitted in reactions in which there is little loss of kinetic energy, implying that the reactions occur on the periphery of the target nucleus and, therefore, the yields should vary as $A_T{}^{1/3}$. The fragmentation component decreases rapidly with increasing angle and at larger angles the spectra acquire shapes characteristic of thermal emission ($\sigma \sim e^{-E/T}$). The large excitation energies indicated by the high-energy tails of these spectra suggest more central collisions. Thus, the larger-angle light-ion yields should vary with target A as $A_T^{2/3}$ for surface interactions or as A_T for volume interactions. The observed $A_T^{2/3}$ dependence is consistent with suggestions[5,6] that energetic light particles are emitted from a hot source at the interface between the projectile and target nuclei.

Since the process dominating light-ion emission apparently changes with detection angle, a combination of models might be employed to fit all of the data, as was done for example in Ref. 7. However, in the interest of comparison with other measurements and projectile energy regimes, we restrict our analysis to the larger, thermally dominated, emission angles. A simple parametrization has been found to give good fits to inclusive light-ion spectra at lower projectile energies.[8,9] Particles are assumed to be emitted with a Maxwellian distribution by a heated, moving source described by a velocity (v_s), normally given relative to the projectile velocity ($v_{\rm proj}$), and an effective temperature (T). This "source" was used to fit the proton spectra, restricting the input data to angles $\geq 24°$ to reduce the influence of the fragmentation component. The parameters extracted from measurements at 100-MeV/u projectile energy are nearly the same for all four targets. The velocity ratio, $v_s/v_{\rm proj}$, is in the range 0.52 to 0.56 and the temperature increases only slightly with increasing A_T (from 16.5 MeV for Al to 18.4 MeV for Au). The change in temperature with A_T is significantly smaller than that deduced in Ref. 1, using a similar type of "source," where the temperatures were found to increase from 13.0–13.8 MeV for C, Al, and Cu targets to 16.6–17.0 MeV for Ag and Au targets (for protons with $E > 40$ MeV emitted at $\theta = 90°$). The velocities and temperatures deduced from fitting these data can be compared with those which would be obtained for an equilibrated compound system. For complete fusion and no preequilibrium emission, the compound-nucleus velocities ($v_{\rm CN}$) would vary from $v_{\rm CN}/v_{\rm proj} = 0.37$ for $^{16}O + ^{27}Al$ to 0.075 for $^{16}O + ^{197}Au$. The corresponding temperatures, assuming $T = (8E^*/A_{\rm CN})^{1/2}$, would be 13.7 MeV for Al and 7.5 MeV for Au. This comparison is obviously oversimplified but does indicate that if compound-nucleus emission were dominant, then the light-ion spectra should have quite different shapes for different A_T.

Velocity and temperature parameters obtained by fitting proton spectra from 50-, 100-, and

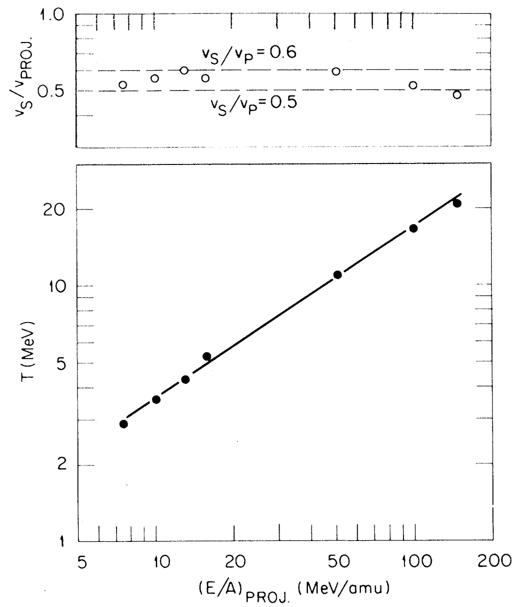

FIG. 3. Systematics of moving-source parameters obtained by fitting proton spectra from ^{12}C or ^{16}O on Ni at projectile energies ranging from 7.5 to 147 MeV/u. The low-energy data ($E/A \leq 16$ MeV) are for ^{12}C projectiles (Ref. 9) and the high-energy data are from the present measurements at $\theta \geq 24°$.

147-MeV/u ^{16}O on Ni are compared, in Fig. 3, with those found at lower projectile energies[9] (7.5–15.75 MeV/u ^{12}C). While the physical significance of these parameters is debatable, they nevertheless provide a convenient means of comparing data taken with different experimental parameters. One notable feature of the values displayed in Fig. 3 is that there are no obvious discontinuities which one might expect to appear if drastic changes in reaction mechanism or saturation of a particular mechanism were to occur. The nearly constant value of $v_s/v_{\rm proj} \approx 0.5$ indicates that the "source" mass is about twice the projectile mass. Thus, the target and projectile contributions to the "source" are approximately equal, independent of $(E/A)_{\rm proj}$ and, from the target-A results discussed above, of A_T. The temperature, however, changes rather rapidly with $(E/A)_{\rm proj}$. The line drawn through the points in Fig. 3 is given by $T \approx 0.79(E/A)_{\rm proj}^{2/3}$. This energy dependence is compatible with the temperatures compiled by Scott[10] for $(E/A)_{\rm proj}$ extending up to 800 MeV/u.

In summary, the present study has examined the importance of target A on the yields of energetic light ions produced in medium-energy ^{16}O-induced reactions. The observed transition from an $A^{1/3}$ dependence for the yields at small angles to an $\approx A^{2/3}$ dependence at larger angles is quite different from the weaker target-mass dependence reported at a lower projectile energy. Additional measurements in the 20–50-MeV/u projectile energy region are needed to study this change in behavior. Light ions emitted at angles $>24°$ display thermal emission characteristics and can be parametrized in terms of a moving heated source. Velocity and temperature parameters, when compared with those reported at lower projectile energies, suggest little change in or saturation of the mechanisms responsible for energetic light-ion emission over projectile energies in the range 7.5 to 147 MeV/u.

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More Evidence for Dibaryon Resonances from the Measurement of the Tensor Polarization t_{20} in π^+-d Scattering

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The tensor polarization t_{20} of π^+-d elastic scattering has been measured at 120 and 138 MeV as a function of scattering angle. While at the higher energy a strong oscillatory behavior prevails over the angular range measured (105°–180° c.m.), a considerable flattening is observed at the lower energy over the angular range 140°–170° c.m. This energy dependence and other observations are believed to manifest further evidence for the presence of nonconventional dynamics in this energy region.

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The analyses of the experimental results of cross-section data of p-p scattering with polarized particles,[1] the analyzing power iT_{11} of π^+-d scattering,[2] and the recently measured tensor polarization t_{20} of the recoiling deuteron in π^+-d scattering[3] suggest the existence of dibaryon resonances. Since it became evident in the last decade that the constituents of nucleons are quarks

