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LIGHT-PARTICLE EMISSION FROM HEAVY-ION REACTIONS*

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Experimental studies of energetic light (Z = 1,2) ions from heavy-ion-induced reactions are reported. Energy spectra of p, d, t, ^{3}He, and α from 208.2-MeV ^{16}O on targets of carbon, iron, and zirconium show only small variations with target mass. Coincidence measurements for 194-MeV ^{12}C on ^{60}Ni show much higher multiplicity for energetic protons in coincidence with Z=1,2 ions than with projectile-like ions. Gamma rays measured in coincidence with energetic protons show a large number of target-like nuclei to be produced with none more than 4% abundant.

Studies of energy spectra of protons and alpha particles from medium-energy heavy-ion-induced reactions have shown large forward-peaked components with particle energies well above those of compound-nucleus statistical emission spectra.[1,2] Recently reported measurements[3] of spectra of Z = 1 particles from the reaction of 192-MeV ^{12}C with ^{56}Fe showed the proton, deuteron, and triton spectra at forward angles to extend to energies far above the energy per nucleon of the incident projectile; e.g. the proton spectra extend to about 70 MeV.

There has been considerable recent discussion of possible mechanisms for production of these high-energy nuclear particles[3-8] but the results reported until now do

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not establish which of the proposed mechanisms are most valid. We have undertaken a program designed to obtain a variety of data to assist in the understanding of this phenomenon. These studies include (a) measurements of energy spectra vs. angle of light ions from reactions with a range of incident particle energies and target masses, (b) measurement of light ions (Z = 1,2) in coincidence with light ions, (c) measurement of heavy ions ($Z \geq 3$) in coincidence with light ions, (d) measurement of γ rays in coincidence with light ions, and (e) measurement of γ-ray multiplicities in coincidence with heavy and with light ions. We report here some results of type (a), (b), (c), and (d) data.

The singles data are from 208-MeV ^{16}O (13 MeV/amu) on targets of carbon (Z = 6), iron (Z = 26), and zirconium (Z = 40). Measurements were made at laboratory angles of 8° and 20°. The beam was from the Oak Ridge Isochronous Cyclotron and the experimental arrangement is the same as that described in Ref. 3.

In Fig. 1 we compare observed energy spectra (at 8° lab) for protons, deuterons, tritons, and alpha particles for the three targets. ^{3}He spectra are similar to those for tritons; this suggests that energy spectra of neutrons are likely to be similar to those of protons.

These data indicate that for energetic Z = 1,2 particles the variations of cross section with target mass are relatively small. For example the cross sections at 8° for protons above 13 MeV (E/A of the incident projectile) are 335, 440, 460 mb/sr, respectively, for target of carbon, iron and zirconium; at 20° the respective cross sections are 210, 300, 295 mb/sr. For the composite light particles

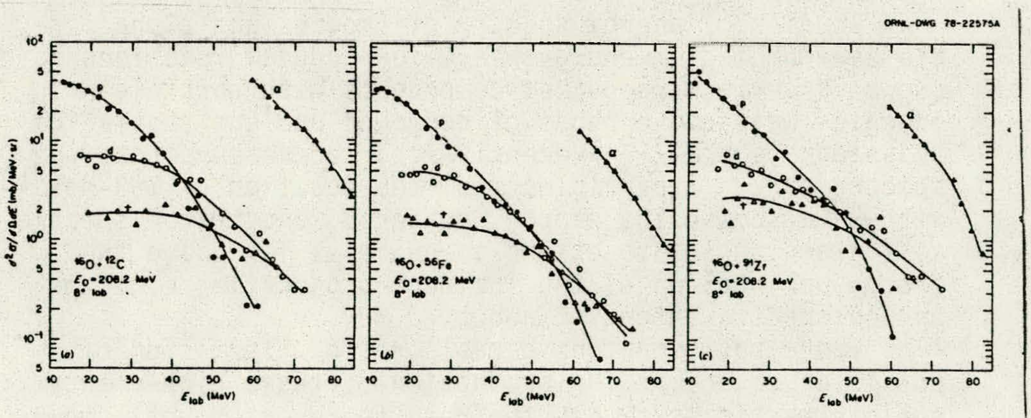

FIGURE 1, Energy spectra of Z = 1 and 2 particles at 8° from reactions of 208-MeV ^{16}O on targets of carbon, iron, and zirconium.

the variations of cross sections with target mass are no more pronounced.

Coincidence measurements were performed with beams of ^{12}C ions bombarding a ^{60}Ni target at energies of 138 and 194 MeV. Some of the 194-MeV data are presented here. The detectors included a ΔE-E heavy ion telescope at 17° (also used for lower energy light ions); four energetic light-ion telescopes at 17°, 38°, -23°, and -49°; two Ge(Li) γ-ray detectors; and five NaI γ-ray detectors. Data from all of the detectors were stored on magnetic tape in a list mode for subsequent scanning for selected coincidence events.

The results are presented here in terms of a multiplicity q, where q is defined as the number of particles B emitted in coincidence with a gating particle A. Angular correlations between the various combinations of A and B are not known; we assumed the particles in coincidence have the same angular distributions as singles. With this assumption we obtained values of q by gating on Z = 1,2 particles at the four angles of the light-ion telescopes and scanning the data tapes for various coincident particles in the "heavy-ion" telescope at 17°.

Figure 2 presents the measured multiplicities of hydrogen and of helium ions in coincidence with protons. The gating protons are divided into four energy groups while the coincident Z = 1,2 ions have velocities below that of the incident projectile. We note that the probability is large for simultaneous emission of several protons and α particles in a single reaction when the proton energy is low and that this probability decreases as the gating

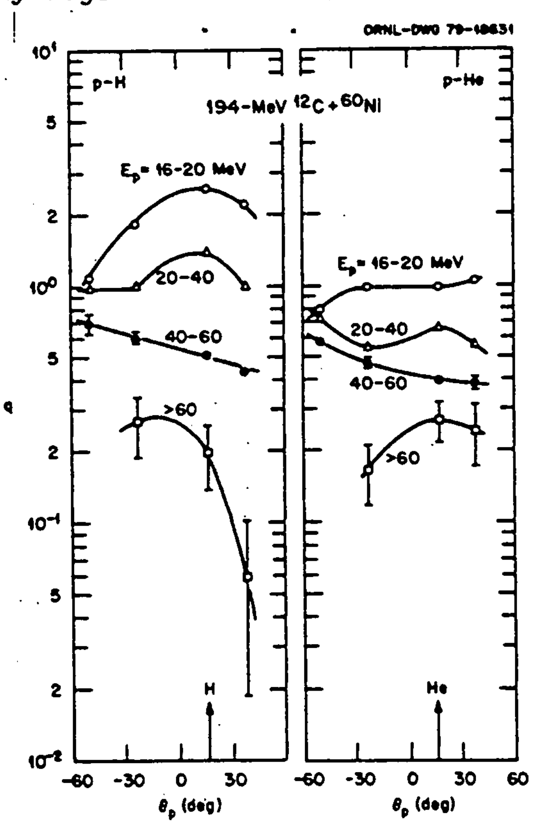

FIGURE 2. Multiplicity q for hydrogen ions or helium ions being emitted in coincidence with protons in the energy groups noted.

proton energy is increased. From data of this type we conclude that for a gating proton of E_p = 16-20 MeV ∿ 11 nucleons are emitted as $Z \leq 2$ particles; for E_p > 60 MeV the estimated number of $Z \leq 2$ particles is about 5 nucleons.

Figure 3 compares the multiplicities of Li, B, and C ions that occur in coincidence with protons. The multiplicities of heavy fragments (Z > 2) in coincidence with protons are lower by ∿ 10^2 than for Z = 1,2 particles. Thus, energetic protons do not result frequently from reactions that leave large pieces of the incident projectile intact. There is a change in character between the Z = 3 and the Z = 5,6 coincidence results. The pronounced minima at 17° for boron and carbon suggests that the emission of protons and projectile-like fragments at the same angle is inhibited. Another interesting point is that the multiplicities are similar for boron and carbon ions emitted in coincidence

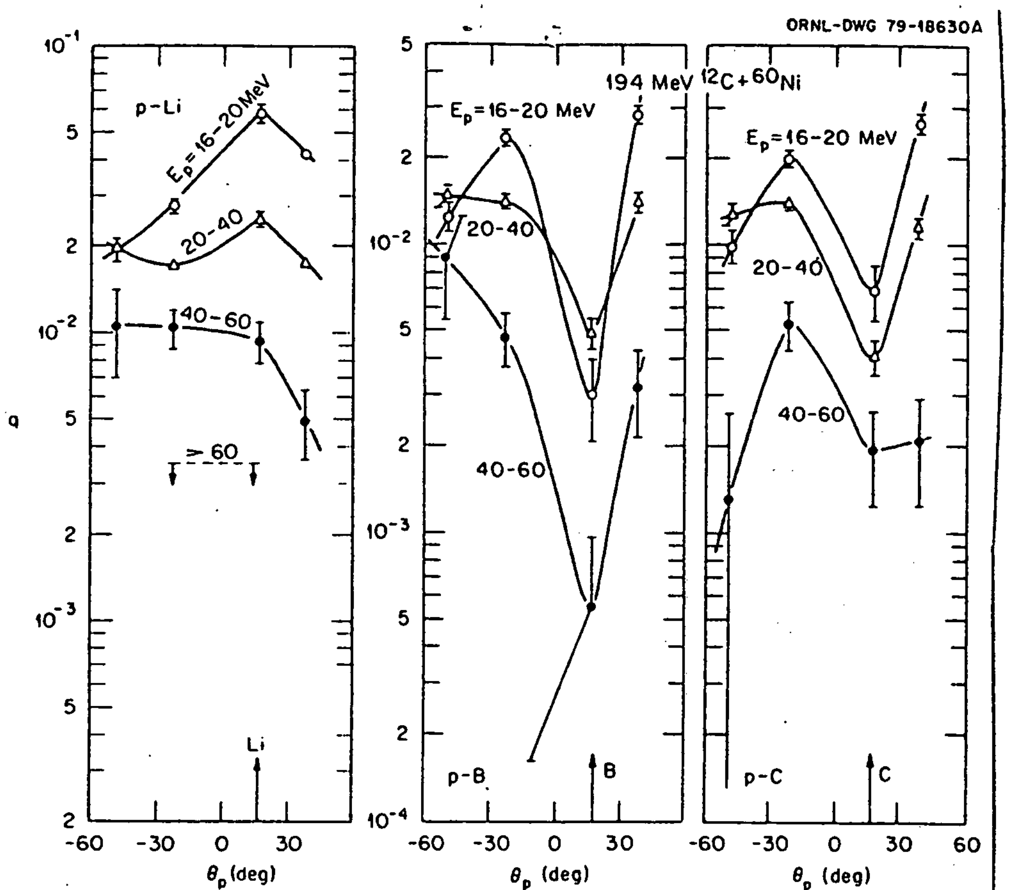

FIGURE 3, Multiplicities for lithium, boron, and carbon ions being emitted in coincidences with protons in the energy bins noted.

with protons. For carbon a proton must be removed from the target nucleus; the similarity of p-C and p-B coincidence data suggests that protons in coincidence with boron are also involve removal of a proton from the target nucleus.

Examples of coincidence measurements for heavy fragments when the gating particles are α particles are shown in Fig. 4. Again the values of q are small but for lithium ions they are larger than when the gating particles are protons (Fig. 3). One interesting difference between the p-Li and α-Li coincidences is that the latter is strongly peaked at 17°. This suggests different reaction mechanisms. The α-C data indicate the multiplicity for emission of an energetic α-particle associated with an α being removed from the target nucleus.

Measurements of γ rays in coincidence with energetic protons were performed to identify which residual nuclei are produced. The data indicate that many isotopes near A = 60 (the target mass) are produced in the reaction and that no single isotope is produced with a probability greater than 4%.

The weak dependence of the singles spectra of Z = 1,2 ions on target mass is in comportment with a reaction mechanism based on peripheral reactions. Although results obtained thus far from our coincidence studies do not clearly establish the dominant reaction mechanism, they do offer some new insights. These include:

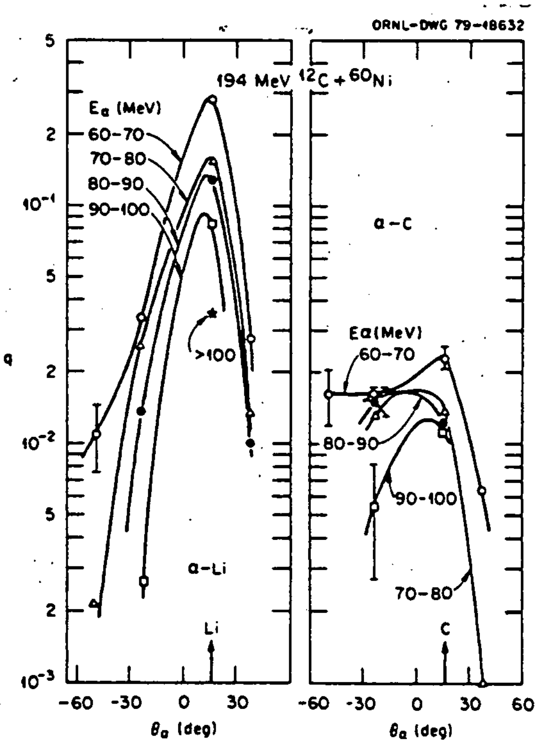

FIGURE 4, Multiplicities for lithium and for carbon ions being emitted in coincidence with an α particle in the energy bins noted.

1. If the energetic protons are emitted from an excited projectile-like nucleus (as we suggested earlier[3]) the latter, for the most part, disintegrates almost entirely into light fragments.
2. The difference between the q-plots for $Z \leq 3$ particles and with $Z \geq 5$ particles in coincidence with energetic protons suggests different predominant reaction mechanisms for these two groups.
3. The principal mechanism for the energetic α particles differs from that for the energetic protons. The large multiplicities of Li ions in coincidence with α particles at the same angle suggests these are due to fragmentation of a projectile-like nucleus.

Further analyses and interpretation of the coincidence data are underway.

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