Particle Emission at a ^{20}Ne Projectile Velocity Comparable to the Fermi Velocity

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(Received 13 July 1981)

Inclusive energy spectra of the H and He isotopes emitted in the reactions of 860-MeV ^{20}Ne with Ni, Ag, and Ta provide evidence that a statistically dominated projectile fragmentation mechanism entirely analogous to that observed at relativistic energies occurs when the projectile velocity becomes comparable to the Fermi velocity in the projectile. Additional particle emission not characteristic of either a fragmentation or compound nucleus source is observed.

PACS numbers: 25.70.-z, 25.70.Bc

Marked changes in the mechanisms of heavy-ion reactions are expected to occur in the transition region between low (several megaelectronvolts per nucleon) and high (relativistic) energies.[1] One expected change is the evolution of the dominant peripheral reactions from quasielastic transfer to statistically dominated projectile fragmentation. Earlier studies of projectilelike fragments produced in ^{16}O irradiations[2] were interpreted as indicating that "asymptopia" for projectile fragmentation is reached by 20 MeV/nucleon. However, recent observations of projectilelike fragments in the reactions of 20-MeV/nucleon ^{20}Ne with ^{197}Au appear to contradict this interpretation.[3] This Letter reports the results of experiments in which energy spectra and angular distributions of H and He isotopes produced in the reactions of 43-MeV/nucleon ^{20}Ne with Ni, Ag, and Ta were measured. At forward angles the spectra are dominated by components peaking at energies per nucleon only slightly less than that of the projectile and having nucleon momentum widths[4,5] $\sigma_0 = 85.1 \pm 3.6$ MeV/c. Thus the observable characteristics of projectile fragmentation at 43 MeV/nucleon are identical to those characterizing fragmentation at gigaelectronvolt-per-nucleon projectile energies.[6]

Observations of additional particle emission, not characteristic of simple fragmentation processes, indicate emission from sources with velocities intermediate between that of the projectile and that of the center of mass. Parametrized in terms of temperature, the high-energy tails of the spectra of these additional particles correspond to values of $T = 13$ to 16 MeV.

The experiment was performed at the low-energy beam line at the Lawrence Berkeley Laboratory Bevalac using a beam of 60-MeV/nucleon ^{20}Ne. Following passage through an air gap and diagnostic elements, the magnetically analyzed beam was found to have an energy of 860 MeV. Self-supporting targets of Ni (8.88 mg/cm^2), Ag (20.9 mg/cm^2), and Ta (42.6 mg/cm^2) were used. Light particles were detected in two telescopes consisting of 273- and 408-μm Si ΔE detectors backed by a 3.8-cm-thick NaI crystal with a 25-μm Al entrance window. A third telescope consisting of a gas ionization detector (3-μm Si equivalent), a 1-mm-thick position-sensitive Si detector, and a 3.8-cm-thick NaI detector was employed to detect heavy reaction products having $2 \leq Z \leq 10$. This heavy-ion telescope, two monitor detectors, and an ionization chamber which stopped the beam were used to determine the relative normalizations of the light-ion energy spectra. Uncertainties in the absolute beam intensity prevent us from reporting absolute cross sections at this time.

In Figs. 1(a)–1(c) the energy spectra of H and He isotopes observed at $\theta_{\rm lab} = 15°$ are presented. No spectral correction has been made for the small losses resulting from nuclear reactions in the NaI. Arrows in the figure indicate the expected energies of particles with $1 \leq A \leq 4$ moving with the projectile velocity. Each spectrum contains a component peaking slightly below the energy corresponding to the projectile velocity indicating that many particles originate from projectiles before significant energy dissipation occurs.

Transformation of these spectra into the projectile frame allows a characterization of the spectra by either a temperature T or a momentum width σ characteristic of the virtual fragment in the projectile, where

$$\sigma^2 = \left(\frac{P_F{}^2}{5}\right)\left(\frac{F(A-F)}{A-1}\right) = \sigma_0{}^2 \frac{F(A-F)}{A-1} \qquad (1)$$

and

$$T = \left(\frac{A}{A-1}\right)\frac{\sigma_0{}^2}{m}. \qquad (2)$$

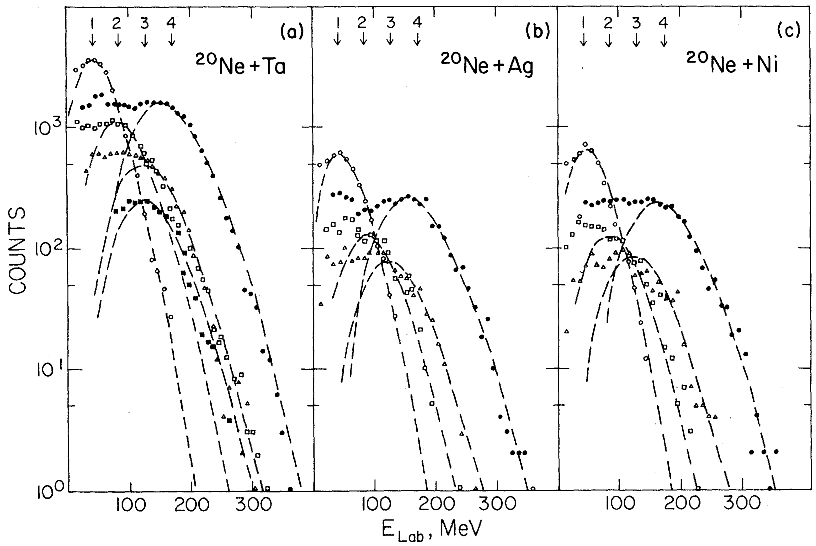

FIG. 1. Light-particle spectra observed at $\theta_L = 15°$. The spectra of H and He isotopes from (a) Ta, (b) Ag, and (c) Ni targets are shown. p, open circles; d, open squares; t, triangles; ^{3}He, solid squares; ^{4}He, solid circles. Dashed lines represent fragmentation model calculations with $\sigma_0 = 85$ MeV/c. See text.

In these equations P_F is the Fermi momentum, F is the fragment mass, A is the projectile mass, σ_0 is the width characterizing the momentum distribution of individual nucleons in the projectile,[4] and m is the nucleon mass.

In Fig. 2 plots of $\ln[E^{-1/2}(\partial^2\sigma/\partial\Omega\,\partial E)]$ vs E in the projectile frame are plotted for each particle spectrum presented in Fig. 1(a). From such plots of forward-angle data, the parameters T and σ_0 have been extracted. The ^{3}He spectra were excluded because of poor statistics. These values are presented in Table I. Note that the preexponential term assumed for the spectral distribution is $E^{1/2}$, corresponding to volume emission.[5,7] Using all the individual values from Table I, we find a mean σ_0 of 85.1 ± 3.6 MeV/c. This mean width parameter has been used to calculate the shapes of the laboratory spectra expected for fragmentation. These spectra are represented by the dashed lines in Figs. 1(a)–1(c) individually normalized to the data at energies near 43 MeV/nucleon. The agreement between the calculated spectral shapes and the high-energy portions of the experimental spectra is very good.

High-energy peaks observed in the forward-angle spectra of C, N, and O also show peaks consistent with the fragmentation interpretation but the data are not statistically sufficient to extract accurate isotopic momentum widths.

The present light-particle data indicate that the dominant mechanism contributing to the forward-directed high-energy particles in the inclusive spectra is projectile fragmentation entirely analogous to that observed at relativistic energies. This result may be contrasted to particle data obtained from reactions with 20-MeV/nucleon ^{16}O

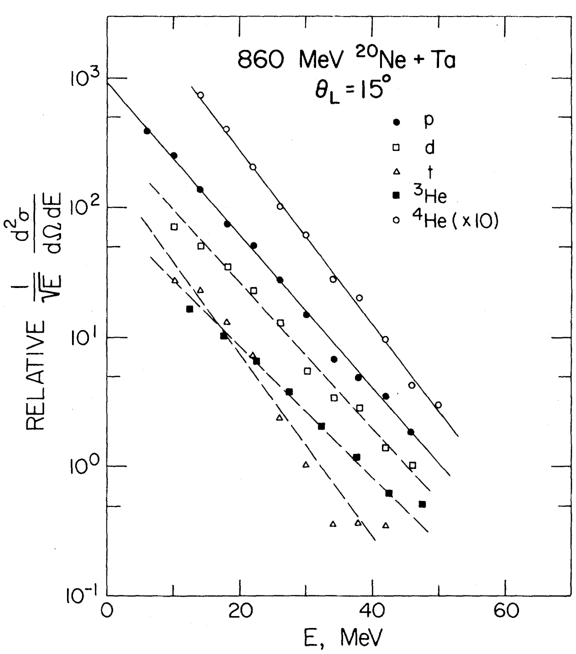

FIG. 2. Slope determinations for Ta data at $\theta_L = 15°$. The data have been transformed into the projectile frame.

TABLE I. Widths, σ_0 (MeV/c), and temperatures, T (MeV), extracted from forward-angle data transformed to the projectile frame, for various particles (p, d, t, α) and targets (Ni, Ag, Ta).

	p		d		t		α	
	σ_0	T	σ_0	T	σ_0	T	σ_0	T
Ni	84.8 ± 1.5	8.1 ± 0.3	88.3 ± 3.0	8.7 ± 0.6	85.5 ± 3.0	8.2 ± 0.6	84.3 ± 3.0	8.0 ± 0.5
Ag	82.4 ± 1.5	7.6 ± 0.3	91.0 ± 2.5	9.3 ± 0.5	84.9 ± 2.5	8.1 ± 0.5	83.5 ± 3.2	7.8 ± 0.6
Ta	82.0 ± 1.5	7.5 ± 0.3	89.2 ± 1.5	8.9 ± 0.3	80.3 ± 2.0	7.2 ± 0.4	85.7 ± 1.5	8.2 ± 0.3

ions where the energy spectra for light particles peak at energies significantly lower than the energies corresponding to the beam velocity.[8-10]

For the systems studied, this projectile energy of 43 MeV/nucleon corresponds to center-of-mass energies of 30 to 34 MeV/nucleon over the entrance-channel Coulomb barrier. The Fermi energy for a nucleon in ^{20}Ne is about 29 MeV.[11] Apparently, exceeding the Fermi energy is a sufficient condition to ensure that the projectile fragmentation is characterized by purely statistical behavior.[4,5] Further evidence for this conclusion is provided by the large fragmentation component observed in reactions induced by 35-MeV/nucleon α particles.[12]

In Fig. 3, the energy spectra measured at laboratory angles from 15° to 85° are presented for protons and α particles resulting from the reactions of 860-MeV ^{20}Ne with Ta. The data obtained from Ni and Ag targets show very similar trends. The dashed lines in Fig. 3 represent some spectra calculated using the fragmentation model.[2] The calculations were normalized to the 15° data at an energy of 43 MeV/nucleon. No orbital dispersion was assumed since such effects appear to be small for fragments far removed from the projectile.[13] The calculated decrease of the high-energy fragmentationlike peak with angle is consistent with the apparent disappearance of that component in the backward-angle spectra.

The lower-energy portions of the forward-angle data and the large relative cross section for particles observed at large angles are not consistent with a single fragmentation source nor are they

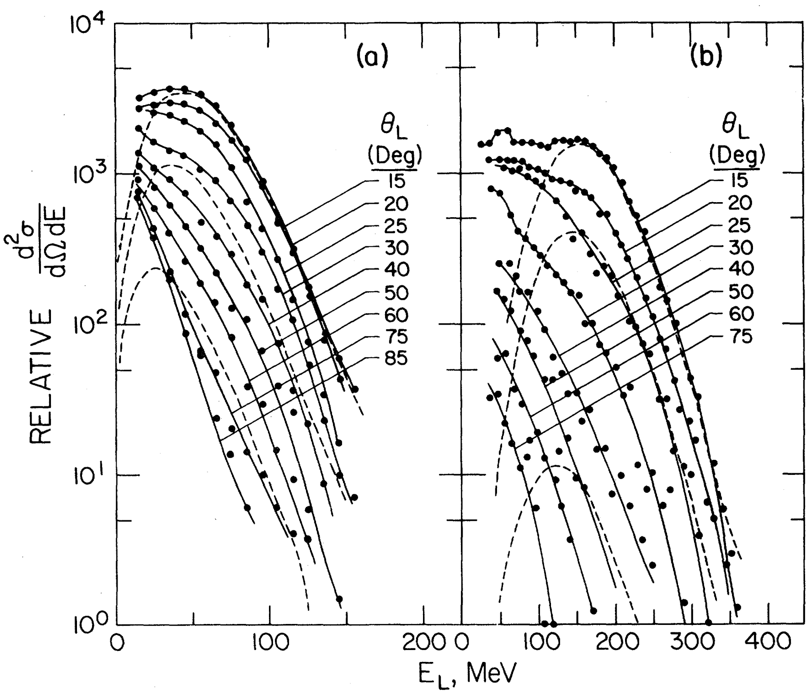

FIG. 3. Energy spectra for (a) protons and (b) α particles resulting from the reactions of 860-MeV ^{20}Ne with Ta. The dashed lines represent the fragmentation calculation with $\sigma_0 = 85$ MeV/c. Calculations are presented for $\theta_L = 15°$, 30°, and 45° for protons and $\theta_L = 15°$, 20°, and 30° for α particles.

consistent with emission from a source moving with the center-of-mass velocity. Attempts to fit the spectra under the assumption of two or three sources of particle emission, Maxwellian in the rest frame of the source, lead us to the conclusion that the bulk (but not all) of the additional particles in each system may be parametrized as being emitted from sources with velocities 0.6 to 0.7 times that of the projectile (close to sound velocity) and temperatures of 13 to 16 MeV. Within the statistical constraints of the fitting procedures, this result is not too different from the systematics for light ejectiles recently observed by Awes *et al.*,[10] in their measurements of the inclusive particle spectra produced in reactions with ^{16}O projectiles with energies ≤ 20 MeV/nucleon. These authors point out that those systematics agree with a simple Fermi-gas model in which it is assumed that equal numbers of nucleons from the target and projectile participate in the source. However, more complete experiments are necessary to separate the possible multitude of mechanisms which may contribute to the inclusive spectra. Such mechanisms might include nucleon-nucleon scattering[14,15] and delayed fragmentation.[16]

We thank P. J. Siemens, C. M. Ko, and D. Sperber for many valuable discussions. G. Westfall and D. Morrissey helped us greatly during the experiment at Lawrence Berkeley Laboratory. S. Mao assisted in the data analysis. This research was supported by the U. S. Department of Energy and the Robert A. Welch Foundation.

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