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Rapid Communications

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Momentum widths in the fragmentation of 32 MeV/u ^{10}B

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Momentum widths of fragments produced in the reactions of 320 MeV ^{10}B with ^{181}Ta have been measured. At forward angles the energy spectra of light particles ($Z=1,2$) exhibit energy peaks characterized by a reduced momentum width $\sigma_0=54$ MeV/c, which is well below the values near 85 MeV/c observed in the reactions of 43 MeV/u ^{20}Ne with ^{181}Ta and in reactions induced by relativistic heavy ions. These results suggest a rapid increase in momentum widths, or apparent temperature, in the 32 to 43 MeV/u range.

[NUCLEAR REACTIONS ^{181}Ta(^{10}B,X), $E=320$ MeV, projectile fragmentation; measured energy spectra of H and He isotopes at forward angles, extracted momentum widths.]

The characteristics of projectile fragmentation in peripheral heavy ion collisions in the intermediate energy range of 20–100 MeV/u have been the subject of several recent studies.[1–4] The interest in this process results from the expected occurrence of transitions in the nature of nuclear collisions from low energy to high energy behavior in this energy range. In the reactions of 860 MeV ^{20}Ne with Ni, Ag, and Ta targets we observed[1] that the forward angle spectra of H and He isotopes exhibited fragmentation components which can be characterized by apparent nucleon momentum widths $\sigma_0=85.1$ MeV/c, essentially identical to those found at relativistic energies,[5] and much larger than the value of about 40 MeV/c obtained in reactions at 20 MeV/u.[2] In the present Rapid Communication, we report nucleon momentum widths extracted from H and He spectra observed in the reactions of 320 MeV ^{10}B projectiles with ^{181}Ta. The widths are only slightly greater than those observed at 20 MeV/u, indicating that the transition to asymptotic high energy behavior occurs quite rapidly between 32 and 43 MeV/u.

The experiment was performed using 320 MeV ^{10}B^{5+} ions extracted from the Texas A & M University Cyclotron. The beam intensity obtained with this fully stripped ion was only about 10^7 particles per second. A tantalum target of thickness 42.6 mg per cm^2 was used. Energy spectra of products with $Z=1$–5 were measured using three detector telescopes, two of which were primarily used for H and He and consisted of two 400 μm Si ΔE detectors backed by a 3.8 cm thick NaI crystal. The third telescope consisted of four silicon detectors with a total thickness of 9.2 mm. Relative normalization of the spectra taken at different angles was determined by keeping one of the telescopes fixed while the other one was moved to different angles. An ionization chamber positioned at zero degrees to count the beam particles also provided relative normalization. Absolute cross sections were not measured in this experiment.

The spectra of H isotopes and ^{4}He measured at $\theta_{\rm lab}=6$ deg are shown in Figs. 1(a)–1(d). The Si(ΔE)-NaI(E) telescope was used in these measurements. The spectra are dominated by a component peaking at energies-per-nucleon close to the value for the incident projectile. This component is especially distinct in the case of protons and ^{4}He. We interpret this component as originating from the fragmentation of the projectile in collisions where only a slight energy dissipation occurs.

In the simple fragmentation picture, one assumes that the fragment momentum distribution in the projectile rest frame is a Gaussian,

$$\frac{d^3\sigma}{dp^3} \propto \exp\left(-\frac{p^2}{2\sigma^2}\right) \quad (1)$$

with a width given by

$$\sigma^2=\sigma_0{}^2\frac{(A-F)F}{A-1} \;,$$

where A and F are the projectile and fragment mass number, respectively, and σ_0 is the width of the momentum distribution of individual nucleons in the projectile.[6,7] Alternatively, the fragment energy distribution can be parametrized in terms of a temperature T which is related to the reduced width σ_0 by the equation $T=A\sigma_0{}^2/m(A-1)$, where m is the nucleon mass.

We have fitted the high energy part of the proton and ^{4}He spectra to the shape given by the simple fragmentation model assuming an isotropic, Gaussian momentum distribution in the projectile frame. The velocity of the projectile undergoing fragmentation and the momentum width σ_0 were treated as free parameters. The fits shown in Figs. 1(a) and 1(d) yield σ_0 values of 50.6 and 50.8 MeV/c for

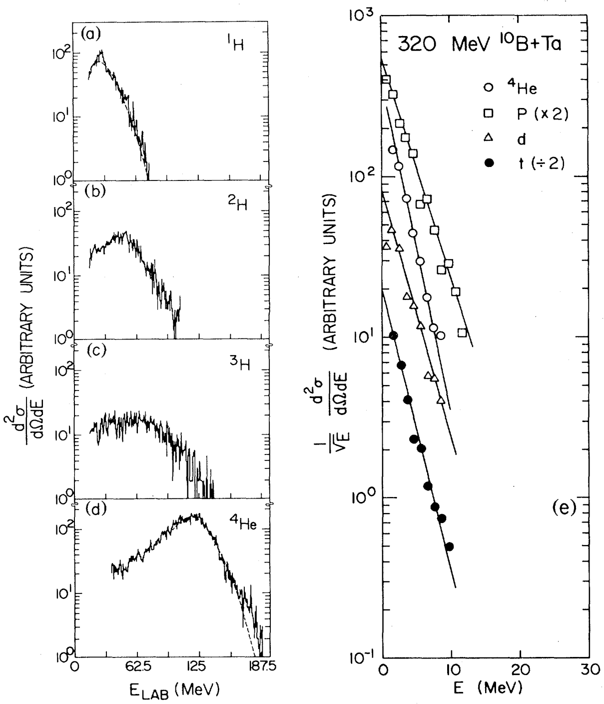

FIG. 1. (a)–(d): Energy specta of light particles observed at $\theta_{\text{lab}}=6$ deg. (a) Protons, (b) deuterons, (c) tritons, (d) alpha particles. In parts (a) and (d) the fits to the fragmentation model are also shown as dashed lines; (e) plot for extracting momentum widths from light particle spectra. $\theta_{\text{lab}}=6$ deg. The spectra have been transformed to a moving frame with $V=0.95\times V_{\text{proj}}$.

protons and ^{4}He, respectively. By fitting the entire ^{4}He spectrum including the lower energies to a sum of the fragmentation component and a second component arising from another moving thermal source, one obtains the slightly lower value of 45 MeV/c for σ_0 for the fragmentation component. These fits resulted in a value for the velocity of the fragmentation source equal to 0.95 times the incident projectile velocity.

An alternative method for obtaining σ_0 is given in Fig. 1(e). Here we have transformed the data to a moving frame with a velocity of $0.95\times V_{\text{proj}}$ (this choice being suggested by the fits), and plotted the quantity

$$\log_{10}\frac{1}{\sqrt{E}}\frac{d^2\sigma}{dE\,d\Omega}$$

in the projectile frame against E. Equation (1) implies that the ordinate is proportional to $-E/\sigma^2$ in the nonrelativistic limit. It may be noted that the use of the factor $1/\sqrt{E}$ is consistent with an evaporation spectrum involving volume emission.[8] From the slopes of the plots, values of σ_0 and T are extracted (see Table I). The reduced widths for the three H isotopes and for ^{4}He are essentially identical and average to 54.0 MeV/c, corresponding to an average T of 3.5 MeV. (If the spectra are transformed to a moving frame with full projectile velocity, an average reduced width σ_0 of 49.3 MeV/c, corresponding to $T=2.9$ MeV, is obtained.)

The angular distribution of the fragmentation component is depicted in Fig. 2, where ^{4}He spectra taken at five angles in the range from 3 to 19 deg are shown. The cutoff at high energies seen in the spectra is due to the finite thickness (9.2 mm) of the Si detector telescope used. This cutoff does not seriously affect our ability to extract a width parameter from the spectra. The five spectra in Fig. 2 were fitted together to a sum of two components as described be-

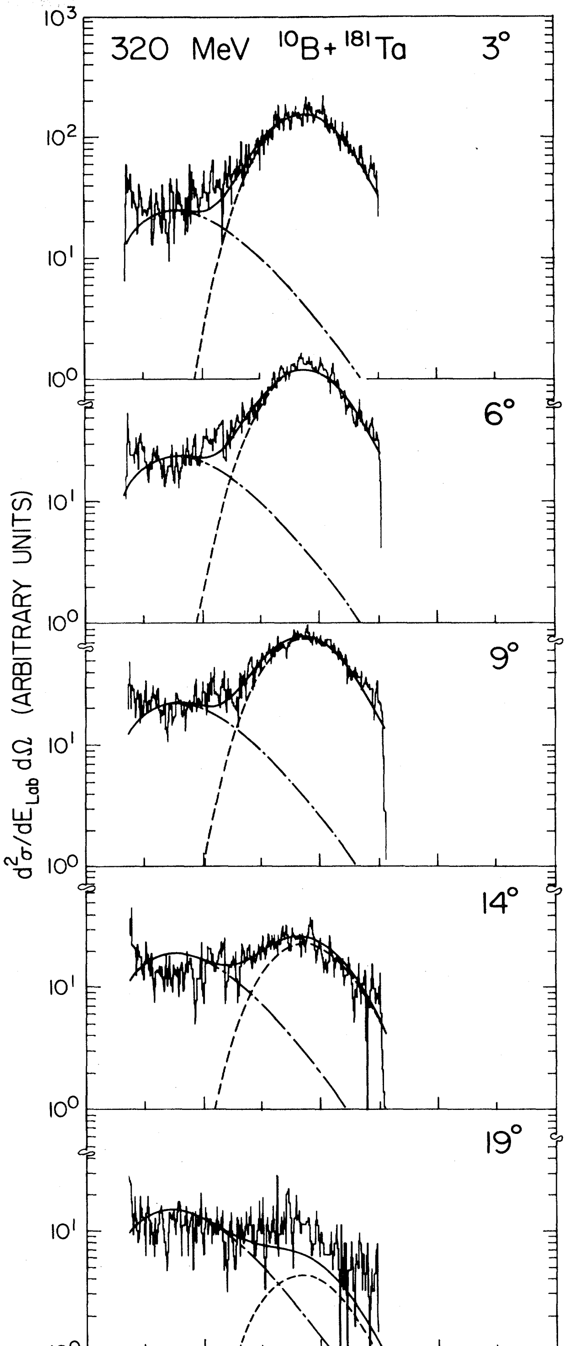

FIG. 2. Spectra of ^{4}He observed at forward angles. The solid curve: a fit of all the spectra together to a sum of two components; (1) dashed line: fragmentation component; $\sigma_{\parallel}=85.5$ MeV/c, $\sigma_{\perp}=113.5$ MeV/c, $v/v_{\text{proj}}=0.95$; (2) dot-dashed line: $T=8.9$ MeV, $v/v_{\text{proj}}=0.56$.

TABLE I. Reduced width σ_0 and temperature T extracted from the forward angle spectra of light particles in the system 320 MeV $^{10}B+^{181}Ta$.

Particle	σ_0 (MeV/c)	T (MeV)
p	54.0 ±1.5	3.5 ±0.2
d	53.5 ±2.0	3.4 ±0.3
t	54.2 ±1.5	3.5 ±0.2
^{4}He	54.3 ±1.0	3.5 ±0.2

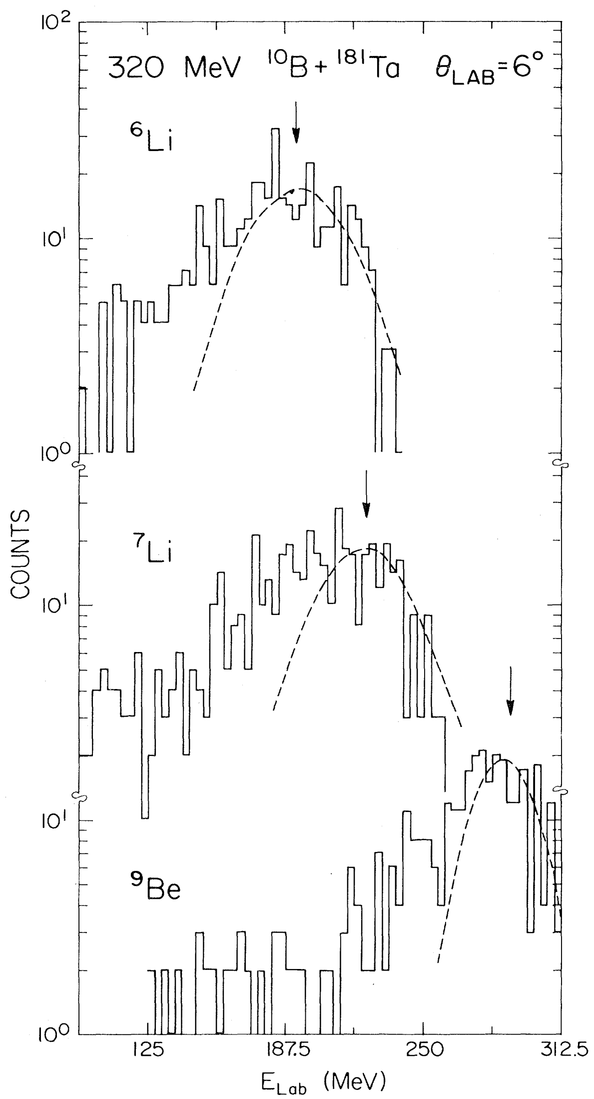

FIG. 3. Energy spectra of various fragments measured at 6 deg lab. The dashed lines show fragmentation model calculations with $\sigma_0=54$ MeV/c. The arrows represent fragment energies corresponding to the incident projectile velocity.

fore. In the present case, the longitudinal and transverse momentum widths of the fragmentation component, $\sigma_{\parallel}$ and $\sigma_{\perp}$, respectively, were allowed to vary independently in addition to the velocity of the projectile undergoing fragmentation. The fits, shown in Fig. 2, give $\sigma_{\parallel}=84.4$ MeV/c (corresponding to reduced width, $\sigma_0=52.3$) and $\sigma_{\perp}=113$ MeV/c for the fragmentation component. Thus, no large anisotropy in σ is indicated by our data for ^{4}He. For fragments close to the projectile, Van Bibber *et al.* observed $\sigma_{\perp}$ values twice as large as $\sigma_{\parallel}$ in the system $^{16}O+Au$ and $^{16}O+Al$ at 90 and 125 MeV/u and interpreted the results as due to orbital deflection of the projectile.[3] This effect is expected to be small for fragments much lighter than the projectile.

Forward angle spectra of Li and Be isotopes also exhibit peaks very close to the projectile velocity (Fig. 3). The data suffer from poor statistics and do not allow us to extract the widths unambiguously. The dashed curves in Fig. 3 represent the spectra calculated from the fragmentation model with $\sigma_0=54.0$ MeV/c and $V=V_{proj}$. Although the experimental spectra peak close to the velocity of the projectile, they are somewhat broader than the calculated ones. This suggests, perhaps, that the energy spectra of all fragments cannot be accounted for by a constant σ_0 parameter.[6] It is also possible that mechanisms involving significant energy loss are contributing to the observed spectra, in addition to the fragmentation process occurring without much energy dissipation.

The results are summarized in Fig. 4 where the nucleon momentum widths obtained in the present work and in some other recent studies are plotted against the energy per nuleon above the Coulomb barrier. It is seen that σ_0 for 32 MeV/u ^{10}B fragmentation measured here is clearly lower than the result obtained for 43 MeV/u ^{20}Ne in Ref. 1, the latter value being essentially identical to the result at relativistic energies. Thus, a rapid transition in σ_0 or T occurs

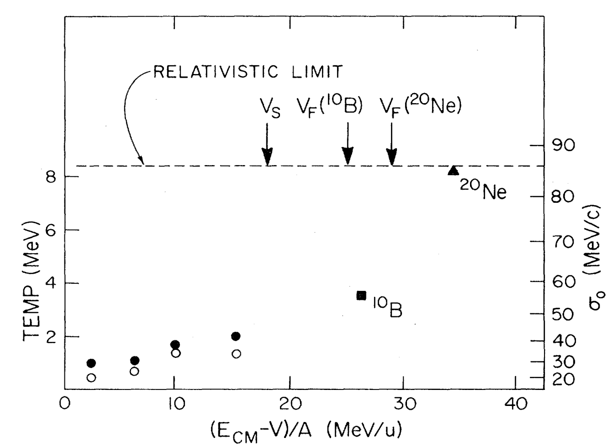

FIG. 4. Reduced width σ_0 and temperature T plotted as a function of the energy per nucleon over the Coulomb barrier. Square: present work. Triangle: result from Ref. 1 for 43 MeV/u ^{20}Ne. Closed and open circles: results from Ref. 2 for ^{16}O and ^{12}C reactions. The Fermi energies of nucleons in ^{20}Ne and ^{10}B are indicated by arrows. V_s represents the energy corresponding to the velocity of sound in nuclear matter.

just above the projectile energy employed in the present experiment.

The Fermi energies of nucleons in ^{10}B and ^{20}Ne are about 25 and 29 MeV, respectively[9] (see Fig. 4). As pointed out in Ref. 1, it is possible that the Fermi energy may represent an approximate boundary between low- and high-energy phenomena and that as the projectile energy per nucleon exceeds the Fermi energy, projectile fragmentation is characterized by the statistically dominated limiting behavior observed at relativistic energies. In Fig. 4, we have also indicated the energy corresponding to the velocity of sound in nuclear matter[8] (derived from the value of nuclear matter incompressibility[10]) which may be another relevant quantity in defining the boundary between low- and high-energy behavior.

Since the structural differences between ^{20}Ne and ^{10}B may be partly responsible for the marked difference observed in the present work, it would be interesting to make measurements over the energy range of 30–45 MeV/u using the same projectile throughout. Such experiments are planned for the near future. It may be noted in this connection that recent fragmentation measurements with a ^{12}C beam at 30 MeV/u have yielded σ_0 values very similar to the present results.[11]

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