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Dependence of ^{12}B excitation energy on its kinetic energy in the ^{14}N + Ag reaction at $E/A = 35$ MeV

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We observed the 19 keV neutron decay from the 3.388-MeV state of ^{12}B by measuring ^{11}B-neutron coincidences in colinear geometry at several angles. The ratio of this yield to the yield of particle-stable ^{12}B nuclei is a measure of the excitation energy of ^{12}B fragments produced in the reaction. The extreme kinematic focusing of the 19-keV decay enabled us to obtain the dependence of this ratio on fragment kinetic energy. For ^{12}B nuclei emitted with kinetic energies $E/A \lesssim 15$ MeV the ratio is surprisingly constant; for ^{12}B nuclei of higher kinetic energy it decreases monotonically.

Excited fragments are emitted from nuclear systems formed in intermediate energy, heavy ion collisions. Thus far, it has not been possible to make a straightforward connection between two observables that should be related: the kinetic energy spectra of the fragments and the relative populations of their states.[1-4] The slopes of the kinetic energy spectra of light fragments, $A \leqq 8$, indicate "kinetic" temperatures ($\tau \approx 10$–12 MeV for ^{14}N + Au at $E_i/A = 35$ MeV, $\tau \approx 14$–18 MeV for ^{40}Ar + Au at $E_i/A = 60$ MeV, and $\tau \approx 17$–20 MeV for ^{16}O + Au at $E_i/A = 94$ MeV) (Ref. 4) which are considerably higher than the "emission" temperatures which were extracted from the relative populations of states of these fragments ($T \approx 5$ MeV).[3,4]

Most experiments performed up to now have not explored the detailed dependence of the relative populations of states upon the kinetic energy of the emitted fragments. For fragments evaporated from a hydrodynamically stable compound nucleus, cooling by particle emission could lead to a correlation between the relative populations of excited states and the kinetic energy of emitted fragments. In this case, the fastest fragments on the extreme tails of the evaporation spectrum would be preferentially emitted when the nucleus is most highly excited, while slower fragments could also be emitted after the nucleus has cooled by particle emission. An even stronger decrease of temperature with time might be expected if the emitting system also expands with time. In general, cooling of the emitting system may lead to dependences of the populations of states on the fragment kinetic energy. Additional dependences on emission angle could be expected for emission from nonequilibrium systems.

In this Rapid Communication, we present definitive evidence for a strong kinetic energy dependence of the relative population of the first unbound state and the bound states of ^{12}B nuclei produced in the reaction Ag + ^{14}N at $E_i/A = 35$ MeV. In particular, we have measured the cross sections for ^{12}B nuclei emitted in their 3.388 MeV state, σ(3.4 MeV), and in their particle stable states, σ(bound). σ(3.4 MeV) was determined from ^{11}B$-n$ coincidence measurements, and σ(bound) was obtained from ^{12}B singles measurements. The latter cross section includes production of ^{12}B in its four bound excited states, which decay to the ground state by γ-ray emission. The ratio

$$R = \sigma(3.4\ \text{MeV})/\sigma(\text{bound})$$

is a measure of the excitation energy of ^{12}B fragments. In a thermal model, it is determined by the temperature of the emitting system.

Natural Ag foils of 3.9 and 5.0 mg/cm^2 areal density were bombarded by a 490 MeV $^{14}N^{5+}$ beam from the K500 Cyclotron at Michigan State University. The fragments were detected inside a steel vacuum chamber[5] (with 3-mm wall thickness and 91-cm diam) using ΔE-E silicon telescopes at angles from 15° to 83°. The neutron detectors (cylinders of liquid scintillator 12.7 cm in diameter and 7.6 cm long) were placed in colinear geometry at distances of 456 cm at 15°, 437 cm at 31°, and 353 cm at 64°. To improve the statistics, we had clusters of three,

seven, and seven detectors, respectively, at the three angles. Thin plastic scintillator paddles were placed in front of the neutron detectors to discriminate against high-energy protons. The time resolution between the fragment telescopes and the neutron detectors was typically 1 ns. In order to determine background contributions to the spectra shadow bars were placed directly between the target and the neutron detectors several times during the experiment. Neutrons were separated from γ rays off-line by pulse shape discrimination. The neutron detector efficiencies were computed; attenuation of the neutrons by the Si and other material between the target and the detector was taken into account.[6]

For each boron-neutron coincidence, the velocity $V_{^{11}B}$ of the fragment was derived from its measured kinetic energy and mass, the velocity V_n of the neutron was determined from its measured time of flight, and the relative velocity, $V_{rel}=V_{^{11}B}-V_n$, was calculated. The 3.388 MeV, 3^- level[7] of ^{12}B is only 19 keV above the neutron separation energy. Kinematic focusing of the neutrons significantly enhances their detection even for fragments with kinetic energies of only a few MeV/nucleon. Since the cross section for ^{12}B production is relatively large, the event rates for $^{11}B+n$ coincidence and ^{12}B singles measurements were high enough to provide good statistics for narrow fragment energy bins and, therefore, to determine the population ratio as a function of fragment kinetic energy. As an example, Fig. 1 shows a relative velocity spectrum measured at 31°. The sharp peak at zero relative velocity is due to decay of the 3.388-MeV state of ^{12}B. This peak contains data used to produce one of the points of Fig. 2. Its detailed line shape is understood quantitatively, as shown by the Monte Carlo calculations[6] for the expected detector response (solid lines). In these calculations all known experimental circumstances and kinematic details of the neutron decay are taken into account. The agree-

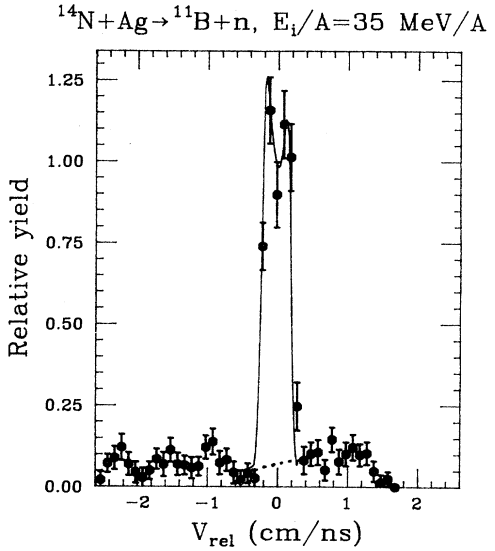

FIG. 1. Relative velocity spectrum for neutrons detected in coincidence with ^{11}B nuclei at 31°. The ^{11}B kinetic energy bin is $E/A=8$–10 MeV. The dotted line represents the background assumed in the analysis; the solid line shows a Monte Carlo fit after background subtraction.

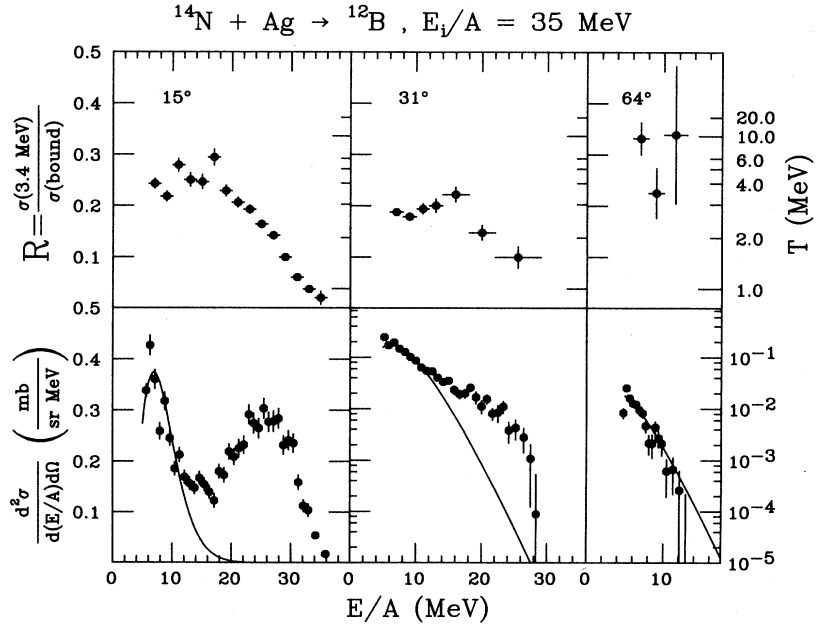

FIG. 2. Upper part: ratio, $R=\sigma(3.4\ MeV)/\sigma(bound)$, of cross sections for the emission of ^{12}B nuclei in their 3.388-MeV state and in their particle-stable states. The horizontal bars indicate the energy bins over which the cross sections were integrated. The right-hand scale gives the temperature for the simplifying assumption of negligible feeding by sequential decays. Lower part: kinetic energy spectra of stable ^{12}B nuclei. The curves show the contribution of the strongly damped component extrapolated from a moving source fit to spectra at six angles, $\theta\geqq 31°$. The detection angles for both upper and lower parts are indicated in the figure.

ment between the data and calculations demonstrates that the cross section, σ(3.4 MeV), can be determined with good accuracy.

Kinetic energy spectra of ^{12}B fragments and measured ratios R are shown in the lower and upper parts of Fig. 2. At 15° the energy spectrum shows two components. A quasielastic component dominates the spectrum at fragment kinetic energies for $E/A \gtrsim 18$ MeV, and a strongly damped component dominates the spectrum at lower energies. The ratio R shows a gradual increase as the energy of the fragment decreases, leveling off at $R \sim 0.25$ for $E/A \lesssim 15$ MeV. For fragments emitted with beam velocity ($E_i/A \approx 35$ MeV), the population of the 3.388-MeV state becomes negligible, $R \approx 0$, indicating that these fragments are emitted with little internal excitation energy. With decreasing fragment kinetic energy, the damping of the quasielastic component increases and more fragments are emitted in the 3.388-MeV state. For orientation, the upper right-hand scale gives the relation between the temperature of the emitting system and the ratio R for primary fragments. For small values, $R \leqq 0.1$, perturbations from sequential decays should be negligible and the temperature scale should be fairly accurate. For larger values of R, sequential decays can introduce larger uncertainties for the exact relation between the emission temperature and the measured values of the populations of states.

At 31° the quasielastic component is strongly suppressed but perhaps not entirely negligible. The energy dependence of R is qualitatively similar to that observed at 15°. At 64° the quasielastic component is clearly insignificant and no statistically significant energy dependence of R is detected. At all angles measured, R is approximately independent of fragment kinetic energy for the strongly damped component, $E/A \lesssim 15$ MeV; the saturation values are $R \approx 0.25$, 0.20, and 0.3 at 15°, 31°, and 64°, respectively. The angular dependence is small and statistically not significant. Provided that side feeding does not lead to significant changes of the saturation values of R, the mean value of 0.24 ± 0.04 would correspond to a temperature of $T \approx 4^{+1.5}_{-1}$ MeV.

It is interesting to compare the emission temperature of 4 MeV with the kinetic temperature of 13 MeV which characterizes the strongly damped component of the ^{12}B kinetic energy spectra. As in earlier experiments,[1-4] the value of the kinetic temperature is larger than that of the emission temperature. The curves in the lower half of Fig. 2 show the results of calculations using parameters of a moving source fit to the ^{12}B spectra at 57°, 64°, 72°, and 83° and to the low-energy parts, $E/A \leqq 12$ MeV, of the spectra at 31° and 38°. The low-energy part of the 15° spectrum is described quite well by a source of velocity $v/c = 0.085 \pm 0.005$ and temperature $T = 13.2 \pm 0.4$ MeV, in spite of the fact that 15° data were not included in the fitting process.

Previous experiments have explored the dependence of emission temperatures, extracted from relative populations of states, upon the kinetic energy of fragments emitted back of the grazing angle, where quasielastic reactions are negligible. For the ^{14}N+Au reaction at $E_i/A = 35$ MeV, a slight energy dependence was measured[2] for the populations of states in ^{6}Li, indicating an increase of the emission temperatures for more energetic particles by about a factor of two if perturbations from sequential feeding could be neglected. However, due to the relatively small level separation of the states investigated, perturbations due to feeding made this result uncertain.[2] Measurements of the relative populations of widely separated states $\Delta E \geqq T$ are less sensitive to perturbations due to feeding. Such measurements were performed for the ^{40}Ar+Au and ^{16}O+Au reactions at $E_i/A = 60$ and 94 MeV, respectively.[3,4] The extracted emission temperatures, $T = 5 \pm 1$ MeV, did not exhibit a significant dependence upon fragment energy; dependences as large as those reported in Ref. 2 were ruled out. Our result for the strongly damped component of the kinetic energy spectrum, showing only a slight, if any, energy dependence of the relative populations of states, is consistent with the latter findings. The strong energy dependence found for the quasielastic component is significant since it establishes a monotonic relation between the relative populations of states and the kinetic energy loss for particles emitted in peripheral reactions, thus providing a quantitative measure of the inelasticity of these reactions. Such measurements could provide useful stimuli to the refinement of models of peripheral reactions.

For a better understanding of the strongly damped component, statistical approaches may be useful. In the model of Friedman[8] for the decay of an expanding "compound" nucleus, the system proceeds through a sequence of temperatures. Yet, complex fragment emission is predicted to occur predominantly over a surprisingly narrow range of temperatures, $T \approx 5 \pm 1$ MeV. While our measurements for the strongly damped component qualitatively support the concept of a characteristic fragment emission temperature,[8] a more stringent test should be performed by investigating model predictions for the relation between the fragment kinetic energy and the relative populations of states.

In summary, we have shown how a measurement of ^{11}B+n coincidences in colinear geometry combined with measurements of inclusive ^{12}B spectra gives direct experimental information on the dependence of ^{12}B excitation on kinetic energy and angle of those fragments. This information bears on the mechanics of the reaction producing the fragments. In the particular reaction investigated, the collisions of ^{14}N ions with Ag at $E_i/A = 35$ MeV, we observed a gradual increase of the excitation of the ^{12}B fragments with decreasing kinetic energy in the energy range where the quasielastic component dominates. Where the strongly damped part dominates the fragment excitation was approximately independent of kinetic energy and of angle.

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