RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 34, NUMBER 2 AUGUST 1986

Thermal population of nuclear excited states

D. J. Morrissey
National Superconducting Cyclotron Laboratory and Department of Chemistry,
Michigan State University, East Lansing, Michigan 48824

C. Bloch, W. Benenson, and E. Kashy
National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy,
Michigan State University, East Lansing, Michigan 48824

R. A. Blue, R. M. Ronningen, and R. Aryaeinejad
National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824

(Received 21 March 1986)

The bound state populations of ^{10}B and ^{7}Be fragments emitted from ^{26}Al compound nuclei formed in the reaction of ^{14}N with ^{12}C have been measured. At bombarding energies in the range of 87.5–112 MeV, these populations are consistent with emission from the thermally equilibrated compound nucleus when the rotational energy of the compound system is taken into account. The results demonstrate for the first time that nuclear excited state populations reflect the temperature of compound nuclei which reach statistical equilibrium. At higher bombarding energies the population distributions remain constant which signals the onset of non-compound nucleus reactions.

Compound nucleus reactions are those in which the projectile and target combine to produce a nucleus in full statistical equilibrium. Such an equilibrium is characterized by a temperature, usually identified with Maxwell-Boltzmann distributions of the kinetic energy degrees of freedom. Morrissey *et al.* have suggested recently that nuclear temperatures also can be characterized by the relative population of bound states of heavy fragments emitted in nuclear reactions.[1,2] This technique has been extended by Pochodzalla *et al.* to measurements of the charged particle decay of unbound states in similar fragments.[3] Interestingly, the populations of the excited states of fragments emitted in these intermediate energy reactions are significantly lower than the apparent temperatures inferred from the kinetic energy distributions of these fragments, implying a lack of statistical equilibrium. Because of these discrepancies, the level-population technique needs to be checked in a system already shown to be in statistical equilibrium. Here we report measurements of the population of bound states of ^{7}Be and ^{10}B fragments from the well-studied reaction of ^{14}N with ^{12}C.[4-6] The present measurements, at bombarding energies from 6.25 to 25 MeV/nucleon, span a region in which the role of the compound nucleus mechanism changes dramatically.[4]

The ratio R of the populations of the ground and excited state in thermal equilibrium is written as

$$R=\frac{(2j_{\mathrm{ex}}+1)}{(2j_{\mathrm{g.s.}}+1)}e^{-\Delta E/kT} , \tag{1}$$

where $j_{\mathrm{g.s.}}$ and j_{ex} are the spins of the ground and excited states, respectively, ΔE is the energy gap between the ground and excited states, and kT is the nuclear temperature. However, this ratio is not directly measurable because the lifetimes of the γ-ray emitting states are short. Rather the *fraction* of the observed nuclei that emit specific γ rays can be obtained from particle-γ-ray coincidence measurements. For systems with only *one* bound excited state (e.g., ^{7}Be) the γ-ray fraction is equal to the fraction of the population initially in the excited state:

$$f_{\mathrm{ex}}=R/(1+R) . \tag{2a}$$

In general, the fraction of the population f_n in a given excited state n is given by

$$f_n=\frac{(2j_n+1)e^{-\Delta E_n/kT}}{\sum_i(2j_i+1)e^{-\Delta E_i/kt}} , \tag{2b}$$

where the sum over i in the denominator, usually called the partition function, includes all the states of the system. The γ-ray fraction for these nuclei is not generally equal to the fraction of the population *initially* in a given state due to γ-ray branching and cascades. The fraction of nuclei in coincidence with a specific γ-ray is rather

$$f_{E_\gamma}=\frac{\sum_n a_n(E_\gamma)(2j_n+1)e^{-\Delta E_n/kt}}{\sum_i(2j_i+1)e^{-\Delta E_i/kt}} . \tag{3}$$

Note that the sum with an index n extends over all higher-lying states that cascade through the state emitting the observed γ ray and includes the branching ratios $a_n(E_\gamma)$. The variation of this γ-ray fraction with temperature is shown for ^{7}Be and ^{10}B in Fig. 1. The effect of cascades can be quite important for transitions to the ground state. Agreement of the population distribution among several pairs of levels is also a good test of thermal equilibrium that does rely on the production of the ground state. Problems involving preferential feeding of any level by the decay of unbound higher mass nuclei (notably the ground state as discussed in Refs. 1 and 2) can be identified by in-

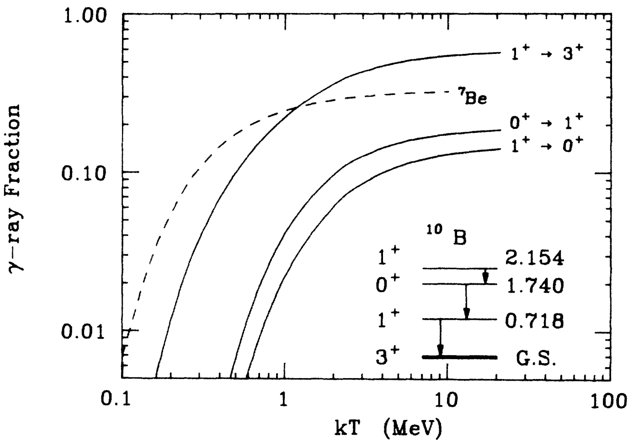

FIG. 1. The calculated fraction of thermally excited ^{10}B (solid curves) and ^{7}Be (dashed curve) nuclei emitting specific deexcitation γ-ray transitions as a function of the temperature. A schematic diagram of the lowest levels of ^{10}B is shown and the ^{10}B curves are labeled by the spins of the states. The branching ratios were taken from Ajzenberg-Selove, Nucl. Phys. **A413**, 1 (1984).

consistencies among the ratios of several levels. It is important to note that these fractions are calculated for first chance emission; second chance emission will occur from nuclei which are at significantly lower temperatures yielding lower fractions.

Another nucleus with only one excited state that has been used in previous studies is ^{7}Li.[1,2] However, ^{7}Li fragments cannot be separated from the decay products of ^{8}Be (correlated alpha particles) by Si surface barrier telescopes,[7] and the number of inclusive ^{7}Li fragments must be corrected for this contamination. This complication is particularly difficult to overcome in the $^{14}\mathrm{N}+{}^{12}\mathrm{C}$ reaction because the cross section for ^{8}Be (isospin zero) is approximately an order of magnitude larger than that for ^{7}Li (isospin $\frac{1}{2}$). Such contamination may contribute to the perplexing disagreement of only the ^{7}Li cross section with Hauser-Feshbach statistical model calculations.[6]

The production of light nuclei in their ground and excited states was studied in the reaction of ^{14}N with carbon using beams with 87.5, 101.5, 112, 168, 210, 280, and 350 MeV provided by the National Superconducting Cyclotron Laboratory at Michigan State University. Bombarding energies of 87.5 and 101.5 MeV were obtained by degrading a 112 MeV beam from the K500 cyclotron with 6.0 and 12.0 mg/cm^2 aluminum foils, respectively, before the first bending magnet of the beam transport system.

A large amount of data was obtained on the inclusive kinetic energy and angular distributions of reaction products from these reactions and on the coincident γ-ray spectra and multiplicities. The details of the experimental arrangement have been discussed in Ref. 2. Briefly, the light nuclei were completely identified by Z, A, and the kinetic energy in one of a set of four silicon surface barrier detector stacks (ΔE 50 μm or 100 μm thick and E 1000 μm thick). Coincident γ-rays were detected in a set of eight 7.6×7.6 cm NaI (Tl) detectors. The solid angles of the particle detectors were 24 msr in the reactions induced by $E/A > 8$ MeV/nucleon ^{14}N ions and 16 msr for the lower bombarding energies. The photopeak efficiency of the γ-ray array was 4.5% at 400 keV. The beryllium and boron nuclei were detected at eight angles ranging from 30 to 65° in 5° steps. The inclusive kinetic energy spectra of the particles were generally exponential in shape, extending up to either the two-body kinematic limit at low bombarding energies or the charged-particle detector cutoffs. The coincidence spectra were quite similar.

The γ rays in coincidence with ^{7}Be and ^{10}B were corrected for Doppler shifts on an event-by-event basis. The spectra in coincidence with ^{7}Be fragments contained only the 428 keV γ ray, whereas the ^{10}B coincidence spectra contained the 414, 718, and 1022 keV transitions on very low backgrounds and with a resolution expected for the detectors ($\approx 7\%$). The γ-ray fractions for the deexcitation transitions of ^{10}B and ^{7}Be were obtained from the ratio of the efficiency-corrected number of full-energy γ-ray coincidences per unit beam current to the total number of particles per unit beam current of the same nucleus. The most complete set of coincidence data, i.e., excited state populations, was obtained at 35° (lab). These γ-ray fractions are shown in Fig. 2. All the additional measurements were consistent with these results with poorer statistics.

In the ^{7}Be case, for which only one γ ray was observed, the temperature was obtained by inverting Eq. (2a) and solving for the temperature. The temperature of the source of the ^{10}B fragments, from which three γ rays were observed, was obtained by a least-squares fit to three simultaneous equations for the γ-ray fractions. The three equations each contained a sum over feeding states and a single temperature, similar to Eq. (3). The results of these determinations are shown in Fig. 3 as a function of bombarding energy. Note that the temperatures obtained from the γ-ray fractions of the two isotopes agree at each bombarding energy. Alternatively, the ^{10}B γ rays can be used to determine the ratios of the populations among the excited states which are also consistent with the temperatures in Fig. 3. This indicates that, at least for this case,

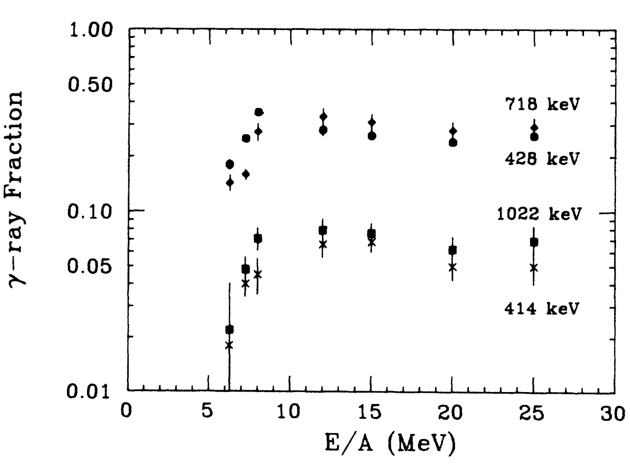

FIG. 2. The measured fractions of ^{7}Be and ^{10}B nuclei ($\theta_{\mathrm{lab}}=35°$) in coincidence with specific γ-ray transitions as a function of the beam velocity (in MeV/A). The data points are labeled by transition energy.

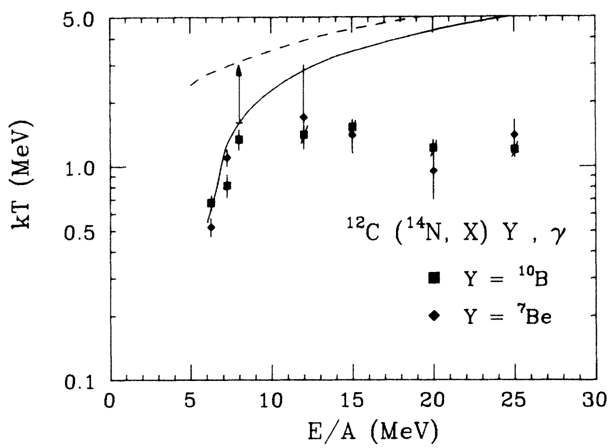

FIG. 3. "Population distribution" temperature of ^{7}Be and ^{10}B fragments from the reaction of $^{14}N+^{12}C$ as a function of bombarding energy. The expected temperature with a rotational energy of 36 MeV follows the solid curve (see the text). The expected temperature with zero rotational energy is indicated by the dashed curve.

decay of higher mass nuclei is not an important factor. Our results indicate an increasing temperature over the range of 87.5 to approximately 112 MeV. At higher energies we observe a constant source temperature.

We can make a simple estimate of the variation of the temperature of the compound nucleus ^{26}Al with beam energy, by relying on previous measurements of this system. In the Fermi gas model the temperature of a compound nucleus is $kT \approx (E_{\rm th}/a)^{1/2}$, where a is the level density parameter. We expect that the excited state populations of these large fragments will reflect the average thermal excitation of the compound nucleus $\langle E_{\rm th}\rangle$ written as

$$\langle E_{\rm th}\rangle = E_X - \frac{\langle l\rangle^2\hbar^2}{2\mathcal{J}} , \qquad (4)$$

where E_X is the total excitation energy of the system (equal to the energy in the center of mass plus Q_0, the ground state Q value for forming ^{26}Al). The second term in Eq. (4) represents the average rotational energy of the system with $\langle l\rangle\hbar$ as the average angular momentum and $\mathcal{J}$, as the moment of inertia of the compound nucleus. Reasonable values of the maximum angular momentum ($26\hbar$) and the rotational constant ($2\mathcal{J}/\hbar^2 = 8$ MeV^{-1}) can be obtained from previous studies[4] which are in good agreement with the rotating liquid drop model predictions.[8] We note that for the bombarding energies used in the present study the average angular momentum of the compound nucleus remains approximately constant at $17\hbar$. Figure 3 shows the variation of the temperature before subtracting the rotational energy (dashed curve) and that calculated after subtracting a constant rotational energy of 36 MeV (solid curve). The level density parameter had a value of 4.8 MeV^{-1}.[9] The agreement between the calculated and measured temperature is quite good up to ≈ 112 MeV; at higher energies the data fall well below the expected temperature. Thus, we find that the excited state populations drop below the expected values in the same bombarding energy range at which previous measurements have shown both a dramatic increase in the yield of direct reactions[4] and production of Li and Be fragments as evaporation residues.[10] We note that the energy tied up in rotation of the emitting systems in intermediate energy heavy-ion reactions is usually not considered and could be part of the explanation of the low temperatures obtained in Refs. 1-3.

In summary, we have tested a new technique for measuring the temperature of a nuclear system which relies on the populations of the ground and excited states of emitted nuclei. We have shown that the populations of ^{7}Be and ^{10}B nuclei emitted in their ground and excited states from the reaction of $^{14}N+^{12}C$ are consistent with thermal equilibrium at bombarding energies below ≈ 112 MeV but not above.

We would like to thank R. G. Stokstad for suggesting that we test our technique with the $^{14}N+^{12}C$ system. This work was supported by the National Science Foundation under Grant No. PHY-83-12245.

---

[1] D. J. Morrissey, W. Benenson, E. Kashy, B. Sherrill, A. D. Panagiotou, R. A. Blue, R. M. Ronningen, J. van der Plicht, and H. Utsunomiya, Phys. Lett. **148B**, 423 (1984).

[2] D. J. Morrissey, W. Benenson, E. Kashy, C. Bloch, M. Lowe, R. A. Blue, R. M. Ronningen, B. Sherrill, H. Utsunomiya, and I. Kelson, Phys. Rev. C **32**, 877 (1985).

[3] J. Pochodzalla, W. A. Friedman, C. K. Gelbke, W. G. Lynch, M. Maier, D. Ardouin, H. Delagrange, H. Doubre, C. Grégoire, A. Kyanowski, W. Mittig, A. Péghaire, J. Péter, F. Saint-Laurent, Y. P. Viyogi, B. Zwieglinski, G. Bizard, F. Lefèbvres, B. Tamain, and J. Québert, Phys. Rev. Lett. **55**, 177 (1985).

[4] J. Gomez del Campo, J. A. Biggerstaff, R. A. Dayras, D. Shapira, A. H. Snell, P. H. Stelson, and R. G. Stokstad, Phys. Rev. C **29**, 1722 (1984); R. G. Stokstad, R. A. Dayras, J. Gomez del Campo, P. H. Stelson, C. Olmer, and M. S. Zisman, Phys. Lett. **70B**, 289 (1977), and references therein.

[5] R. G. Stokstad, M. N. Namboodiri, E. T. Chulick, J. B. Natowitz, and D. L. Hanson, Phys. Rev. C **16**, 2249 (1977).

[6] R. G. Stokstad, in *Proceedings of the International Conference on Reactions Between Complex Nuclei, Nashville, Tennessee, 1974,* edited by R. L. Robinson, F. K. McGowan, J. B. Ball, and J. H. Hamilton (North-Holland, Amsterdam, 1974), Vol. II, p. 327.

[7] G. J. Wozniak, H. L. Harney, K. H. Wilcox, and J. Cerny, Phys. Rev. Lett. **28**, 1278 (1972).

[8] S. Cohen, F. Plasil, and W. J. Swiatecki, Ann. Phys. (N.Y.) **82**, 27 (1974).

[9] J. Toke and W. J. Swiatecki, Nucl. Phys. **A372**, 141 (1981).

[10] J. Gomez del Campo, R. G. Stokstad, J. A. Biggerstaff, R. A. Dayras, A. H. Snell, and P. H. Stelson, Phys. Rev. C **19**, 2170 (1979).