PHYSICAL REVIEW C VOLUME 41, NUMBER 5 MAY 1990

New test of the excited state population method for measurements of nuclear temperatures

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(Received 21 August 1989)

Excited state production has been measured for ^{7}Li, ^{7}Be, and ^{10}B fragments emitted in the ^{40}Ar+^{12}C reaction at $E/A=8$, 10, and 12 MeV. The use of reverse kinematics and a system with low rotational kinetic energy permitted a more direct test of the excited state method for temperature determination than had previously been possible. The results show that the population of excited states reflects the temperature expected from Fermi gas calculations at the appropriate excitation energy for the compound nucleus and is consistent with the temperature determined from the slope of the fragment spectra.

A key question in the study of nuclear dynamics at medium and high energies concerns the temperature and degree of equilibrium reached in collisions between complex nuclei. Until a few years ago the inverse slope parameter of the light particle spectra was taken to be a measurement of the temperature reached in the collision. A perplexing puzzle was that the temperature determined this way seemed to pass smoothly through and well beyond the point at which nuclear matter should undergo a liquid-gas phase transition. An alternate method[1] for temperature determination, the excited state population method, was proposed and gave significantly different temperatures from those determined from the particle spectra. One attempt[2] to establish the reliability of the new method by studying a compound nuclear system with a known temperature was hindered by the small moment of inertia of the system, which permitted a large fraction of the available energy to go into rotational motion. In addition, the low bombarding energy led to laboratory conditions in which a fairly large fraction of the fragment spectra were obscured by detector thresholds. The present experiment is a new attempt to establish the excited state population method for nuclear temperature determination for a better choice of system and experimental situation.

The excited state population method for nuclear temperature measurement relies on the Boltzmann factor for a system with energy levels in equilibrium at a finite temperature. For example, the ratio of the population of a state with excitation energy $E_{\rm ex}$ and angular momentum $J_{\rm ex}$ to that of the ground state should be given by

$$R=\frac{(2j_{\rm ex}+1)}{(2j_{\rm gs}+1)}e^{-(E_{\rm ex}/kT)}\,, \tag{1}$$

where $j_{\rm gs}$ is the ground-state angular momentum, and T is the temperature. It follows that the γ fraction f_n of the detected particles that are in the nth excited state is given by

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

where the summation in the denominator extends over all states that lead to the ground state. In addition if there are gamma-ray cascades within the nucleus being studied, the formula has to modified for such feeding as was done in formula (3) of Ref. 2. Measurements that employed this method for bound[1,3] and a variation on it for unbound[4] states produced in reactions in the intermediate energy ($E/A>20$ MeV) range yielded temperatures that seem to be independent of bombarding energy and are consistently lower than the temperature obtained from the energy spectra of the emitted light fragments. The simple explanation for this disagreement could be that the population method is not applicable to the nuclear case.[5] Another explanation is that the difference arises from preferential feeding of the ground state by sequential decay.[6] However, sequential decay only distorts the measured population of excited states if the temperature is high enough to excite fragments into states that lie above their neutron, proton, and alpha separation ener-

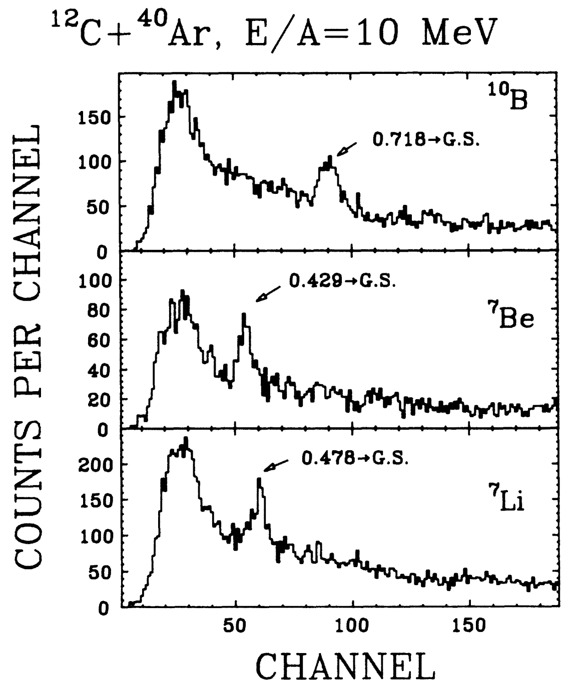

FIG. 1. Doppler shift corrected γ-ray energy spectra in coincidence with light fragments at $E/A=10$ MeV.

gies. Since these nuclei are produced with much more negative Q values, they are formed weakly and do not contribute to the feeding to ^{7}Be or ^{7}Li appreciably at low bombarding energies. For example at $E/A=8$ MeV, the yield of ^{8}Li is less than 1% of that for ^{7}Li, and even at $E/A=12$ MeV, it is less than 4%.

An attempt to test the population method for the determination of nuclear temperatures was made by Morrissey *et al.*[2] who studied ^{10}Be and ^{7}Be fragments from the ^{12}C+^{14}N reaction in and just above the compound nucleus regime, 6 MEV $<E/A<20$ MeV. At all energies a very good internal consistency was found for the four levels of ^{10}B, which have different spins ranging from 0^{+} to 3^{+}. At the lowest beam energies the measured temperatures from the different transitions in ^{10}B agreed very well with those obtained from ^{7}Be and ^{7}Li. However, in order to bring the population distribution temperature into agreement with that calculated from the Q value and center-of-mass energy, a correction had to be made for the rotational energy of the compound system. Although certainly correct, this procedure has inherent uncertainties and at the lowest energies is a dominant contribution to the calculation of the available thermal energy. This problem can be eliminated by the choice of a compound system that has a moment of inertia appreciably larger than that of ^{26}Al. The present experiment utilized the ^{40}Ar+^{12}C reaction to avoid this problem and in addition, because of the reverse kinematics, permitted the detection of many more heavy fragments and, for the light fragments, a much greater range of energies in the center-of-mass frame.

The experiment was carried out at the National Superconducting Cyclotron Laboratory with the $k500$ cyclotron. The beams were $E/A=8$, 10, and 12 MeV ^{40}Ar, and the target was a self-supporting foil of ^{12}C, 490-μg/cm^{2} thick. The same NaI detector array described in Ref. 3 was used in the present experiment for γ-ray detection. In addition a pair of Ge γ-ray detectors were employed for resolving levels in the heavier fragments. Four charged particle detector telescopes were located at $\theta=11$ deg and $\phi=4$, 176, 184, and 356 degrees. This angle θ is greater than the classical grazing angle for this reaction (6 deg). Each telescope included three elements 3, 75, and 1000 μm thick, respectively. Isotope identification was obtained up to $Z=11$ with these detector telescopes. The ^{7}Li data were corrected for the contamination due to ^{8}Be decays.[7] Because of the relatively small solid angle of the particle detectors, this was not a major correction (4 to 10% depending on beam energy). Fragments with $A>12$ have complex decay schemes that include rotational bands and many unmeasured branching ratios. The results from these heavier fragments will appear in a later publication. More details on the experiment can be found in the doctoral dissertation of J. H. Lee.[8]

The gamma-ray spectra in coincidence with the various detected fragments were corrected for Doppler shift on an event-by-event basis. Figure 1 gives the gamma-ray spectra in the NaI detectors Doppler shifted and summed. The background under the gamma-ray peaks of

TABLE I. Deduced nuclear temperatures from ^{7}Li, ^{7}Be, and ^{10}B.

E/A (MeV)	Isotope	E_{γ} (keV)	$f_n(the)$[a]	$f_n(\exp)$	kT (meV)
8	^{7}Li	478	0.260	0.287±0.024	$2.2^{+2.3}_{-0.8}$
	^{7}Be	429	0.266	0.279±0.038	$1.7^{+4.0}_{-0.8}$
	^{10}B	718	0.370	0.317±0.054	$1.6^{+0.5}_{-0.4}$
10	^{7}Li	478	0.272	0.291±0.038	$2.4^{+20}_{-1.2}$
	^{7}Be	429	0.278	0.290±0.034	$2.1^{+7.9}_{-0.9}$
	^{10}B	718	0.400	0.406±0.062	$2.6^{+1.6}_{-0.6}$
12	^{7}Li	478	0.284	0.204±0.016	$0.72^{+0.11}_{-0.10}$
	^{7}Be	429	0.289	0.238±0.022	$0.91^{+0.29}_{-0.19}$
	^{10}B	718	0.432	0.374±0.046	$2.2^{+0.4}_{-0.3}$

[a]Predicted gamma fraction. See the text for details.

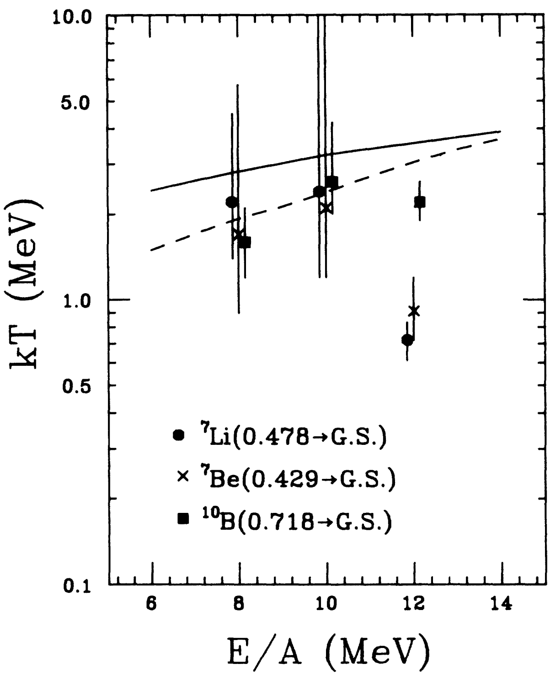

FIG. 2. Observed temperatures from the γ-ray transitions in ^{7}Li, ^{7}Be, and ^{10}B. The solid and dashed lines are the predictions of the Fermi gas model with and without correction for the rotational energy as described in the text.

interest is due to the gamma rays emitted by other products of the collision. Its shape was estimated from the gamma spectra in coincidence with ^{6}Li fragments which have no excited states which emit gamma rays in this spectral range. An appreciable portion of the uncertainty in the population determination derives from this background subtraction process. The efficiency of the NaI detectors was determined to within 5% by placing radioactive sources at the target position.

A summary of the results of the population determinations is given by Table I and in Fig. 2. The uncertainty in the temperature was calculated by evaluating Eq. (2) for the range of values given by the population and its uncertainty. This leads to large and rather asymmetric uncertainties for the temperature. The measured values for the fraction of nuclei in each excited state, however, can be compared to that calculated with the Fermi gas model for the compound system. In this case the compound system was taken to be ^{52}Cr at the scission point for breaking into two fragments with masses similar to those under study. Since the system is rotating, not all of the energy is thermal. A correction for this can be made by subtracting the calculated rotational energy from the excitation energy. Thus the available thermal energy E^*_{th} is given by

$$E^*_{\mathrm{th}} = E^* - \langle E_{\mathrm{rot}} \rangle \,, \tag{3}$$

where

$$E^* = E^*_{\mathrm{CMS}} + Q \tag{4}$$

and E^*_{CMS} is the kinetic energy available in the center-of-mass system (CMS), and Q is the Q value for formation of the compound nucleus system. In this case the Q value is that for $^{12}C+^{40}Ar$ leading to ^{52}Cr but corrected by 31.1 MeV for the surface energy difference between a spherical compound nucleus and one at the scission point. The quantity $\langle E_{\mathrm{rot}} \rangle$ is the average rotational energy which is taken to be

$$\langle E_{\mathrm{rot}} \rangle = \bar{l}(\bar{l}+1)/2\zeta \,. \tag{5}$$

The moment of inertia ζ was assumed to be that of a rigid sphere, and the average value of the angular momentum of the rotating compound nucleus, $\bar{l}$, was calculated from estimates of the critical angular momentum for fusion of the system. The relation between the excitation energy and the temperature was taken to be

$$E^* = a(kT)^2 \,. \tag{6}$$

The parameter a was taken from the prescription of Toke and Swiatecki.[9] The resulting calculated temperatures $\langle kT \rangle$ are given in Table II and in Fig. 2 by the dashed line. The solid curve indicates the nuclear temperature, in the column labeled kT in Table II, before the removal of the rotational energy. For the most part, the measurements are in good agreement with the predictions of statistical equilibrium at the lower two beam energies. The population temperature drops significantly below the calculated values at $E/A=12$ MeV because of the onset of sequential feeding to the ground state by particle unbound states of heavier fragments. This can be seen in Fig. 3, which shows the calculated effect of this feeding according to the quantum statistical model.[6] This result is in good agreement with the conclusions of Gomez del Campo *et al.*[10] who studied the $^{58}Ni+^{58}Ni$ system at $E/A=11$ MeV.

The singles kinetic-energy spectra of the emitted particles in the center-of-mass frame were fit by a chi-squared minimization procedure using a Maxwell-Boltzmann function

$$N(E) \propto (E-C)e^{-(E-C)/kT} \,, \tag{7}$$

TABLE II. Nuclear temperatures in the Fermi gas model (units in MeV) as compared to the slope temperatures.

E/A	E^*	kT	$\langle E_{\mathrm{rot}} \rangle$	$E^*-\langle E_{\mathrm{rot}} \rangle$	$\langle kT \rangle^a$	kT_{slope}
8	63.2	2.82	33.4	29.8	1.93	3.28±0.14
10	81.7	3.23	36.1	45.6	2.39	3.98±0.28
12	100.1	3.55	36.1	74.0	3.04	4.04±0.18

[a]Average temperature with rotational energy taken into account.

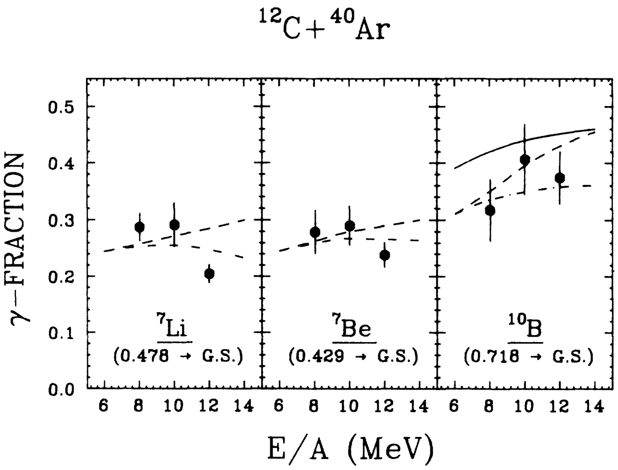

FIG. 3. The effect of sequential feeding on the fraction of nuclei in excited states. The solid line is the fraction calculated from the nuclear temperature according to the Fermi gas model. The solid line has been omitted from the first two panels since it lies very close to the dashed line which is the fraction corrected for rotational energy. The dot-dashed line is corrected for both sequential decay according to Ref. 6 and the rotational energy as described in the text.

where kT is the slope parameter, called kT_{slope} in Table II, and C is the Coulomb barrier correction. Complete moving source fits, as normally carried out at higher energies, were not possible because the data were taken at one fixed angle. Table II gives the average slope parameters obtained for the three isotopes and three beams energies described in the present paper. The slope temperature should reflect the available thermal energy E^*, uncorrected for the rotational energy.[11] The agreement of the slope temperatures with the calculated nuclear temperature is fair and not as good as the population temperatures. However, it has been suggested that the spectra should be fitted with Gaussians in this energy domain.[10] However, a comparison to methods used at higher beam energies (Boltzmann distributions) is more meaningful if identical techniques are used as much as possible.

The main conclusion of the present work is that excited state populations give a good measure of the temperature of the emitting system provided the fragments are the primary ones produced by a system in statistical equilibrium. At beam energies above $E/A=10$ MeV, the effects of sequential feeding must either be measured (as was done by Bloch *et al.*[12]) or calculated to be able to make an accurate temperature determination. Alternately the effects of sequential feeding can be minimized by comparison of high-lying excited state populations or by comparisons of states which do not include ground states. The disagreement between the slope and population temperatures at higher beam energies is therefore a serious problem, the solution of which may lie in the time evolution of the system as pointed out by Boal[13] and Friedman.[14].

This work was supported in part by the National Science Foundation under Grant No. PHY 86-11210.

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[1] D. J. Morrissey *et al.*, Phys. Lett. **148B**, 423 (1984).
[2] D. J. Morrissey *et al.*, Phys. Rev. C **34**, 761 (1986).
[3] C. Bloch *et al.*, Phys. Rev. C **36**, 203 (1987).
[4] A. Kiss *et al.*, Phys. Lett. B **184**, 149 (1987); J. Pochadzalla *et al.*, Phys. Lett. **161B**, 275 (1985); Phys. Rev. C **35**, 1695 (1987).
[5] N. R. Dagdeviren, Phys. Lett. **B176**, 283 (1986).
[6] D. Hahn and H. Stoecker, Phys. Rev. C **35**, 1311 (1987).
[7] C. Bloch *et al.*, Phys. Rev. C **34**, 850 (1986).
[8] J. H. Lee, Ph.D. thesis, Michigan State University (unpublished).
[9] J. Toke and W. J. Swiatecki, Nucl. Phys. **A372**, 141 (1981).
[10] J. Gomez del Campo *et al.*, Phys. Rev. Lett. **61**, 290 (1989).
[11] R. C. Reedy, M. J. Fluss, G. F. Herzog, L. Kowalski, and J. M. Miller, Phys. Rev. C **188**, 1771 (1969).
[12] C. Bloch *et al.*, Phys. Rev. C **36**, 203 (1987).
[13] D. Boal, Phys. Rev. C **30**, 749 (1984).
[14] W. A. Friedman, Phys. Rev. Lett. **21**, 2125 (1988).