Nuclear Temperatures and the Population of Particle-Unstable States of ^{6}Li in ^{40}Ar-Induced Reactions on ^{197}Au at $E/A = 60$ MeV

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Correlations between coincident alpha particles and deuterons emitted in ^{40}Ar-induced reactions on ^{197}Au at $E/A = 60$ MeV were measured. The relative populations of particle-unstable states of ^{6}Li were extracted. The measured spectra are consistent with a mean nuclear temperature at emission of $T \approx 5$ MeV. Limitations of temperature measurements via the population of excited states are discussed.

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Complex-particle emission in intermediate- and high-energy nucleus-nucleus collisions presents a problem of such complexity that recourse to statistical methods seems appropriate. Statistical-model calculations are often based on the assumption of particle emission from equilibrated subsets of nucleons.[1–4] In specifying the phase space of decay configurations, in-medium corrections are nearly always neglected and the *asymptotic* nuclear states (bound and unbound) are used. Such calculations make specific predictions about the relative populations of ground and excited states of the emitted fragments. Indeed, in each model a unique relation exists between the relative population of states and the temperature at the point at which the particles leave the equilibrated subsystem. In principle, this "emission temperature" can be deduced from the relative population of excited states.

An approach of this nature involving a measurement of the relative population of ground and particle-stable excited states was recently used[5] to determine the emission temperature for ^{14}N-induced reactions on ^{107}Ag at $E/A = 35$ MeV. Surprisingly few ^{6}Li, ^{7}Li, and ^{7}Be nuclei were observed in particle-stable excited states. This observation was interpreted to imply emission temperatures $T \leq 1$ MeV, significantly smaller than either the temperature of the compound nucleus or the temperature parameters which characterize the kinetic-energy spectra of these light nuclei.[5] However, the relative population of ground and *long-lived* excited states can be altered by the sequential decay of primary fragments produced in particle-unbound states[5] or by neutron-induced deexcitations[6] which can occur after emission from an equilibrated system. In order to reduce the effects from sequential decay, it is desirable to investigate the population of *short-lived* particle-unstable states.

We have measured the population of particle-unbound states of ^{6}Li for ^{40}Ar-induced reactions on ^{197}Au at $E/A = 60$ MeV. For this heavier projectile-target combination, complicating surface and finite–particle-number effects should be reduced, and a higher degree of thermalization might be expected. Inclusive cross sections, measured for ^{40}Ar + ^{197}Au collisions over a large range of energies and fragment masses, were interpreted in terms of statistical emission mechanisms.[7]

The experiment was performed at the Laboratoire Grand Accélérateur National d'Ions Lourds, at Caën. A gold target of 10-mg/cm^2 areal density was irradiat- by a beam of ^{40}Ar of $E/A = 60$ MeV incident energy. The size of the beam spot on target was approximately 1×2 mm^2. Light particles ($Z \leq 3$) were detected by a close-packed hexagonal array of ΔE-E telescopes, each consisting of a 400-μm-thick Si detector and a 10-cm-thick NaI detector. The center of the hodoscope was positioned at a laboratory angle of 30°. Each telescope subtended a solid angle of 0.46 msr; the angular separation between adjacent telescopes was 4.2°. The energy calibrations of the hodoscope, established for all isotopes with $Z \leqslant 3$, are accurate to within 2%. A complete description of the experimental details will be given elsewhere.

Figure 1 shows the measured α-d correlation function, $R(q)$, defined by

$$\sigma_{\alpha d}(\mathbf{p}_\alpha, \mathbf{p}_d) = C\sigma_\alpha(\mathbf{p}_\alpha)\sigma_d(\mathbf{p}_d)[1+R(q)]. \qquad (1)$$

Here, $\sigma_{\alpha d}$ and σ_α, σ_d denote the two-particle and single-particle inclusive cross sections for alpha particles and deuterons, respectively; $\mathbf{p}_\alpha$ and $\mathbf{p}_d$ are the laboratory momenta; q is the momentum of relative motion; and C is a normalization constant which is determined by the requirement that $R(q)=0$ for $q = 160$–200 MeV/c. The measured correlation function exhibits two maxima corresponding to the $T=0$, $J^\pi = 3^+$ state in ^{6}Li at 2.186 MeV ($\Gamma = 24$ keV, $\Gamma_\alpha/\Gamma_{tot} = 1.00$) and the overlapping $T=0$, $J^\pi = 2^+$ states at 4.31 MeV ($\Gamma = 1.3$ MeV, $\Gamma_\alpha/\Gamma_{tot} = 0.97$), and at 5.65 MeV ($\Gamma = 1.9$ MeV, $\Gamma_\alpha/\Gamma_{tot} = 0.74$).[8]

The coincidence yield resulting from the decay of excited ^{6}Li nuclei was obtained by the assumption that the α-d coincidence yield is given by $Y_{\alpha d} = Y_{^6\mathrm{Li}} + Y_b$, where $Y_{^6\mathrm{Li}}$ denotes the yield from decaying ^{6}Li nuclei and Y_b denotes the "background" yield. The background yield was assumed to be given by $Y_b = CY_\alpha Y_d[1+R_c(q)]$, where Y_d and Y_α are the singles yields and $R_c(q)$ corresponds to the correlation function expected from the Coulomb repulsion of the two coincident particles.[9,10] This background is indicated by the solid curves in Fig. 1. Yields of particle-unstable excited ^{6}Li nuclei, shown in Fig. 2, were extracted by binning of the experimental yield with respect to the kinetic energy in the ^{6}Li rest frame and subtraction of the background yield shown in Fig. 1.

The yield $Y_{^6\mathrm{Li}}(E^*)$ is related to the energy spectrum, $dn(E)/dE$, in the ^{6}Li center-of-mass frame by the equation

$$Y_{^6\mathrm{Li}}(E^*) = \int \epsilon(E^*, E)\, \frac{dn(E)}{dE}\, dE. \qquad (2)$$

Here, $\epsilon(E^*, E)$ is the efficiency function for the response of the hodoscope to α-d pairs arising from the decay of excited ^{6}Li nuclei; E and E^* denote the actual and measured excitation energies, respectively.

The efficiency function for our hodoscope was calculated for the precise geometry, light-particle-detection thresholds ($E_d \geqslant 15$ MeV, $E_\alpha \geqslant 40$ MeV), and detector energy resolution that was determined during the experiment. In these calculations, the parent nucleus, ^{6}Li*, was assumed to decay isotropical-in its rest frame. The laboratory energy spectra and angular distributions of excited ^{6}Li nuclei were constrained to be identical to the spectra shown in Fig. 3 for the emission of particle-stable ^{6}Li nuclei. Because of the high detection thresholds for particle-stable Li nuclei, it was necessary to extrapolate the measured cross sections toward lower energies. For this extrapolation, simple analytic functions were fitted to the data. Two different extrapolations are shown in the figure. The calculated yields are insensitive to the detailed form of these parametrizations, provided that they reproduce the measured ^{6}Li cross sections.

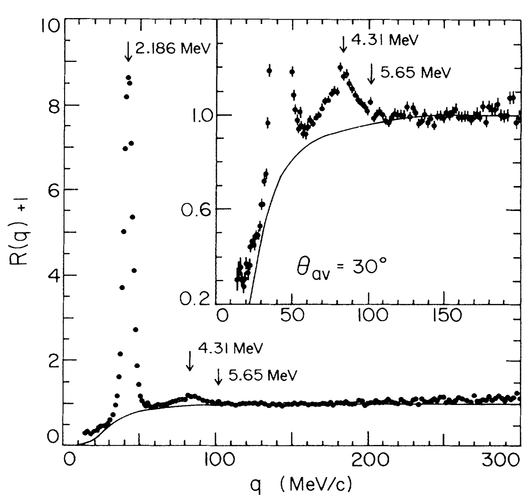

FIG. 1. Correlation function for coincident deuterons and alpha particles for ^{40}Ar-induced reactions on ^{197}Au at $E/A = 60$ MeV. The curve is explained in the text.

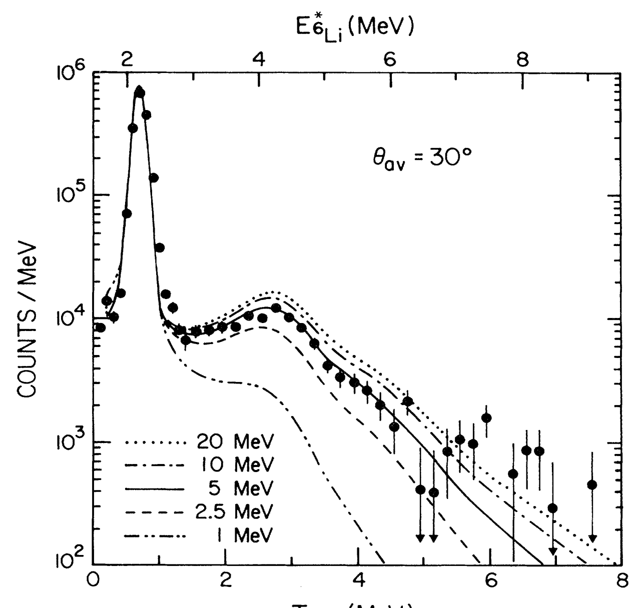

FIG. 2. Energy spectrum resulting from the decay of particle-unbound states in ^{6}Li. The curves correspond to thermal distributions, $T = 1$, 2.5, 5, 10, and 20 MeV in Eq. (2), taking the response of the hodoscope into account.

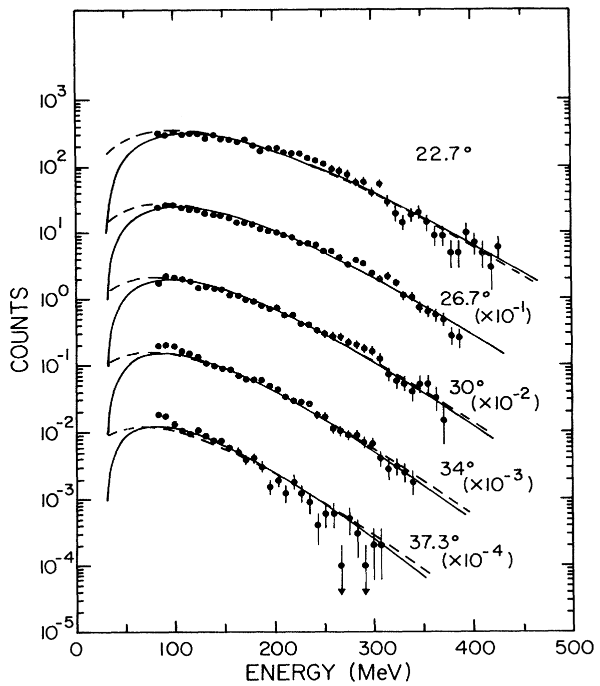

FIG. 3. Energy spectra of particle-stable ^{6}Li nuclei and two examples of cross-section parametrizations used for the calculations of the hodoscope response. The parametrizations were of the form $d^2\sigma/dEd\Omega = CE'^{1/2}\exp(-E'\sin^2\theta/T_1 - E^*/T_2)$, with $E' = E - V_c$, $E^* = E'\cos^2\theta + E_0 - 2(E'E_0)^{1/2}\cos\theta$, and $E_0 = mv_0^2/2$; m is the mass of ^{6}Li. The solid curves correspond to the parameters $T_1 = 17.7$ MeV, $T_2 = 40.1$ MeV, $v_0/c = 0.16$, and $V_c = 30$ MeV; the dashed curves correspond to $T_1 = 19.5$ MeV, $T_2 = 29.7$ MeV, $v_0/c = 0.186$, and $V_c = 0$.

The excitation energy spectrum dn/dE for thermally emitted ^{6}Li nuclei is given by

$$\frac{dn(E)}{dE} = Ne^{-E/T} \cdot \sum_i \left[\frac{(2J_i+1)\Gamma_i/2\pi}{(E-E_i)^2 + \Gamma_i^2/4} \frac{\Gamma_{\alpha,i}}{\Gamma_i} \right], \quad (3)$$

where N is a normalization constant and the sum includes the three $T=0$ excited states of ^{6}Li below 10 MeV excitation energy. Equation (3) corresponds to the phase-space modifications arising from the α-d interaction[11]

$$\frac{dn}{dE} = \frac{1}{\pi} \sum_J (2J+1) e^{-E/T} \frac{\partial \delta_J(E)}{\partial E}, \quad (4)$$

if the energy dependence of the phase shifts, $\delta_J(E)$, is dominated by a series of resonances. For narrow resonances, the relative yields are given by

$$\exp(-E_i/T)(2J_i+1)\Gamma_{\alpha,i}/\Gamma_i. \quad (5)$$

Calculations based on Eqs. (2) and (3) are shown in Fig. 2 for a variety of emission temperatures. The calculations were normalized to reproduce the experimental yield over the energy range of $T_{\text{c.m.}} = 0.3$–1.2 MeV. The spectral shapes are sensitive to emission temperatures smaller than the level separation; higher emission temperatures are more difficult to distinguish. The experimental yields are consistent with an emission temperature of $T \approx 5$ MeV. This value is lower than the temperature parameter $T \approx 20$ MeV which characterizes the energy spectra of complex nuclei emitted at intermediate rapidity,[7] but higher than the one reported[5] for ^{14}N-induced reactions at $E/A = 35$ MeV.

At this point, we wish to caution that temperatures deduced from measurements of the relative population of states may have large uncertainties whenever the primary population ratio is altered by secondary processes. To demonstrate this, we consider the population ratio of two states separated by the excitation energy ΔE. If the primary population ratio $R = C\exp(-\Delta E/T)$ is altered by a factor α, and if the resulting ratio is then interpreted in terms of a temperature T', i.e., $C\exp(-\Delta E/T') = \alpha R$, one obtains $T' = T/(1 + T/\beta)$, with $\beta = -\Delta E/\ln(\alpha)$. Only in the limit $\beta >> T$ will T' agree with the temperature T; if, on the other hand, $\beta << T$, one obtains $T' = \beta = -\Delta E/\ln(\alpha)$, independent of T. Large values of β can be achieved by selection of states whose population is not altered after emission from the equilibrated system and/or by comparison of states which are widely separated in energy. If one cannot ensure that α is close to unity (or else that the value of α is precisely known), the population ratios will only be useful for $T \leqslant \Delta E$.

The ground state, in particular, can be strongly fed by the sequential decay of primary fragments. From our measurements we obtain a population ratio $\sigma_1/\sigma_0 = 0.8 \pm 0.2$, where σ_0 denotes the integrated cross section for particle-stable ^{6}Li and σ_1 denotes the integrated cross section of ^{6}Li emitted in the 2.186-MeV state. If one ignored the complication of sequential decay, this ratio would indicate a temperature of $T' = 2.2^{+0.7}_{-0.6}$ MeV. The measured population ratio can also result from an emission temperature of 5 MeV and a secondary enhancement of the ground-state population by a factor of 1.7.

The present investigation confirms that particle-unstable states of light nuclei are strongly populated in intermediate-energy nucleus-nucleus collisions. The shape of the experimental excitation energy spectrum is consistent with a thermal distribution characterized by an emission temperature of $T \approx 5$ MeV. Higher temperatures cannot be ruled out with certainty since the interpretation of the data becomes uncertain for $T >> \Delta E$. The extent to which the spectrum is influenced by processes which occur after emission requires further detailed investigations.

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