ENERGY DEPENDENCE OF SOURCE RADII AND EMISSION TEMPERATURES FOR ^{14}N INDUCED REACTIONS AT E/A = 35 MeV

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Received 20 February 1986

Correlations between coincident alpha particles and deuterons emitted in ^{14}N induced reactions on ^{197}Au at E/A = 35 MeV are measured. Source radii ($r_0 \approx 3$–4 fm) and emission temperatures ($T \approx 9$–3 MeV) are extracted and shown to depend on the kinetic energy of the emitted particles.

The emission of complex particles prior to the attainment of full statistical equilibrium of the composite system is clearly established for intermediate energy nucleus–nucleus collisions [1,2]. In the absence of a complete dynamical treatment, recourse is often taken to models based on the assumption of statistical particle emission from subsets of nucleons [1–5] characterised by their average velocity, space–time extent, and excitation energy or "temperature". The experimental determination of the detailed characteristics of these subsets from single-particle inclusive cross sections [6] can be uncertain due to sensitivities to collective motion [7] and the temporal evolution of the emitting system [2,8–10].

Information about the space–time extent of the emitting system can be obtained from the two-particle correlation function [11–13]. "Emission temperatures" can be extracted from the relative population of states [14–17]. To first order within the framework of equilibrium thermodynamics, the two-particle correlation function and the relative decay yields are independent functions of one variable each [13], the source volume and temperature, respectively. In this approximation, measurements of these two experimental quantities provide independent information on the temperature and the space–time evolution of the emitting system. In this letter, we simultaneously investigate source dimensions *and* emission temperatures for ^{14}N induced reactions at E/A = 35 MeV, by measuring correlations betwen coincident deuterons and alpha particles. Evidence is presented for a dependence of source radii and emission temperatures on the kinetic energy of the detected particles.

The experiment was performed at the National Superconducting Cyclotron Laboratory of Michigan State University. A gold target of 19 mg/cm^2 areal density was irradiated by a beam of ^{14}N of E/A = 35 MeV incident energy. Light particles ($Z \leqslant 2$) were detected by a close-packed hexagonal array of 13 ΔE – E telescopes, each consisting of a 400 μm thick Si detector and a 10 cm thick NaI detector. Each telescope subtended a solid angle of 0.94 msr; the angular separation between adjacent telescopes was 6.1°. The energy calibrations of individual detectors are accurate to within 3%. Measurements were performed with the center of the hodoscope positioned at laboratory angles of 35° and 50°. Single-particle inclusive cross sections of ^{6}Li were measured in a separate experiment

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0370-2693/86/$ 03.50

using standard ΔE–E techniques.

The α–d correlation function, $R(q)$, is defined in terms of the singles yields, $Y_\alpha(\boldsymbol{p}_\alpha)$ and $Y_d(\boldsymbol{p}_d)$, and the coincidence yield, $Y_{\alpha d}(\boldsymbol{p}_\alpha, \boldsymbol{p}_d)$:

$$Y_{\alpha d}(\boldsymbol{p}_\alpha, \boldsymbol{p}_d) = C Y_\alpha(\boldsymbol{p}_\alpha) Y_d(\boldsymbol{p}_d)[1 + R(q)] \ . \qquad (1)$$

Here, $\boldsymbol{p}_\alpha$ and $\boldsymbol{p}_d$ are the laboratory momenta of alpha particles and deuterons, respectively; q is the momentum of relative motion; and C is a normalization constant. The experimental correlation functions were obtained by inserting the measured yields into eq. (1) and summing both sides of the equation over all energies and angles corresponding to a given constraint. In fig. 1 we show α–d correlation functions measured with the center of the hodoscope positioned at 35° (upper part) and 50° (lower part). The following constraints were applied: $E_\alpha \geqslant 40$ MeV, $E_d \geqslant 15$ MeV *and:* 55 MeV $< E_\alpha + E_d \leqslant 10$ MeV (left-hand part), 100 MeV $< E_\alpha + E_d \leqslant 150$ MeV (center part), 150 MeV $< E_\alpha + E_d \leqslant 220$ MeV (right-hand part). As observed previously [16], the α–d correlation functions exhibit two maxima corresponding to the $T = 0$ state in ^{6}Li at 2.186 MeV ($J^\pi = 3^+$, $\Gamma = 24$ keV, $\Gamma_\alpha/\Gamma_{tot} = 1.00$) and the overlapping $T = 0$ states at 4.31 MeV ($J^\pi = 2^+$, $\Gamma = 1.3$ MeV, $\Gamma_\alpha/\Gamma_{tot} = 0.97$) and at 5.65 MeV ($J^\pi = 1^+$, $\Gamma = 1.9$ MeV, $\Gamma_\alpha/\Gamma_{tot} = 0.74$) [18].

If one assumes thermal equilibrium for a system contained within a sphere of volume V, one can approximate the correlation function as [13]

$$R(q) = \frac{2\pi}{(2s_1 + 1)(2s_2 + 1) V q^2} \sum_{J,l} (2J + 1) \frac{\partial \delta_{J,l}}{\partial q} \ . \qquad (2)$$

Here, s_1 and s_2 denote the spins of the two coincident particles and $\delta_{J,l}$ denotes the scattering phase shift (assumed to be diagonal in l and J). To first order within the thermal model, the correlation function depends on the volume of the emitting source but not its temperature [13]. Instead of using eq. (2) directly, we have performed calculations of the α–d correlation function which correspond to a generalization of the final-state interaction model of ref. [11]. For these

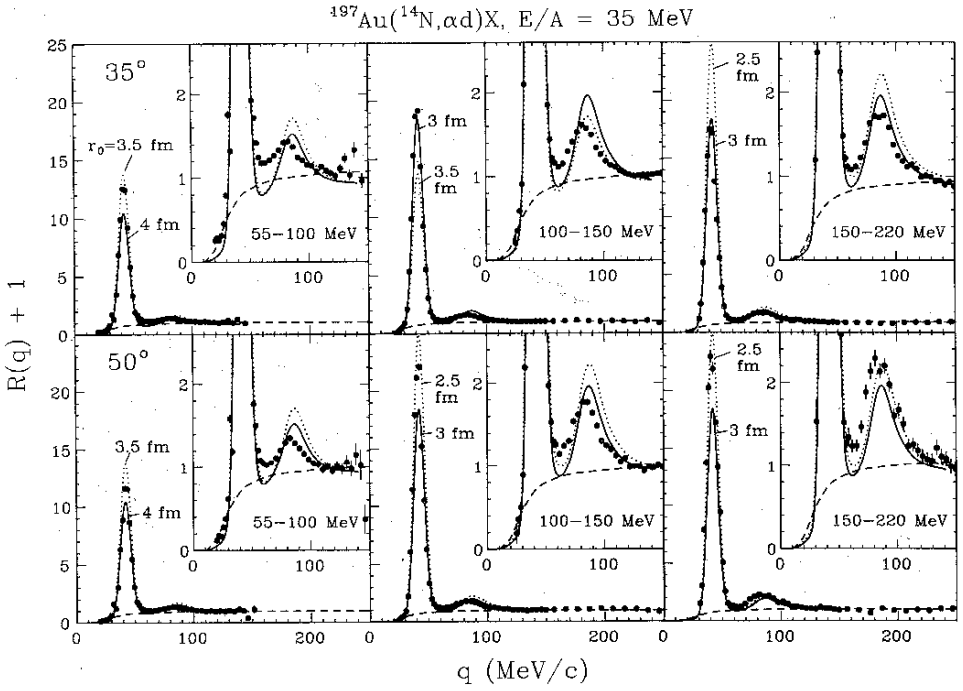

Fig. 1. Correlation functions measured for coincident deuterons and alpha particles for ^{14}N induced reactions on ^{197}Au at E/A = 35 MeV. A detailed discussion of the figure is given in the text.

Table 1
Emission temperatures and source radii extracted from the decay $^6Li^* \rightarrow \alpha + d$.

Constraint on $E_1 + E_2$	$\Theta = 35°$		$\Theta = 50°$	
	T(MeV)	r_0(fm)	T(MeV)	r_0(fm)
55–220 MeV	4	3.4	4	3.6
55–100 MeV	4	3.8	3	3.9
100–150 MeV	4	3.0	5	2.8
150–220 MeV	7	3.0	9	2.7

calculations, a source of gaussian spatial density, $\rho(r) = \rho_0 \exp(-r^2/r_0^2)$, was assumed and finite lifetime effects were neglected. In this approximation, the model becomes equivalent with the thermal model [13]. Technical details are given in ref. [12]. The calculations are shown by the solid and dotted lines in fig. 1; here, the calculated line shapes were corrected for the finite resolution of the hodoscope. The measured correlations do not exhibit a strong dependence on angle, but become more pronounced with increasing kinetic energies, $E_\alpha + E_d$, indicating that more energetic particles may originate from subsets of nucleons which are more localised in space–time. This feature is quantified by the estimated source radii summarized in table 1.

Emission temperatures were obtained by comparing the experimental yields of particle unstable ^{6}Li nuclei with thermal calculations. The experimental yield of particle unstable decays $^6Li^* \rightarrow \alpha + d$, Y_c, was assumed to be given by $Y_c = Y_{\alpha d} - CY_\alpha Y_d [1 + R_b(q)]$, where $R_b(q)$ denotes the "background correlation function" [16] shown by the dashed lines in fig. 1. The resulting yields are shown in fig. 2 as a function of the kinetic energy, T_{cm}, in the ^{6}Li rest frame.

The theoretical yield of particle unstable decays $^6Li^* \rightarrow \alpha + d$, $Y_c(E^*, T)$, was calculated according to the equation [16]

$$Y_c(E^*, T) = \int dE\, \epsilon_c(E^*, E) e^{-E/T} \times \sum_i \frac{(2J_i + 1)\Gamma_i/2\pi}{(E - E_i)^2 + \Gamma_i^2/4} \frac{\Gamma_{c,i}}{\Gamma_i}. \quad (3)$$

The sum includes the excited states of ^{6}Li below 10 MeV excitation energy; the subscript c denotes the channel $^6Li^* \rightarrow \alpha + d$; E and $E^* = T_{cm} + 1.475$ MeV

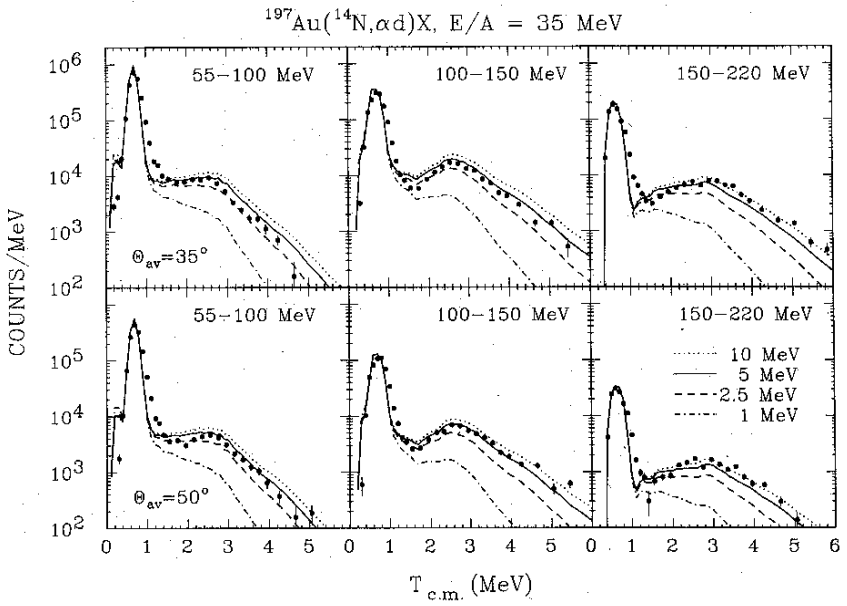

Fig. 2. Energy spectra resulting from the decay $^6Li^* \rightarrow \alpha + d$. A detailed discussion of the figure is given in the text.

denote the actual and measured excitation energies of the decaying ^{6}Li nucleus, respectively; T is the emission temperature. (This *operational* definition of the emission temperature is useful for the characterisation of the excitation energy density for both equilibrium and nonequilibrium processes. In its present form, however, it neglects the unknown effects of feeding from higher lying states.) The efficiency function, $\epsilon_c(E^*, E)$, for the detection of the decay products was calculated for the precise geometry, detection thresholds and energy resolution of the experiment using the appropriate constraints on $E_\alpha + E_d$. Each resonance was assumed to decay isotropically in its center-of-mass frame. Spectra and angular distributions of excited ^{6}Li nuclei were taken to be identical to the measured spectra of particle stable ^{6}Li nuclei.

Calculations based on eq. (3) are shown in fig. 2 for emission temperatures of $T = 1, 2.5, 5$, and 10 MeV. The curves are normalised to reproduce the experimental yield integrated over the energy range of $T_{cm} = 0.3$–1.2 MeV. In order to extract emission temperatures, we have integrated the decay yields over the energy ranges of $T_{cm} = 0.25$–1.45 and 1.5–6.25 MeV and compared the ratio of these yields to the corresponding ratio calculated from eq. (3). The results are summarized in table 1. Higher emission temperatures are extracted for higher kinetic energies, $E_\alpha + E_d$, of the emitted particles.

The temperatures extracted from the α–d coincidence yields can have considerable systematic errors due to uncertainties in the α–d background correlation function and due to the saturation of the coincidence yields at higher temperatures; statistical uncertainties are negligible. At $T \approx 5$ MeV, the temperatures are believed to be accurate within 25%; at higher temperatures the uncertainties can be larger. Uncertainties of the absolute temperature scale may be caused by feeding from higher lying states. Quantum statistical calculations [19] for infinite nuclear systems suggest that sequential decay corrections to the emission temperatures extracted with eq. (3) from the $^6\mathrm{Li}^* \rightarrow \alpha + \mathrm{d}$ decay could result in temperatures 10–50% higher, depending on breakup density.

In general, the determination of temperatures from the populations of states becomes insensitive to secondary processes only in the limit that the level separation is much larger than the emission temperature. This limit is satisfied by the decays: $^5\mathrm{Li}_{g.s.} \rightarrow \alpha + \mathrm{p}$, $^5\mathrm{Li}^*_{16.7} \rightarrow \mathrm{d} + {}^3\mathrm{He}$, for which statistical calculations indicate negligible feeding from higher lying states [19]. Mean emission temperatures for ^{5}Li of $T = 4.4 \pm 0.4$ MeV are extracted at both angles from the energy integrated coincidence yields; they are consistent with the ones extracted from the decay of $^6\mathrm{Li}^*$. Unfortunately, the angular separation (6.1°) between neighboring telescopes was too large to permit an exploration of the energy dependence of the relative population of these states in ^{5}Li.

The temperatures determined in the present experiment are about an order of magnitude larger than the ones reported in refs. [14,15]. This discrepancy is probably caused by feeding of the ground state by sequential decay [14–17,19] rendering the method employed in refs. [14,15] inaccurate [16,19].

In summary, higher emission temperatures and smaller source radii are extracted for higher kinetic energies of the emitted particles. These findings are consistent with particle emission from a subsystem which is in the process of cooling and expanding. Cooling and expanding subsystems of high excitation could arise from the equilibration of participant matter with the surrounding cold target nuclear matter [2] or from an isentropic expansion as expected from intranuclear cascade calculations [20]. It is also conceivable that the measured energy dependence of the emission temperatures arises from an energy dependence of the feeding from higher lying particle-unstable states. This possibility can be investigated by measuring the relative population of states with level separations larger than the emission temperature.

This article is based upon work supported by the National Science Foundation under grant PHY 83-12245 and by the Natural Sciences and Engineering Research Council of Canada. One of us (W.G.L.) acknowledges the receipt of a National Science Foundation Young Presidential Investigator Award.

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