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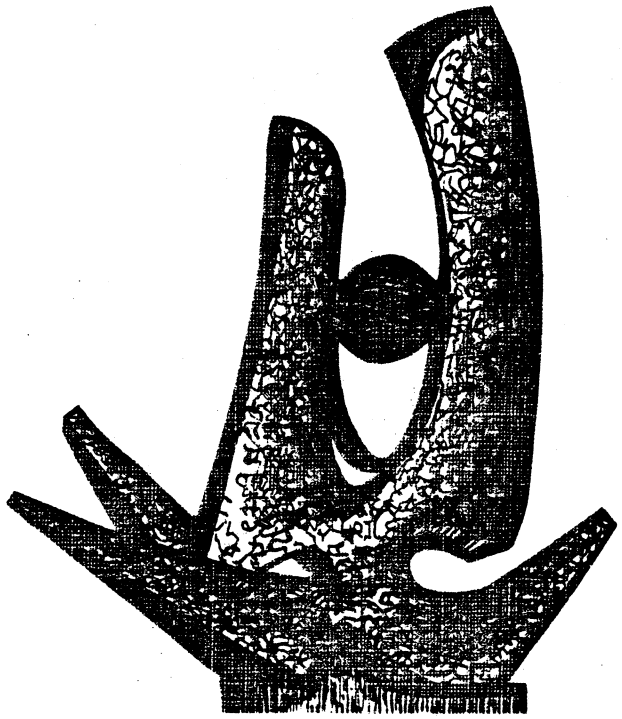

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Hadronic Thermometry and Final State Interactions

by

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Abstract

Final state interaction in the expanding fireball of a heavy ion reaction may allow the depletion of excited states of nuclei through hadronic reactions. Such depletion would result in a cooler apparent temperature as measured by excited state population distributions than what is found by fitting inclusive cross sections. This idea is applied to the recently measured lithium and beryllium distributions in the 35A MeV ^{14}N+Ag reaction, and the temperature predicted to be associated with the excited state populations is shown to be in the range observed experimentally.

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The thermal model approach[1] to the analysis of the inclusive particle spectra in heavy ion reactions assumes that particle emission arises from a hot zone in kinetic and possibly chemical equilibrium. There has been considerable controversy[2] as to whether the nuclear systems in these reactions can actually reach thermal and chemical equilibrium, particularly given the small number of nucleons in and the short lifetime of the interaction region. In proton induced reactions, the p/n ratio of the ejected nucleons has been used[3] as a test of the approach to chemical equilibrium, since the p/n ratio in the first stage of the reaction (single NN scattering) is very different from its value at equilibrium. The analysis showed that the lifetime of the equlibrated zone in these reactions was fairly short.

In heavy ion reactions, a recent experiment[4] attempted a self-consistency check on the temperature in the thermal model by contrasting the temperature determined by the first excited state to ground state population ratios (of ^{6}Li, ^{7}Li and ^{7}Be) with the temperature found in the conventional single source thermal model analysis of the inclusive energy spectra. These nuclei were chosen as their first excited state cannot be populated by decays from above. The results show what is, at face value, an inconsistency. The temperature associated with the inclusive spectra in this experiment (35 A MeV ^{14}N+Ag) is 8.6 MeV, in strong contrast to $1.0^{+0.5}_{-1}$, $0.21^{+0.13}_{-0.04}$ and $0.3^{+0.6}_{-0.3}$ MeV found from the excited state population analysis of ^{6}Li, ^{7}Li and ^{7}Be respectively.

However the temperatures obtained by the two methods may not be directly comparable. While the temperature extracted from the inclusive spectra may reflect the temperature of the hot zone emitting the particles, certainly it is not the temperature of the particles when they reach the

detector. Rather, as the emitted particles move away from the emission region, their temperature as measured in a co-moving frame will decrease as a function of time. In hydrodynamics language,[5] thermal energy is being converted into flow energy. Detailed calculations[6-7] show that the energy spectra of the particles does not change appreciably during the latter part of the expansion phase of the reaction.

Up to the freezeout point, excited state populations will be determined by this local temperature. As long as the reaction rates are such that the excited states remain in equilibrium via interactions with their local environment, the populations will decrease with time as does the temperature. The larger the cross section for the interaction of the ejectile with the background, the later the ejectile would be expected to go out of equilibrium.[8] The purpose of this paper is to estimate this freezeout temperature from the excited state experiment. Our attention will be focused on ^{7}Li, since it has the smallest quoted error and hence provides the most stringent test of the hadronic cooling hypothesis.

To estimate the freezeout temperature, one wishes to compare the reaction rate for the depletion of the ^{7}Li excited state, with the expansion time of the system. It will be assumed that the lithium fragments are emitted on the same time scale as the large numbers of nucleons observed in the heavy ion raction. This assumption is justified in part because the inclusive spectra show a temperature in the 10 MeV range, indicating that the incident energy is spread over about 40 nucleons in total (assuming that all of the available energy is indeed thermalized) the size range which one would expect on the basis of geometry for the initial interaction region. For the spatial and temporal evolution of the temperature (T(t)) and density

($\rho(\vec{r},t)$) we use the solution to the Boltzmann equation for a freely expanding gas[9]

$$T(t) = T_0\gamma \tag{1}$$

and

$$\rho(\vec{r},t) = A\left(\frac{\gamma}{2\pi\Delta^2}\right)^{3/2} e^{-\gamma r^2/2\Delta^2} \tag{2}$$

where

$$\gamma = (1 + T_0 t^2/m\Delta^2)^{-1} \tag{3}$$

where $\vec{r}$ and t are the position and time variables. For simplicity, the temperature is assumed to be constant (as a function of distance) across the expanding region, with a value of T_0 at t=0. The parameter Δ is determined by equating the r.m.s. radius of the distribution in Eq. (2) with that of a uniform distribution (initially at normal nuclear matter density) having sharp edge at radius $R=1.2\ A^{1/3}$ fm; that is $\Delta=R/\sqrt{5}$. The characteristic expansion time of the interaction region τ_{exp}, we calculate from the time rate of change of the r.m.s. radius of the density distribution:

$$\tau_{exp}^{-1} = \langle r^2\rangle^{-1/2} \frac{d}{dt} \langle r^2\rangle^{1/2} , \tag{4}$$

so that

$$\tau_{exp} = m\Delta^2/\gamma T_0 t. \tag{5}$$

where m is the nucleon mass. For large t, $\tau_{exp} \to t$.

To use these expressions, we need to know the particle multiplicities for this reaction. The proton and several other multiplicities have been measured[10] for 35 A MeV ^{12}C+Au but the neutrons have not. To estimate the

particle multiplicities, use will be made of a model developed by Friedman and Lynch[11] to describe particle emission in this energy region. The model fits the existing data very well, so one has confidence that the predicted neutron multiplicities should not be inaccurate. For the reaction under consideration, the predicted multiplicities are[12] 12.7, 1.4, 1.1 and 2.4 for ejectiles with 1, 2, 3 and 4 nucleons, respectively. More than half of these ejectiles (i.e. about ten) are neutrons. Because not all of the cross sections necessary to perform the calculations are available, it will be assumed here that the background in which the lithium moves consists of 20 neutrons, and the n+^{7}Li cross sections will be used. The number of neutrons is chosen to be larger than 17.6 (but smaller than the total baryon number of these ejectiles - 28.4) to reflect the fact that the n+^{7}Li cross sections are smaller than, for example, the α+^{7}Li cross sections. This is true for energies above the Coulomb barrier, which are the most relevent for this calculation. In any event, the reaction time calculation here is less sensitive to the multiplicity assumed than it is to the density of the particles in the interaction region. The assumption that this particle multiplicity is appropriate for the local environment for the lithium fragment is supported by an examination of the inclusive Li energy spectrum. The energies of the Li fragments in the coincidence experiment[4] were in the tens of MeV range, corresponding to an energy per nucleon in the 5-10 MeV range. This is similar to the energy of the "thermal bath" of nucleons, so that the Li fragment is moving at a speed not too different from the surrounding nucleons.

To determine the temperature at which the lithium fragments go out of equilibrium, the expansion time should be compared to the reaction time in the central region, τ_{rx}

$$\tau_{rx}^{-1} = \rho(0,t)\langle\sigma v\rangle \tag{6}$$

where

$$\langle\sigma v\rangle = 4\pi\left(\frac{\mu}{2\pi T}\right)^{3/2} \int v^3 \sigma(v) e^{-(\mu v^2/2T)} dv \tag{7}$$

The cross section and relative velocity of the neutron-lithium pair (of reduced mass μ) are denoted by σ and v. It has been assumed that all particles have a Maxwell-Boltzmann energy spectrum.

The cross section in which we are interested is the n+^{7}Li(0.478) inelastic cross section for neutrons in the 1/2 to 15 MeV region. This is not available, of course, so the ground state properties will have to be used for an estimate. The n+^{7}Li(g.s.) inelastic cross section is roughly constant[13] in the 8-14 MeV range at ~350 mb, decreasing[14] substantially below 1 MeV as the inelastic threshold is approached. Much of the cross section is attributable to the ^{7}Li(n,n$_1$)^{7}Li (0.478) reaction which has a cross section of about 250 mb in the 1 to 6 MeV range.[15] This would imply a cross section of at least 500 mb for the reverse reaction, since the ground state has spin 3/2 while the first excited state has spin 1/2.

Assuming, then a cross section of 500 mb for the inelastic cross section of the ^{7}Li excited state, one finds that τ_{rx} exceeds τ_{exp} at a temperature of 0.66 MeV, as is illustrated in Fig. 1. Actually, for constant $\sigma(v)$ and large t this crossover temperature T* can be found analytically as

$$T^* = \left\{\frac{\Delta^4 \pi^4 T_0^3 \mu}{mA^2 \sigma_0^2}\right\}^{1/3} \tag{8}$$

The main uncertainties in this result come from the uncertainty in the cross section and the central density. If the estimated reaction time were in

error by a factor of 2, then the estimated freezeout temperature could change by +0.3 or -0.2 MeV, according to Fig. 1.

In any event, it is clear from the above calculation that hadronic final state interactions can substantially lower the population of the excited states. Two possible tests of this mechanism would be to look at the projectile energy and mass number dependence of the excited state temperature. From Eq. (8), T^*/T_0 is a constant, assuming all other things to be equal, so that the excited state temperature should scale with the inclusive spectrum temperature as the energy is raised. For example at 300 A MeV, T_0 should be about 40 MeV, so that T* would be about 3 MeV. Of course, to make an accurate prediction the change in multiplicity and cross section with energy would also have to be inserted into Eq. (8). Similarly, Eq. (8) shows that $T^* \sim A^{-2/9}$ (recall that $\Delta \propto R \propto A^{1/3}$) so that a smaller source region would result in a larger T* since freezeout occurs earlier. This is a weaker test than the energy dependence, but it indicates that a proton induced reaction should show a larger T* than a heavy ion reaction, although the difference may not be terribly great.

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Figure Caption

Figure 1 - Calculated reaction and expansion time as a function of temperature. The curves cross at an elapsed time of 1.85×10^{-23} sec, and a central density of 1/20 nuclear matter density.