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Fragment Emission and the Lifetime of Pre-equilibrium States

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Abstract

The production of nuclear fragments in the 10-30 mass number range is viewed as a non-equilibrium process in which individual nucleons in kinetic equilibrium coalesce to form fragments. A simplified set of rate equations for fragment formation is solved numerically which allows for a determination of the lifetime of the fragment formation epoch by comparison with data. The lifetime so calculated is about 4×10^{-23} sec.

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The nucleon-nucleon force has similarities to the intermolecular force: attraction at long distances and repulsion at short distances. Such a force could give rise to a van der Waals-like equation of state, which in turn opens up the possibility of a nuclear phase transition,¹ similar to the liquid-gas phase transition observed in the molecular domain. Thermal model analysis² of the inclusive cross sections of both proton induced and heavy ion induced reactions has shown that nuclear matter may be excited to the temperature and density regions appropriate for this transition. Analyses of data³ for the production of heavy fragments have been performed^{4,5} using a thermal liquid drop model,⁶ which assumes that hot nuclear matter cools through a phase transition,⁷ producing nuclear droplets which are the observed heavy fragments. The parameters of the nuclear equation of state which are fitted by this approach have been shown⁵ to be self-consistent.

However, a central question regarding any mechanism for fragmentation is the time scale involved. The fact that the $(p,p')/(p,n)$ ratio is measured⁸ to be about 2 (after correcting for the Z/N ratio in a variety of targets) at 100 MeV bombarding energy argues that chemical equilibrium may not be reached in proton-induced reactions.⁹ The time scale of the reactions may be so short that the nucleons involved only reach kinetic equilibrium. The production data for heavy fragments also shows that complete chemical equilibrium is not achieved. We show schematically in Fig. 1 the time evolution of a system initially composed only of nucleons. Because the binding

energy per nucleon increases with the mass number of the fragment, A_F , one would expect that over time the distribution of masses would ultimately be centered about the region with the greatest binding energy per nucleon, the spread about this region being determined by the temperature, among other things. At temperatures greater than 10 MeV (determined by single fireball analysis of inclusive cross section measurements) much of the data of proton induced reactions look similar to the "intermediate time" curve of Fig. 1. Heavy ion data at lower temperatures shows a dip in the yield as a function of mass, followed by an increase, although it is not clear whether the data approach the "late time" picture.

Because the reaction time is so short, and the number of participants so small in proton induced reactions, it is possible that a better description of fragment production can be found in a detailed solution of reaction rate equations,¹⁰ rather than in a thermodynamic description which may involve a low temperature phase transition. For the kinetic model to be described below to be valid, the system would have to be sufficiently dilute that many-body interactions could be neglected. The purpose of this paper is to solve a simplified set of rate equations which allow an estimate to be made of the reaction time involved. Our purpose here is not to develop a detailed model, but to show that the kinetic picture appears to be valid for the low density regime and to extract the time scale associated with fragment formation.

We will assume that at the beginning of the fragment formation epoch, the initial hot zone (which has a temperature of 75 MeV for proton induced reactions¹¹ in the multi-GeV incident energy range) has cooled and expanded such that the temperature has dropped to about 1/3 its initial value.¹² At this time, which we define as $t = 0$, the distribution of number densities N_i of the species present will be assumed to be of the form

$$\begin{aligned} N_1(t = 0) &\equiv \rho \\ N_i(t = 0) &= 0 \quad 2 \leq i \leq A_T \end{aligned} \quad (1)$$

At this point we will not distinguish between protons and neutrons. At the freeze-out point for pions, the density of nucleons has already decreased¹¹ to at least 1/2 nuclear matter density or one nucleon per 12 fm³. Hence, we will consider only two body interactions in the rate equations. For early times, the break up of heavy nuclei will be assumed to be slow compared to the formation rate, although, as one approaches equilibrium these rates will become comparable. Then the rate equations have the form:

$$\frac{dN_k(t)}{dt} = + \sum_{i,j} \frac{N_i(t)N_j(t)}{1 + \delta_{ij}} \bar{\sigma}_{ij} \delta_{i+j,k} - \sum_i N_i(t)N_k(t) \bar{\sigma}_{ik} \quad (2)$$

Here, $\bar{\sigma}$ is the thermal averaged cross section

$$\bar{\sigma} \equiv 4\pi \left(\frac{\mu}{2\pi T} \right)^{3/2} \int v^3 \sigma(v) e^{-\frac{\mu v^2}{2T}} dv \quad (3)$$

where μ is the reduced mass and v is the relative velocity. For simplicity we have assumed that the main contribution to fragment formation is two particle fusion. The omission of more complicated processes will partly compensate for the omission of break up reactions in these equations.

Before performing a numerical integration of these equations, we can extract a "small time" expansion. For t near zero, assuming that the fusion cross sections do not have a pathological mass number dependence, the rate equations will simplify to

$$\begin{aligned} \frac{dN_1}{dt} &\approx -\frac{\rho^2}{2} \bar{\sigma}_{11} \\ \frac{dN_2}{dt} &\approx \frac{\rho^2}{2} \bar{\sigma}_{11} \\ \frac{dN_3}{dt} &\approx N_2 \rho \bar{\sigma}_{12} \end{aligned} \quad (4)$$

etc. That is, the number density of species i will be building up rapidly as a function of time. One can show that Eq. (4) gives the number densities a general time dependence of the form $N_i \propto t^{A_i-1}$:

$$\begin{aligned}
N_1(t \approx 0) &= \rho \\
N_2(t \approx 0) &\approx \frac{\rho}{2} (\rho \bar{\sigma}_{11} t) \\
N_3(t \approx 0) &\approx \frac{1}{2} \cdot \frac{\rho}{2} (\rho \bar{\sigma}_{11} t) (\rho \bar{\sigma}_{12} t)
\end{aligned} \tag{5}$$

Hence, a plot of the log of the yield of fragments against their mass number would show a straight line with negative slope from which the reaction time t could be obtained. Of course, at large A the cross sections will be increasing, and there will be more reaction channels contributing to a given product, so the expected curve would deviate positively from the straight line decrease. This is indeed what is observed experimentally.

To actually extract an estimate of the reaction time, we will compare with the $p+Kr$ data⁴ at 80–350 GeV. For simplicity the integrated reaction cross section in the energy range of interest will be parametrized as¹³

$$\sigma_{AB} = \pi (r_0 (A + B)^{1/3} + \chi)^2 \tag{5}$$

where χ is the reduced de Broglie wavelength, $r_0 = 1.2$ fm and A and B are the mass numbers of the fusing nuclei. Of course, not all of the total reaction cross section results in fusion. We estimate the relevant part by using σ_{AB} in Eq. (3) but truncating the integral at the Fermi velocity, $v_{\max}$ of nuclear matter at normal density. In other words, a pair of nuclei whose relative velocity is less than $v_{\max}$ will fuse, while those with velocity greater than $v_{\max}$ will

not. This is an obvious oversimplification but will suffice for our purposes here. Lastly, we need a temperature and initial density ρ , which we will take to be 25 MeV (1/3 of the initial proton temperature) and $1/2 \rho_0$ respectively. Again, a more sophisticated calculation would allow these to change as the system expands. This temperature justifies in part the use of Eq. (3) which assumes Maxwell-Boltzmann statistics.

The result of the numerical integration is shown in Fig. 2. To obtain an absolute yield, the calculated number densities must be multiplied by a volume. Here, we neglect this since the data are arbitrarily normalized. The predicted yields match the data well, with deviations occurring at the expected masses. We have not suppressed masses 5 and 8, so they are necessarily overpredicted. Similarly, these two isobars will enhance mass 4 in their decay, so the underprediction of mass 4 is anticipated. That masses 5 and 8 are suppressed by binding energy considerations during the formation period is probably also responsible for the decrease in isobars immediately above them, i.e. 6 and 9 from the prediction. Lastly, although a specific data set has been chosen, the predicted fall off of the mass yield with A should be roughly universal, as the formation times should not depend sensitively on the projectile energy or target involved.

The formation time required to produce the observed distribution is 4×10^{-23} seconds. This estimate is in accord with what is required to explain the $(p,p')/(p,n)$ ratio, and with the estimated¹¹ rate of cooling of the hot zone, namely about 1×10^{-23} sec. One

would expect the fragment formation time to be longer than this as the cross sections involved are larger than (p,p') and therefore the heavy fragments go out of equilibrium somewhat later. Of course, there are several effects which would have to be included in a detailed rate calculation before this estimated time could be regarded as firm. As was pointed out above, some of these effects may cancel. Since the data are proportional to the time raised to a power, it is unlikely that the time will be changed by more than a factor of two in incorporating extra corrections. Hence, a self consistent picture emerges of proton induced reactions in which an initially small region of energetic nucleons is produced (in thermal, but not necessarily chemical equilibrium) in around 10^{-23} seconds, followed by expansion and cooling until fragment formation is complete at around $1/2 \times 10^{-22}$ seconds.

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Figure Captions

Fig. 1. Schematic Representation of the time evolution of the relative abundances in a system composed initially of nucleons.

Fig. 2. Solution to the rate equations for fragment formation with $t = 4 \times 10^{-23}$ sec. The data are from the p + Kr reaction at 80-350 GeV (Ref. 4).

Fig. 1

 A_F

Fig. 2

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