SUBTHRESHOLD PIONS FROM THE COMPOUND NUCLEUS?

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We analyze the pion production cross section of the reaction $^{12}C + {}^{12}C \to \pi_0 + X$ for beam energies of several tens of MeV. Employing the statistical compound decay theory we obtain a good agreement with the data, for the excitation function as well as for the energy distribution of the emitted pions.

A significant pion production cross section has been recently observed at $E_{lab}/A = 35$ MeV in the reaction $^{14}N + {}^{27}Al \to \pi_0 + X$ (Braun-Munzinger et al. [1]). This experiment supplements earlier data obtained by Noll et al. [2]. In heavy ion collisions free pions can be created even if the available energy for a nucleon pair is below the threshold for pion production in free nucleon–nucleon collisions. However at this low energy it is not easy to produce a pion. Two explanations for the underlying mechanism have been advanced: either the necessary additional kinetic energy may arise from the Fermi motion, or the creation of pions is a collective process. Shyam et al. [3] have pointed out that the first explanation fails even at higher beam energies. Grosse [4] has applied a collective model [5] in which the pions are created in a process similar to the electromagnetic bremsstrahlung. This model fits the data at higher energies, but it does not describe the excitation function properly. Furthermore there is an ad hoc parameter in this model related to the deceleration of the nuclei during the collision.

In any case, we think that it is premature to speculate on collective mechanisms before the production via a statistical process has been ruled out or shown to be negligible. We shall show in this letter that the available data of $\sigma(\pi_0)$ and $d\sigma/dE$ can be reproduced by assuming that the creation of pions is entirely statistical with a cross section governed by the available phase space. Thus experiments do not show that collective mechanisms for pion production are present but merely that the hamiltonian is effective in spreading the system into the available phase space.

The basic assumption in our analysis is that the nucleons in the colliding nuclei reach statistical equilibrium in a very short amount of time. Of course, from the point of view of the Boltzmann equation, the equilibration is far from instantaneous. Nevertheless, the assumption may not be so unreasonable because the strong nuclear force induces many of the correlations needed for the transition already in the initial state. Also, to produce an energetic particle by a low-energy collision requires consideration of high-order perturbations on the independent particle wave function. It is plausible that the mathematics of such higher-order perturbations yield results approaching the phase space limit. Given a system in local equilibrium, the time required for a particle emission in a compound decay (5 fm/c) is small compared to the expansion time, or time for other disassembly mechanisms. We thus apply

$$W_{if}(e)\, de = [\rho(U)/\rho(E)]\,[(2S+1)m/\pi^2]\,\sigma_{fi}(e)\, e\, de, \quad (1)$$

where e is the kinetic energy of the evaporated particle, $\rho(U)$ is the level density of the evaporation residue, $\rho(E)$ is the same quantity for the compound nucleus, and σ_{fi} is the inverse cross section for the

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formation of the compound nucleus. The cross section is obtained from the decay rates by the formula

$$d\sigma/de = \sigma_0\, W_{if}(e) \Big/ \sum_j \int W_{ij}(e_j) de_j, \qquad (2)$$

where σ_0 is the cross section to form a compound nucleus in the entrance channel.

We determine the level densities by the Fermi gas model. For our applications, considering excitation energies between 9 and 21 MeV/N, i.e. temperatures between 12 and 23 MeV (at normal nuclear matter density), the standa. l low temperature level density formula is inaccurate and we use instead the general formulas

$$E/V = c \int n(E)\, E^{3/2}\, dE, \qquad (3)$$

$$N/V = c \int n(E)\, E^{1/2}\, dE, \qquad (4)$$

$$S/V = -c \int \{n(E) \log[n(E)] + [1 - n(E)] \log[1 - n(E)]\} E^{1/2} dE, \qquad (5)$$

$$n(E) = 1/[\exp(E - \mu)/T + 1], \qquad (6)$$

where E/V is the kinetic energy density which is known by the kinematics, N/V is the nuclear matter density and S/V is the entropy density. We use eqs. (3) and (4) to determine T and μ for given E/V and N/V. Then we are able to calculate the entropy which is connected with ρ by $\rho = \exp(S)$. It turns out that for a given density N/V the entropy as a function of E can be parametrized very accurately by a square root function. In the calculation we use the following parametrization

$$S/N = (aE/N)^{1/2} + b, \qquad (7)$$

where

$a = 0.188$, $b = 0.238$, for $8.75 \leqslant E/N$ [MeV],

$a = 0.240$, $b = 0.063$, for $3 \leqslant E/N < 8.75$ [MeV],

$a = 0.256$, $b = 0.039$, for $0.5 \leqslant E/N < 3$ [MeV].

We fix the density in our calculation at 0.15 nucleon/fm^3.

At the excitation energies needed to emit a pion the evaporation of an α particle is not very probable [7], therefore we take only nucleons and pions into account. Pion creation is possible not only at the first evaporation step, but also after one or more nucleons are emitted. In our calculation we sum the contributions for each step. The cascade conserves the energy in the average, i.e. after i steps the excitation of the residue (E^{i+1}) is given by

$$E^{i+1} = E^i - \langle E^i_{kin} \rangle - \langle Q^i \rangle, \qquad (8)$$

where $\langle E^i_{kin} \rangle$ is the average kinetic energy of the nucleons emitted in step i and $\langle Q^i \rangle$ is the average of the Q values obtained for neutron and proton emission. Eq. (1) requires the inverse cross section, which we take as geometric for the nucleon absorption $[\sigma(A + n \rightarrow (A + 1)) = \pi R_A^2]$. Due to the large wavelength of the pion, the pion absorption cross section is far from geometric. We parametrize it by

$$\sigma = a(\Gamma/2)^2 / [(E - E_0)^2 + (\Gamma/2)^2]. \qquad (9)$$

Experimental data on pion absorption are available for the reaction $\pi + {}^{12}C$ [8]. We determine the parameters in eq. (9) from this reaction. This results in the values $a = 285$ mb, $E_0 = 140$ MeV and $\Gamma = 160$ MeV.

Fig. 1 shows our calculated cross section in comparison with the data [1] for the total pion produc-

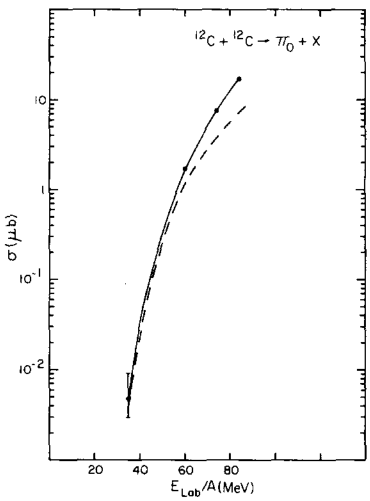

Fig. 1. Calculated total π_0 cross section and the data of ref. [1]. The point at 35 MeV/N is extracted from the reaction ${}^{14}N + {}^{27}Al \rightarrow \pi_0 + X$ as explained in the text. The cross section for forming the compound system in the reaction ${}^{12}C + {}^{12}C$, which finally emits a pion, is taken as $\sigma_0 = 160$ mb. The dotted line shows the cross section of pions emitted in the first step, the full line represents the sum over all steps.

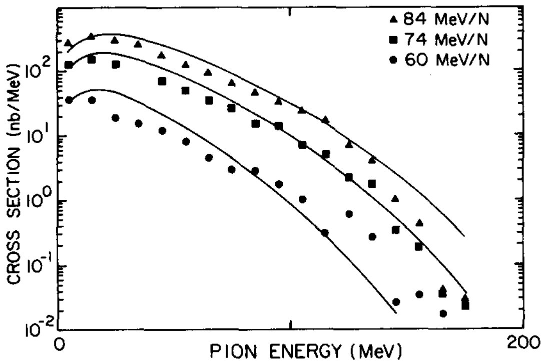

Fig. 2. Angle integrated π_0 spectra from $^{12}C + {}^{12}C$ reactions. The drawn lines are the result of our calculation. The data are taken from ref. [4].

tion $\sigma(\pi_0)$ as a function of the projectile energies. The data point at 35 MeV was obtained by applying our analysis to the reaction 35 MeV/N $^{14}N + {}^{27}Al \to \pi_0 + X$ and transforming it to the $^{12}C + {}^{12}C$ system. This is done in the following way: we calculate the probability P for pion emission of the compound nuclei created in both reactions 35 MeV C + C and 35 MeV N + Al, and scale the compound formation cross sections as Braun-Munzinger did [1]. Then the theoretical pion cross section is given by

$$\sigma_{C+C}(\pi_0) = \sigma_{N+Al}(\pi_0)\,\frac{P(C+C)}{P(N+Al)}\left(\frac{12\times 12}{14\times 27}\right)^{0.68}$$

The dotted line shows the cross section after the first cascade step, the full line that after summing up the contributions from all steps. The overall scale of the theoretical curve is fit by choice of σ_0, which turns out to be 160 mb. This seems to be a quite reasonable value to us: we do not expect the total reaction cross section to participate in pion production because of angular momentum effects. Higher spin values of the compound ^{24}Mg imply lower excitation energies and therefore a decreasing cross section for production of a pion. Hence only small l-values allow a significant production rate.

Fig. 2 shows the calculated π_0 energy distribution compared with the data of ref. [4]. Again the agreement is very good. The data also shows an angular anisotropy which cannot be explained in this simple model because of the neglect of the spin of the compound nucleus. However, we expect that an explicit treatment of spin would give an anisotropy peaking in the forward–backward directions, as is found in the data.

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