New Evidence for "Hot Spots" from Subthreshold Pions

J. Aichelin[a]
National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824
(Received 26 March 1984)

The excitation functions and energy distribution of the reaction $^{12}C + A \rightarrow \pi^0 + X$ for beam energies of several tens of megaelectronvolts per nucleon are analyzed. Statistical-decay theory yields good agreement with the data under the assumption that a hot spot is formed. Its size is determined from the velocity of the emitting source. The cross section for forming a hot spot shows a systematic behavior which fits well with the systematics recently observed in fragmentation reactions.

PACS numbers: 25.70.Gh, 24.60.Dr

Recently excitation functions for π^0 production from various asymmetric reaction systems have been measured.[1] These data supplement earlier results for the symmetric system C+C,[2] and for low projectile energies.[3] Two models have been advanced to describe the underlying mechanism for the production of pions in this energy domain. The first assumes that the necessary energy can be provided by the high-momentum component of the Fermi motion. However, this model fails to reproduce the excitation function as well as the energy distribution, as pointed out by Shyam and Knoll.[4] The other model describes the pion creation by a process similar to that for electromagnetic bremsstrahlung.[5] This model describes the energy distribution properly but fails to reproduce the excitation function. Furthermore, there is an *ad hoc* parameter in this model related to the deceleration of the nuclei during the collision.

We have shown[6] that for the symmetric system C+C the excitation function as well as the pion energy distribution can be remarkably well described by making a statistical hypothesis about the reaction mechanism. The projectile and target are assumed to form a thermalized system whose decay is governed by the available phase space. Because of the time scales involved, this picture cannot be extended to heavier targets. Here the time a nucleon needs to travel through the nucleus [$\sim$(15 fm)/c] is larger than the decay of the system [$\sim$(5 fm)/c]. Therefore complete equilibration of the whole target cannot be expected. I shall assume that the decay is statistical from a thermalized source, but not require that the entire target nucleus participate in the source. The size of the hot-spot source is determined from the angular distribution of the emitting particles, on the assumption that the source emits particles equally into the forward and backward hemispheres in its rest frame. This fixes the velocity of the source, and its size can then be inferred from momentum conservation. Similar hot-spot assumptions have been used successfully to analyze the proton correlations[7] as well as the emission of medium-mass fragments.[8,9] I shall show in this Letter that the excitation function for the π^0 cross section in asymmetric systems can be well reproduced in this model. The same is true for the π^0 energy distribution from the medium-mass Ni target. For the reaction C+U, the high-energy tail of the π^0 energy distribution is not reproduced.

A key assumption in the analysis is that the nucleons in the colliding nuclei reach statistical equilibrium in a very short time. From the point of view of the Boltzmann equation, the equilibration is far from instantaneous. Nevertheless, 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 could yield results approaching the phase-space limit. Certainly the pions are only emitted in the early stages of the reaction, because the hot spot quickly cools by disassembly or by spreading to the entire target nucleus. The time required for particle emission is $\sim$(5 fm)/c, which is smaller than the expansion time or the time for the disassembly mechanism. I will therefore apply the statistical theory for particle emission from a equilibrated source, with the Weisskopf formula[10]

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

Here e is the kinetic energy of the evaporated particle, $\rho(E)$ and $\rho(U)$ are the level densities of the hot spot before and after emitting a particle, and σ_{fi} is the inverse cross section for the formation of the hot spot. The cross section is obtained from the decay rates by the formula

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

where σ_0 is the cross section to form a hot spot in the entrance channel.

At the excitation energies of interest, 9–21 MeV/u, the temperatures are too high to use the standard low-temperature level-density formula, and so the general Fermi-gas theory is applied to obtain the level density.[6] I assume the source has the density of normal nuclear matter (0.15 n/fm^3). The temperatures in the hot spots then range between 12 and 23 MeV.

The calculation includes the possibility of pion emission after nucleons are emitted.[6] More than 95% of the pions are emitted in the first three steps of the reaction, even at the highest energies. This does not mean that after each evaporation step the residue needs a long time to restore thermodynamical equilibrium. It can also be viewed as a consequence of the maximum entropy principle: If we know only that a particle is emitted which carries a certain energy, then an equilibrium for the residue has the highest entropy.

Equation (1) requires knowledge of the inverse cross section, which I take as geometric for nucleon absorption: $\sigma(A+n \rightarrow (A+1)) = \pi R_A^2$, where R_A is the hot-spot radius. The pion cross section is quite difficult to estimate reliably, being far from geometric. I shall base the cross section on the empirical pion absorption cross sections, and recognize that what is desired is the absorption cross section on very highly excited nuclei. Optical-model calculations[11] show that for low energies the nucleus gets increasingly transparent, whereas at higher energies there is enhanced absorption due to the delta resonance. We can extract the π^0 absorption cross section from the available π^+ and π^- measurements by taking the geometrical mean. For heavier targets, two data sets exist.[12,13] Unfortunately they disagree both in absolute magnitude as well as in shape. Because of its agreement with optical-model calculations at lower energies, I fix our parametrization at low energies on the data of Ref. 13, whereas at higher energies I follow the average of both data sets. In this way we arrive at the following convenient parametrization of the π^0 absorption cross section in the range 20–200 MeV:

$$\sigma_{\pi^0}(E) = \sigma_m - \alpha(E - E_0)^2, \tag{3}$$

with $\sigma_m = 390$ and 550 mb, $\alpha = 0.017$ and 0.026 mb/MeV^2, and $E_0 = 145$ and 115 MeV for Al and Ti, respectively. For intermediate-mass nuclei, we make a linear interpolation. The only remaining undetermined parameter in the calculation is σ_0,

TABLE I. The projectile target combination and bombarding energy are listed in the first three columns. The next two columns show the source parameters as deduced from the pion angular distribution. Column six shows the number of entrained nucleons taken as input in the calculation. The next columns show the theoretical pion production probability, which is compared with experiment assuming a source formation cross section given in the eighth column. The values marked with asterisks are obtained from N + A reactions at 35A MeV as explained in the text.

Reaction			Source rapidity	Source Particle number		Theoretical pion emission probability	Formation cross section	Theoretical pion production cross section	Experimental pion production cross section
A_1	A_2	[MeV/u]	y_{cm}	N	N	prob	σ_0[mb]	σ_π^{th}[μb]	σ_π^{ex}[μb]
C	C	84	0.20(1)	24	24	1.86×10^{-4}	102	18.9	18.9
C	C	74	0.21(1)	24	24	8.3×10^{-5}	102	8.5	8.5
C	C	60	0.18(1)	24	24	1.8×10^{-5}	102	1.8	1.7
C	C*	35	–	–	24	$3.\times10^{-8}$	102	$3.\times10^{-3}$	2.6×10^{-3}
C	Ni	84	0.16(1)	32(2)	34	1.97×10^{-4}	321	72	72
C	Ni	74	0.14(1)	34(3)	34	8.85×10^{-5}	321	32.5	31
C	Ni	60	0.12(1)	36(3)	34	1.8×10^{-5}	321	6.6	7
C	Ni*	35	–	–	34	4.0×10^{-8}	321	1.3×10^{-2}	3.4×10^{-3}
C	U	84	0.11(1)	46(4)	43	1.85×10^{-4}	940	174	174
C	U	74	0.10(1)	48(5)	43	7.74×10^{-5}	940	76	63
C	U	60	0.09(1)	48(5)	43	1.22×10^{-5}	940	11.5	13

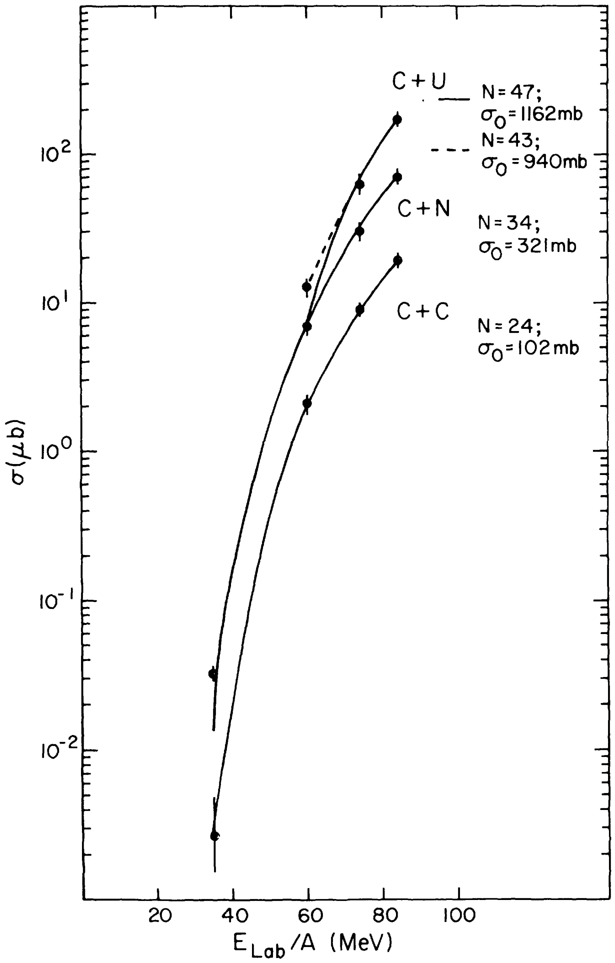

FIG. 1. Calculated total π^0 cross section and the data of Refs. 1 and 3. The points at $35A$ MeV are extracted from the reactions $^{14}N+A \rightarrow \pi^0+X$ as explained in the text. N is the number of entrained nucleons, and σ_0 is the hot-spot formation cross section. In the case of uranium I calculated the excitation function for two different numbers of entrained nucleons (dashed line $N=43$, full line $N=47$).

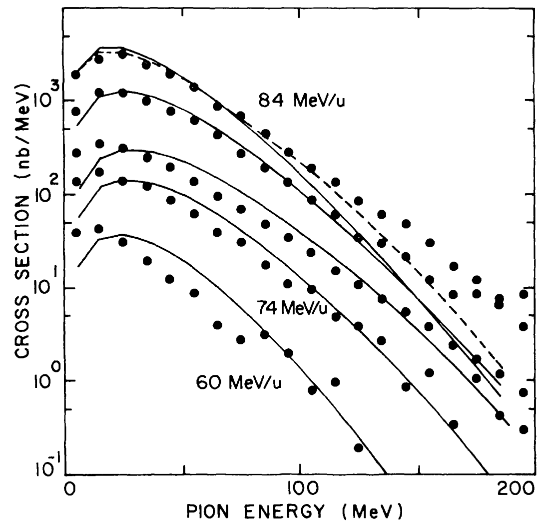

FIG. 2. Angle-integrated π^0 spectra for the reactions $C+A \rightarrow \pi^0+X$. The drawn lines are the result of the present calculation. The data are taken from Ref. 1. The upper three data sets show $84A$-MeV data for $A=U$, Ni, and C, respectively; the lower two data sets $74A$-MeV data for $A=C$ and $60A$-MeV data for $A=C$. For uranium I calculated the energy distribution for 47 entrained nucleons (full line) and 43 entrained nucleons (dashed line), respectively.

the formation cross section for the hot spot. This parameter is fitted to the measured excitation function. The calculation shows that the form of the excitation function is not very sensitive to the particular parametrization of the pion absorption cross section. However, σ_0 and the pion energy distribution are strongly dependent on $\sigma_{\pi^0}(E)$.

Table I shows the input values for the calculation as well as the total pion creation probability and the pion cross section. The data points at 35 MeV were obtained by applying the analysis to the reaction $35A$-MeV $^{14}N+^{27}Al \rightarrow \pi^0+X$ and $^{14}N+^{58}Ni \rightarrow \pi^0+X$ and transforming it to the $^{12}C+A$ system. This was done in the following way: I calculated the probability P for pion emission from the compound nuclei created in both reactions $35A$-MeV $C+A$ ($A=C$,Ni) and $35A$-MeV $N+B$ ($B=Al$,Ni). Then I scaled the compound formation cross sections following Braun-Munzinger.[3] Then the theoretical pion cross section is given by

$$\sigma_{C+A}(\pi^0)\sigma_{N+B}(\pi^0)\frac{P(C+A)}{P(N+B)}\left(\frac{12A}{14B}\right)^{0.68}. \quad (4)$$

Figure 1 shows the predicted excitation function compared with the available data.[1,3] The overall magnitude of the cross section was fitted with a parameter σ_0, corresponding to the formation cross section for the equilibrated system. The agreement in the shape of the excitation function is excellent. To show the dependence of the excitation function on source size, for the case of U I show two sets of parameters.

Figure 2 shows calculated π^0 energy distributions compared with the data of Ref. 1. The three lower curves show energy distributions for $60A$-, $74A$-, and $84A$-MeV C+C, the two upper curves $84A$-MeV C+Ni and C+U, respectively.

The energy distribution is well described in the C+C system but fails at higher energies in the asymmetric systems. An inspection of the rapidity plot shows that the high-energy π^0's from the Ni and U targets originate from a system of higher rapidity. This means fewer participants and therefore higher excitation energy/nucleon. This kind of behavior might be expected from a consideration of the time evolution of the source, starting out small and hot. Alternatively, distribution of collisions over the impact parameter may involve different participant numbers. Finally, the discrepancy at low pion energies could simply be a result of the poor knowledge of the inverse cross section or the finite experimental energy resolution.

We now find that the total compound formation cross section σ_0 shows an expected simple systematic behavior, giving us some confidence in the above analysis. If we express the cross section in the form $\sigma_0 = \pi b_{\max}^2$, then the maximum impact parameter is roughly given by $b_{\max} = R_T - R_p + 1.5$, showing that target and projectile must overlap almost completely.[14] A larger impact parameter results in fragmentation of the projectile as observed by Mougey.[15]

I wish to thank G. Bertsch and P. Braun-Munzinger for helpful discussions and J. M. Alexander for a careful reading of the manuscript. I acknowledge receipt of a NATO fellowship.

[(a)]On leave from University of Heidelberg, Heidelberg, Federal Republic of Germany.

[1]H. Noll, E. Grosse, P. Braun-Munzinger, H. Dabrowski, H. Heckwolf, O. Klepper, C. Michel, W. F. J. Mueller, H. Stelzer, C. Brendel, and W. Roesch, to be published.

[2]E. Grosse, Gesellschaft für Schwerionenforschung Report No. GSI-83-27 (to be published).

[3]P. Braun-Munzinger, P. Paul, L. Ricken, J. Stachel, P. H. Zhang, G. R. Young, F. E. Obenshain, and E. Grosse, Phys. Rev. Lett. **52**, 255 (1984).

[4]R. Shyam and J. Knoll, Gesellschaft für Schwerionenforschung Report No. GSI-83-22 (to be published).

[5]D. Vasak, H. Stöcker, B. Mueller, and W. Greiner, Phys. Lett. **93B**, 243 (1980).

[6]J. Aichelin and G. Bertsch, Phys. Lett. **B138**, 350 (1984).

[7]M. B. Tsang *et al.*, to be published.

[8]J. Aichelin, J. Hüfner, and R. Ibarra, Phys. Rev. C, to be published.

[9]W. A. Friedman and W. G. Lynch, Phys. Rev. C **28**, 16 (1983).

[10]V. Weisskopf, Phys. Rev. **52**, 295 (1937).

[11]R. Kaps, private communication.

[12]D. Ashery, Phys. Rev. C **23**, 2173 (1980); I. Navon *et al.*, Phys. Rev. C **28**, 2548 (1983).

[13]K. Nakai *et al.*, Phys. Rev. Lett. **44**, 1446 (1980).

[14]These systematics are also valid for the data for 44*A*-MeV Ar+Ca and Ar+Sn; see H. Heckwolf, E. Grosse, H. Dabrowski, O. Klepper, C. Michel, W. F. J. Mueller, H. Noll, C. Brendel, W. Roesch, J. Julien, G. S. Pappalardo, G. Bizard, J. L. Laville, A. C. Mueller, and J. Peter, Z. Phys. A **315**, 243 (1984).

[15]J. Mougey, Nucl. Phys. **A387**, 109c (1982).