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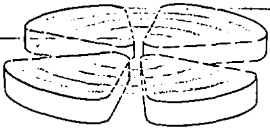

SINGLE NUCLEON-NUCLEON COLLISION MODEL FOR SUBTHRESHOLD PION PRODUCTION IN HEAVY ION COLLISIONS

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ABSTRACT

We show that inclusive experimental data on subthreshold pion production in $^{12}C + ^{12}C$ and $^{16}O + ^{12}C$ collisions can be reproduced using a first chance Nucleon-Nucleon (NN) collision mechanism. Pauli blocking effects are extremely important while π-resorption can be safely neglected for these light systems. We apply our method at various beam energies. The possible importance of collective dynamical effects around the physical threshold is finally suggested.

Pion production in heavy-ion collisions is one of the most striking features of medium energy reactions. Many experiments, of inclusive type, have been performed using different combinations of target and projectiles at different beam energies$^{1,4)}$. Pions have been observed at a beam energy as low as 25 MeV/u$^{4)}$. This is far below the threshold for pion production in free Nucleon-Nucleon collisions. For that reason several mechanisms have been proposed so far $^{5-8)}$.

An intuitive way to understand this effect is to take into account the nucleon Fermi motion inside the two colliding ions$^{9;10)}$. From simple kinematics in a Fermi gas model (sharp spheres in momentum space) we get a threshold value of about 50 MeV/u beam energy. Therefore the lower energy yield means : i) Importance of a diffuse surface in momentum space (high momentum tails) ; ii) Possibility of noticeable effects from phase space collective distortions in the entrance channel.

The analysis of high momentum tails deserves a further discussion. Indeed such high momenta in principle cannot be associated with nucleons of energy $E = P^2/2m$, because these components are off-shell in the ground state. However the mean field is also changing during the collision. Recent microscopic calculations have shown that off-shell momentum components of the ground state are set approximately on-shell through the time-dependence of the mean field$^{11)}$.

In this letter we show that the NN collision model can reproduce many experimental values just with the use of an appropriate Pauli blocking $^{12)}$ and an unpertrubed momentum distribution given by the harmonic oscillator model which fairly well accounts for the main experimental results from electron scattering$^{10)}$. We will consider light p-shell nuclei as projectiles, targets.

In this case the momentum distribution is :

$$g(p) = \frac{4}{[(\pi a^2)\hbar^2]^{3/2}} \left(\frac{2(A-4)}{12} + 1\right) \frac{a^2P^2}{\hbar^2} \exp\left(-\frac{P^2a^2}{\hbar^2}\right) \qquad (1)$$

$$\text{where } a = \sqrt{\frac{\hbar}{m\omega}} \tag{2}$$

is the harmonic oscillator parameter fixed from the nuclear radius, and $\frac{A-4}{12}$ represents an average occupation number of the valence nucleons.

In the first chance NN collision model, the production cross section can be roughly written[10)] :

$$\frac{d^2\sigma}{d\Omega_\pi dE_\pi} \sim \text{(Glauber factor) } R_\pi^{NN} \quad x\text{(Pauli blocking) } xT \tag{3}$$

where : The Glauber factor gives the average number of first chance NN collisions ; R_π^{NN} is an average pion production rate for free NN → πd processes ; T is the transparency factor i.e. it gives the number of pions which are not absorbed while travelling inside the nucleus.

Let us discuss first the π-absorption. Since we are mainly treating low energy produced pions we could expect this correction not much significative, being important only around the Δ-resonance energy, i.e. for $E_\pi \sim 150$ MeV.

To be more quantitative we define the π-transparency factor T as :

$$T = \frac{\sigma_\pi^{tot} - \sigma_\pi^{abs}}{\sigma_\pi^{tot}} \tag{4}$$

where σ_π^{tot} and σ_π^{abs} are respectively the total and absorption part of the cross-section in the π-Nucleus reaction. For the reaction $\pi^+ + {}^{12}C$ we have $\sigma_\pi^{tot} \simeq 600$ mb[13)], and we parametrize σ_π^{abs} according to the formula :

$$\sigma_\pi^{abs} = \frac{a(\Gamma/2)^2}{[(E-E_o)^2 + (\Gamma/2)^2]}$$

a fit to experimental data[13)] gives $E_o = 140$ MeV, a = 190 mb, $\Gamma = 85$ MeV.

For pion kinetic energies of interest we find a transparency factor of T of the order 0.90 ÷ 0.97. Therefore, since we have no experimental data available in the case of π° or π^{-} we can put T = 1 quite safely for light nuclei.

A fully correct treatment of the Pauli blocking can be done in a quantal microscopic model such as TDHF$^{8)}$. Here we want to treat the Pauli principle in an "average" way.

In the harmonic oscillator model the energy spectrum is given by :

$$E_N = (N + \frac{3}{2}) \hbar \omega$$

where ω is calculated from equation (2). For ^{12}C the energy of the not completely filled p-shell is $E_p \sim 38$ MeV$^{15)}$.

Here we give two prescriptions for the Pauli blocking. In the first one we assume that the final energy of the nucleons after producing a pion, E_{final} must be larger than $E_p$$^{9)}$. We refer the results of our calculation to this case with the name of "Hard Pauli blocking".

In the second prescription ("soft Pauli blocking") we consider the following two cases :

i) if the initial energy of a nucleon $E_{initial}$ is larger than E_p, then also $E_{final} \quad E_p$.

ii) if $E_{initial} < E_p$, then $E_{final} > E_{initial}$.

In case ii) indeed we assume that the nucleon in the final state could occupy its initial state again.

Please note that we have introduced no "ad hoc" parameters, other than the H.O. ones fixed from independent experiments.

Let us discuss now the inclusive reaction $^{12}C + ^{12}C \rightarrow \pi^\circ + X$. In fig. 1 the total reaction cross section is plotted versus the laboratory energy per nucleon. The experimental values are taken from ref.[1,4)]. The triangle gives the results of our calculation with the "Hard Pauli blocking", while the full line is obtained when we use the "Soft Pauli blocking". The two theoretical calculations differ of a factor larger than 2 at $E_{lab}/A = 25$ MeV. When we increase the beam energy, we observe that this difference becomes smaller and smaller until it disappears at ≈ 200 MeV/A. This is easy to understand increasing the beam energy, the phase-space available for pion production increases and the difference on phase-space between the two theoretical approaches becomes very small as compared to the entire phase-space available. In figure 2 we show explicitly how the two different ways of treating the Pauli blocking affect the pion distributions at $E_{lab}/A = 35$ MeV for the same reaction considered above. There is almost one order of magnitude between the two methods at the peak of the distribution. In figure 3 we compare the "soft-Pauli blocking" results with experiments at three different lab energies[1)].

In figure 4 we plot the results of our calculation of the double differential cross-section for the system $^{16}O + ^{12}C \rightarrow \pi^+ + X$[16)]. In this case we also include a Coulomb correction in the final kinetic energies of the pion. Such effect is very small, about 4 MeV coming from the Coulomb acceleration when the positive pion is just leaving the charged overall nucleus. Again also in this case we observe a good agreement with experiments.

We have shown how inclusive date on pion production at energies of about 60 MeV/A in the lab system can be explained with the use of a N-N collision model, including Pauli blocking, pion absorption and Coulomb effects in the exit channel.

Of course, some points deserve a further analysis : i) the choice of the momentum distribution, since we are well aware that the harmonic oscillator is inadequate, especially for the high momentum tail ; ii) the Pauli blocking, and in particular the choice of a given Fermi energy.

Moreover some other effect could become important when we go at lower energies. In particular some preliminary calculations show that collective mean field distortions in the approaching ions could imply variations up to one order of magnitude in the π-production around the threshold[17)].

In conclusion we can say that while the predominant mechanism for π-production in heavy ion collisions seems to be the one described in this work, still the problem looks open. Some exclusive measurements are strongly needed as well as more data around the physical threshold for different ions.

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REFERENCES

1. E. Grosse, Proc. "Winter College on Fundamental Nuclear Physics" Eds. K. Dietrich, M. Di Toro and H.J. Mang World. Sci. 1985, p. 1459 and references therein.
2. E. Chiavassa et al., Nucl. Phys. A422 (1984) 621.
3. B. Bernard et al., Nucl. Phys. A423 (1984) 511.
4. F.E. Obenshain et al., "Nucleus-Nucleus Collisions II" vol. I : Contributed papers, p. 173, eds. B. Jakobsson and A. Aleklett.
5. D. Vasak et al., Phys. Lett. 93B (1980) 243 ; Phys. Scripta 22 (1980) 25.
6. R. Shyam and J. Knoll, Phys. Lett. 136B (1984) 221 ; Nucl. Phys. A426 (1984) 606.
7. J. Aichelin and G. Bertsch, Phys. Lett. 138B (1984) 350 ; J. Aichelin, Phys. Rev. Lett. 52 (1984) 2340.
8. M. Tohyama et al., Phys. Lett. 136B (1984) 226 ; Nucl. Phys. A437 (1985) 739.
9. G.F. Bertsch, Phys. Rev. C15 (1977) 713.
10. C. Guet and M. Prakash, Nucl. Phys. 428A (1984) 119c.
11. W. Cassing, "Phase Space Dynamics of Nucleus-Nucleus Collisions", Proc. Int. Meet. "Phase Space Approach to Nuclear Dynamics", ICTP - Trieste 1985 Eds. M. Di Toro et al. World Sci. Publ. in press.
12. A. Bonasera et al., "Subthreshold pion production in heavy ion collisions at E_{lab}/A 20 MeV. Proc. IAEA Topical Meeting "Phase Space Approach to Nuclear Dynamics" ICTP - Trieste 1985, Eds. M. Di Toro et al., World Sci. Publ. in press.
13. O. Ashery, Nucl. Phys. 1335 (1980) 385.
14. P. Hecking, Phys. Lett. 103B (1981) 401.
15. A. Bohr and B.R. Mottelson, "Nucl. Structure", Vol. I, p. 220.
16. Catania-Saclay Collaboration to be published.
17. V. Bellini et al., Proc. "XXIII Winter Meeting on Nuclear Physics", Bormio, Jan. 1985, Ed. I. Iori, p. 58.

FIGURE CAPTIONS

Fig. 1. : Total reaction cross-section versus E_{lab}/A for the reaction $^{12}C + {}^{12}C \rightarrow \pi^{\circ} + X$.

Fig. 2. : Differential cross-section versus pion kinetic energy at $E_{lab}/A = 35$ MeV for the reaction $^{12}C + {}^{12}C \rightarrow \pi^{\circ} + X$.

Fig. 3. : Comparison with experimental data at three different lab energies for the reaction $^{12}C + {}^{12}C \rightarrow \pi^{\circ} + X$.

Fig. 4. : Double differential cross-section for the reaction $^{16}O + {}^{12}C \rightarrow \pi^{+} + X$ at $E_{lab}/A = 94$ MeV.

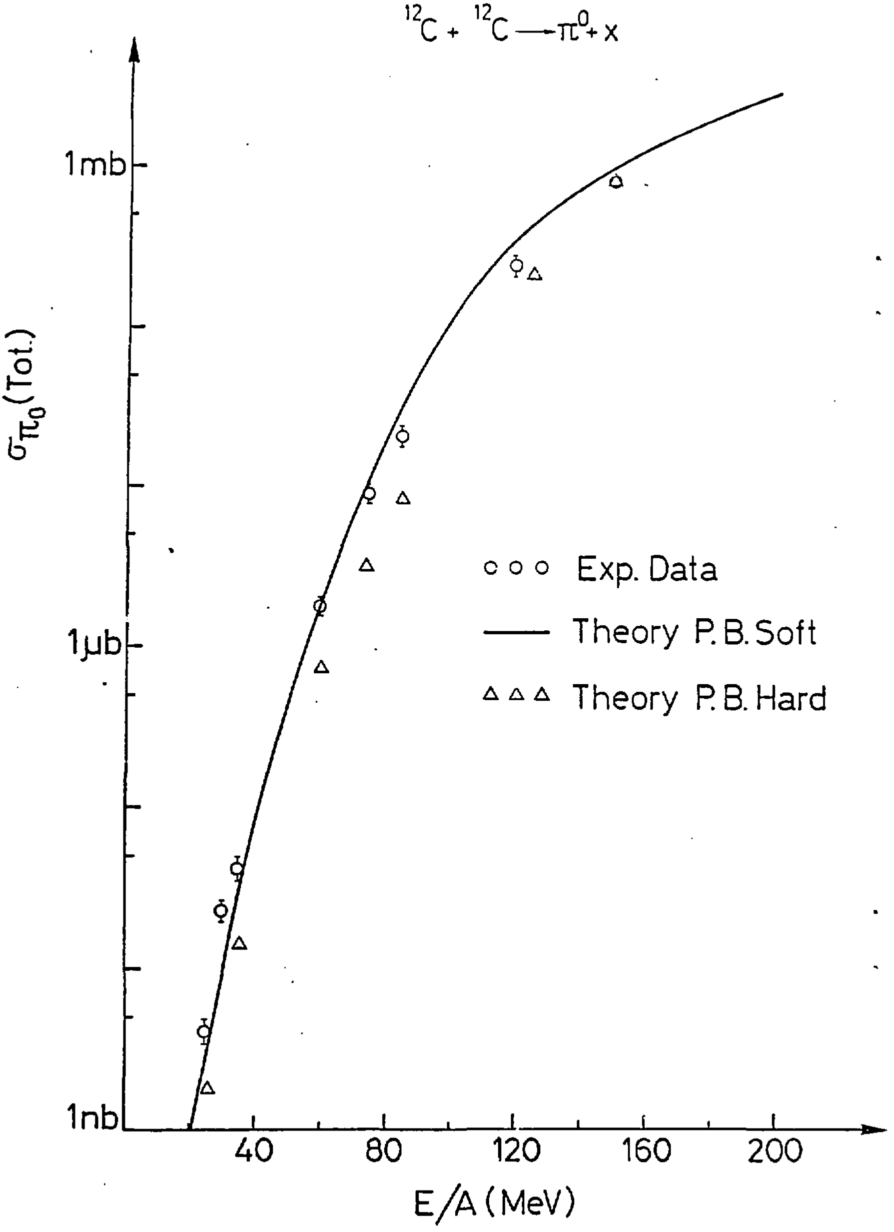
$^{12}C + ^{12}C \longrightarrow \pi^0 + X$
σ_{π_0}(Tot.)
1mb
1μb
1nb
40
80
120
160
200
E/A (MeV)
○ ○ ○ Exp. Data
Theory P.B. Soft
△ △ △ Theory P.B. Hard

Fig. 1

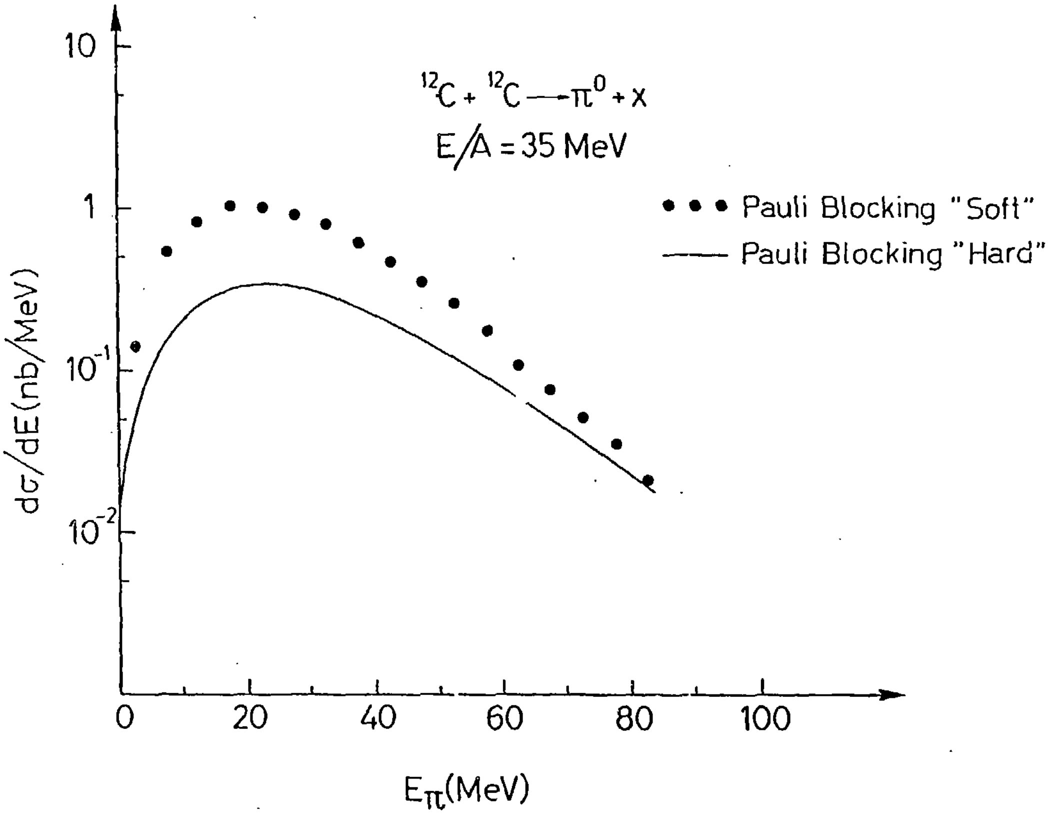

Fig. 2

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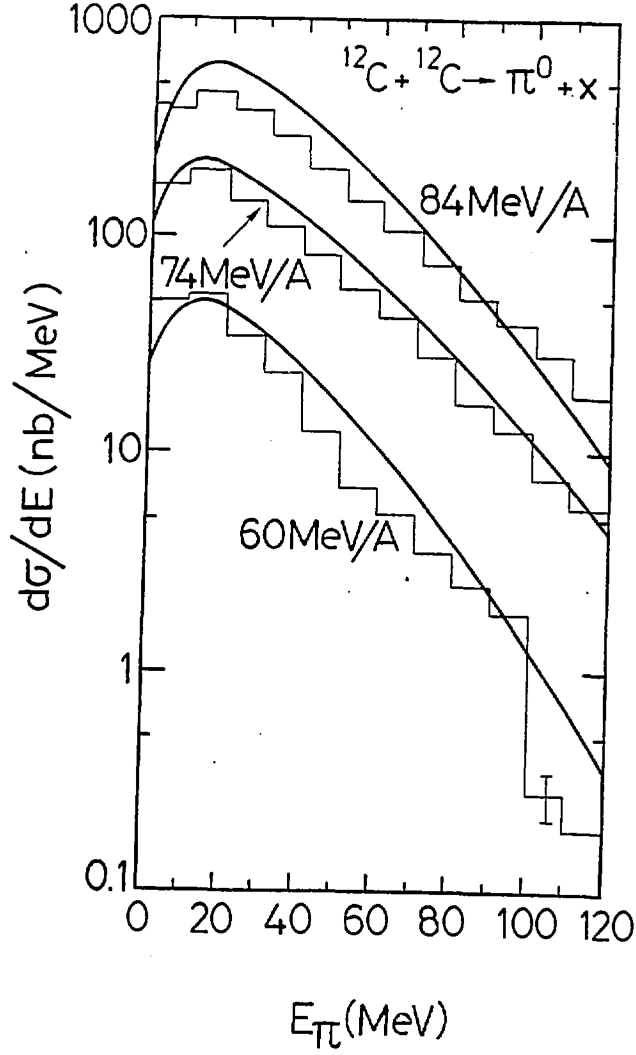
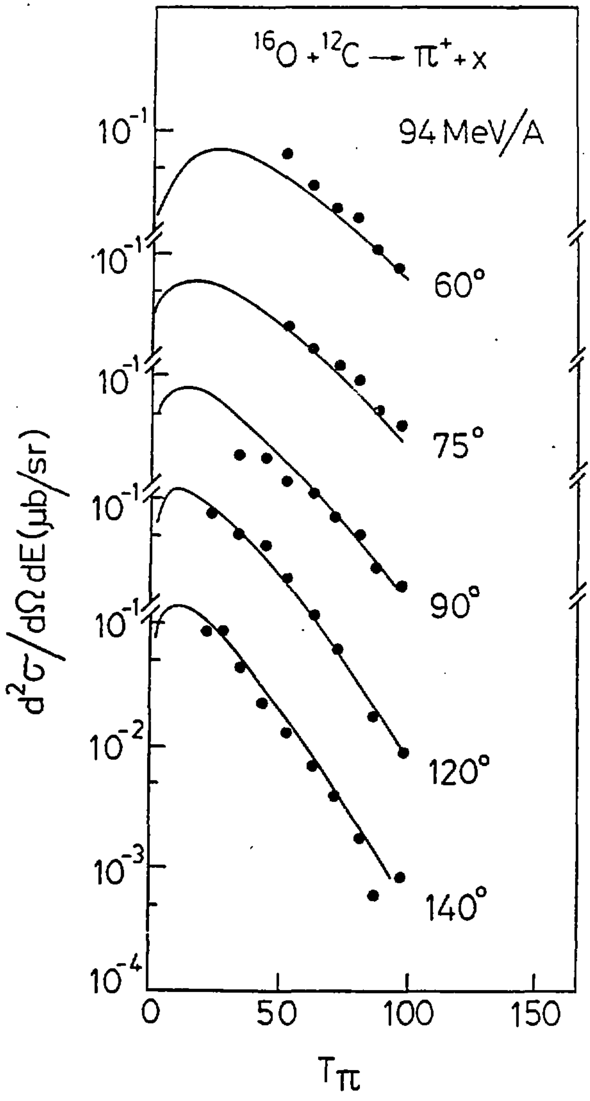


$^{12}C + ^{12}C \rightarrow \pi^0 + x$
84MeV/A
74MeV/A
60MeV/A
$d\sigma/dE$ (nb/MeV)
1000
100
10
1
0.1
0
20
40
60
80
100
120
E_π(MeV)

Fig. 3



$^{16}O + ^{12}C \rightarrow \pi^+ + x$
94 MeV/A
10^{-1}
10^{-1}
10^{-1}
10^{-1}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
60°
75°
90°
120°
140°
$d^2\sigma/d\Omega\,dE\,(\mu b/sr)$
0
50
100
150
T_π

Fig. 4