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New Cascade Model Calculation of Pion Multiplicity in High-Energy Heavy-Ion Collisions

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Abstract: Pion multiplicities in nuclear collisions are calculated using the nuclear cascade model developed by Kitazoe et al. This cascade model differs in particular from previous models in the way binding, Pauli principle, and Fermi motion effects are treated. The treatment of such details in the cascade is found to have significant influence on the pion multiplicities. Close agreement with the Ar + KCl central collision data is obtained without introducing the compression effect postulated by Stock et al.

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One of the goals of high-energy heavy-ion research is to find out whether collective phenomena may be realized in the intermediate stage of heavy-ion collisions. Up to now, several observations have been attributed to the effect of the nuclear collective motion: 1) The forward suppression of low-energy protons ejected in high-multiplicity events (HME) in E_L = 393 MeV/A Ne + U collisions [1]. 2) The bounce-off effect in two-particle correlation functions measured in E_L = 800 MeV/A C + Pb and Ar + Pb collisions [2,3]. 3) The negative-pion multiplicity in HME of Ar + KCl collisions [4]. 4) The different shapes of energy spectra between protons and pions in HME of E_L = 800 MeV/A Ar + KCl collisions [5].

It was reported that some of these data could not be explained by means of the nuclear cascade approach [4,6-8]. Such discrepancies between data and cascade may shed light on collective phenomena in relativistic nuclear collisions. However, it is not clear yet whether the discrepancies are not due to a variety of problems in the treatment of the Pauli principle, the potential well, the pion production, the nucleon-nucleon scattering mechanism, and finally in the framework itself. Here, the framework implies that there are essentially two methods, the time-independent description [9-11] and the time-dependent one [12-15]. The first method is applicable for the case of collisions in which the cascade density is small, since both the nuclear density and the sizes of projectile and target nuclei are kept unchanged during the collision time. The second method can describe more dynamically the development of cascade collisions, since it follows the time-dependent behavior of all the particles.

Recently, Kitazoe et al. [16] have developed a time-dependent cascade model program, which treats the above-mentioned problems in a more complete way. In this paper we apply the cascade model to the problem of pion multiplicity in HME of Ar + KCl collisions. The primary motivation is the observed large discrepancy between Cugnon's cascade model [13] calculation and the experimental data. R. Stock et al. [4] argued that the total pion multiplicity could be linked directly with the high-density stage of collisions and regarded the discrepancy as due to the compression effect, which is not included in the cascade model approach. In this paper, however, we shall demonstrate that there is no essential discrepancy between the experimental data and the result of our cascade calculation.

The main feature of the cascade model is summarized as follows [16]: a) It is a time-dependent description, with momentum of all nucleons being updated during the collision process. b) The experimental data are used to determine the elementary NN scattering process. Protons and neutrons are treated explicitly. The scattering takes place at the distance of closest approach. c) The nucleons move with the Fermi motion in the square well potentials of the projectile and the target nuclei. With the time evolution, they are reflected or refracted at the surfaces of these nuclei. d) The radius and the velocity of the potential well are recalculated due to the collisions, the reflection, and the refraction in each time step. Neutrons go out freely from the surface if the energy is positive, while protons have to pass through the Coulomb barrier. e) The Pauli principle is taken into account by prohibiting the collision process of two-nucleons, if they belong to the same nucleus and are in the bound state or if both or one of them falls into the bound state after the collisions (the bound state of a nucleon is checked by calculating the relative energy of this nucleon measured from the center of mass of the projectile or the target nucleus).

To demonstrate the applicability of the present cascade model, we shall show first the momentum spectra of proton inclusive cross section induced by

E_L = 800 MeV proton on KCl in Fig. 1. The dotted lines are obtained by taking only the elastic N-N scatterings into account. While the sharp quasi-free scattering peak at forward angle and at high momentum is reproduced only by these collisions, the intermediate energy structure is completely missed. The inclusion of the inelastic N-N scatterings through the formation of Δ isobars enhances the inclusive cross section at the intermediate energy region as indicated by the solid lines. We have also calculated the proton inclusive cross sections of identical nucleus-nucleus collisions and of light- and heavy-nucleus collisions without introducing any additional free parameters. The calculated results are satisfactory, as can be seen in Fig. 2 for E_L = 800 MeV/A Ne + Ne and in Fig. 3 for E_L = 393 MeV/A Ne + U collisions. Encouraged by this success, we now discuss the pion multiplicity in Ar + KCl central collisions. The solid circles of Fig. 4 show the result calculated by using the present cascade code, where we assume that the Δ particle decays instantaneously into a pion and a nucleon. The pion is assumed to leave the system with no further interactions. This will on one hand lead to an incorrect pion spectrum [13], while on the other hand we expect an upper bound on the pion multiplicity. Even with such an approximation, our cascade model reproduces the experimental data (triangles) more closely than that of Cugnon's model. It is very difficult to trace the origin of the difference between the two cascade model calculations, where the numerical details differ greatly. To see which effect in our code causes the greatest variation in the pion multiplicity, we have turned on and off various features such as reflections, Pauli blocking, potential well recoil effect, one at a time. Each of these elements was found to induce 10-20% variations on the pion multiplicity. Combined, they lead to 30-60% reduction relative to Cugnon's results. We have found no single source of the reduction relative to

Cugnon. Rather, it appears that the pion multiplicity is sensitive to the combined effects of many elements of the reaction mechanism. To stress the validity of Cugnon's code [13], R. Stock et al. [4] argued that his code can reproduce pion reaction cross sections in proton-nucleus collisions. It should be noted, however, that there is a great difference in the cascade densities between proton-nucleus and nucleus-nucleus collisions. For this reason, the success in proton-nucleus collisions is not sufficient for the applicability of the code. The present cascade model calculation gives a good agreement with the experimental data in such collisions as P + Be and P + C. However, the calculation overestimates the data more and more with increasing target mass number. This overestimate is due to the neglect of pion absorption in our code. Hence the slight overestimation of pion multiplicity in Fig. 4 could probably be removed if pion reabsorption were taken into account.

Finally, let us discuss whether the collective effect such as compression discussed in ref. [4] is expected in Ar + Ar collisions. We present the calculated angular distributions in E_L = 400 MeV/a Ar + Ar collisions in Fig. 5, where the cross sections were divided into the low-energy part $E_C \leq 100$ MeV (circles) and the high-energy part $E_C > 100$ MeV (squares) in the center-of-mass system. The open circles in this figure show that the angular distribution is still anisotropic even in the low-energy part of central collisions ($b \leq 1$ fm). The projectile is rather transparent for these collisions, and it seems very difficult to get the collective motion in such light systems. On the other hand, we can find that the angular distributions become isotropic in E_L = 400 MeV/A Nb + Nb central collisions (this problem will be discussed in detail elsewhere).

In conclusion, we find that our cascade model can reproduce qualititatively the pion multiplicity in relativistic nuclear collisions without introducing the compression effect. The cascade calculations at this stage of study are still dependent on the detailed treatments of the reaction mechanism. Since the results are sensitive to a combination of many subtle details of the reaction mechanism, the extraction of compression energies from such data may be premature.

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Figure Captions

Fig. 1. Proton inclusive cross section in E_L = 800 MeV P + KCl collisions. Calculated result (solid lines) is compared with data (solid circles). Dotted lines show results taking only elastic scatterings into account.

Fig. 2. Proton inclusive cross sections in a) E_L = 800 MeV/A Ne + NaF and b) E_L = 400 MeV/A Ne + U collisions, where calculated results (solid lines) are compared with data (open circles).

Fig. 3. The mean π^- multiplicity as a function of bombarding energy for near-central collisions of ^{40}Ar + KCl. Present results of calculations (solid circles) are compared with those of Cugnon (open circles) and data (triangles).

Fig. 4. Calculated angular distributions of ejected protons in E_L = 400 MeV/A Ar + Ar collisions. The figure shows a forward and backward peaking even for the low-energy protons ($E_C \leq$ 100 MeV) in central collisions.

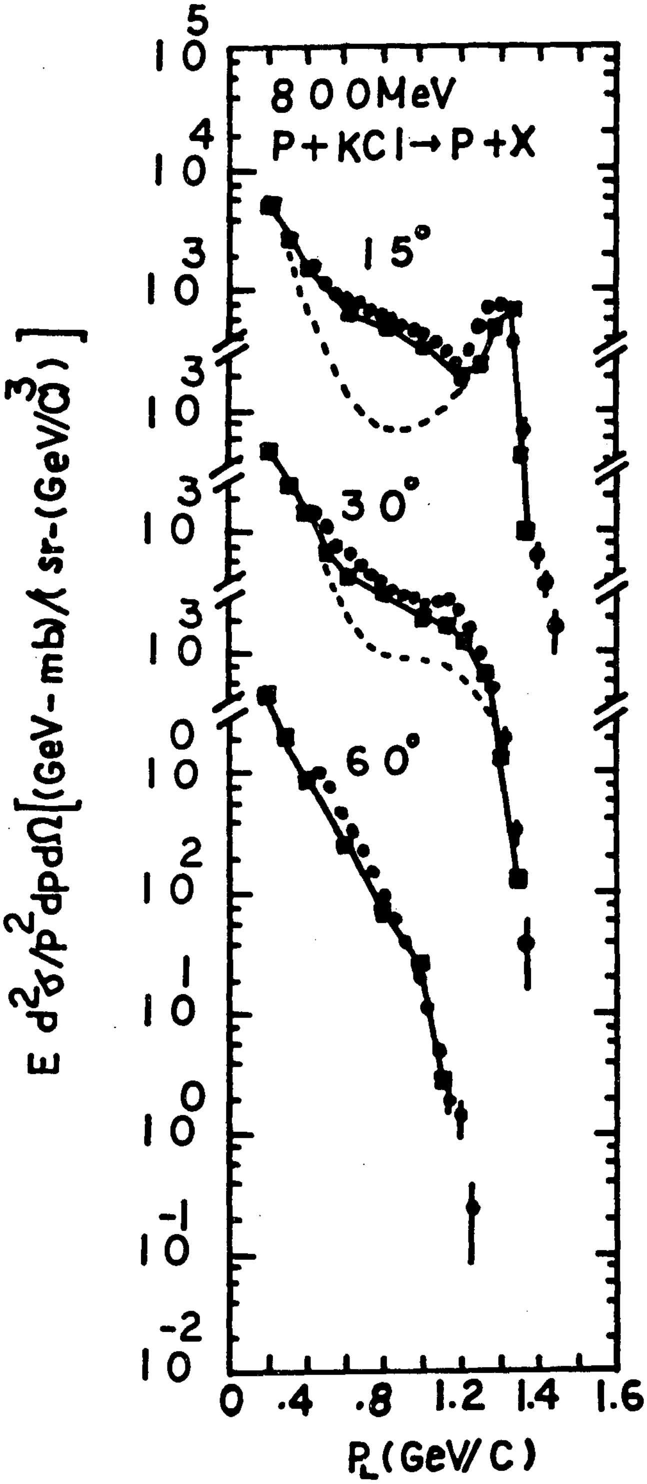

Fig. 1

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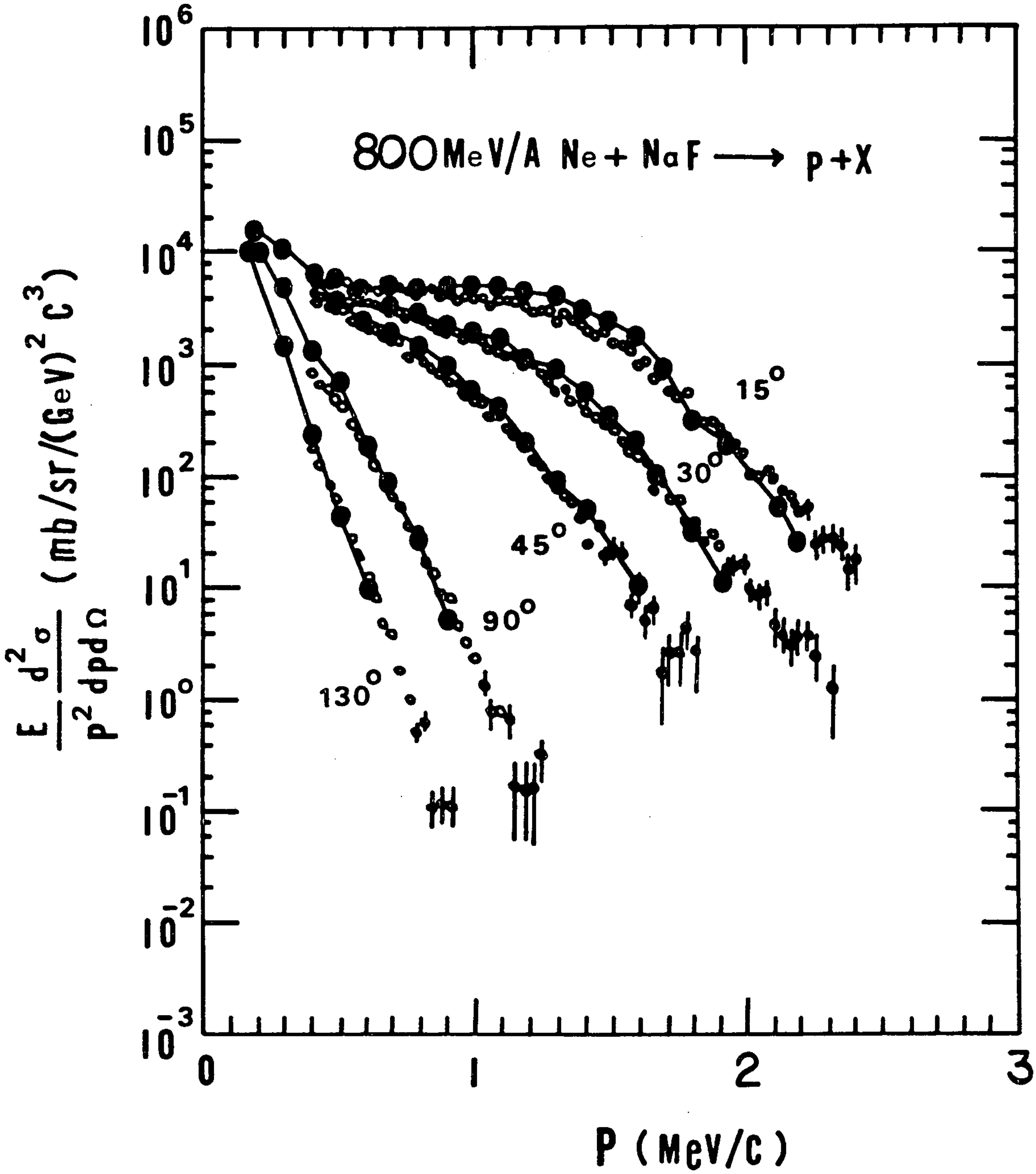

Fig. 2a

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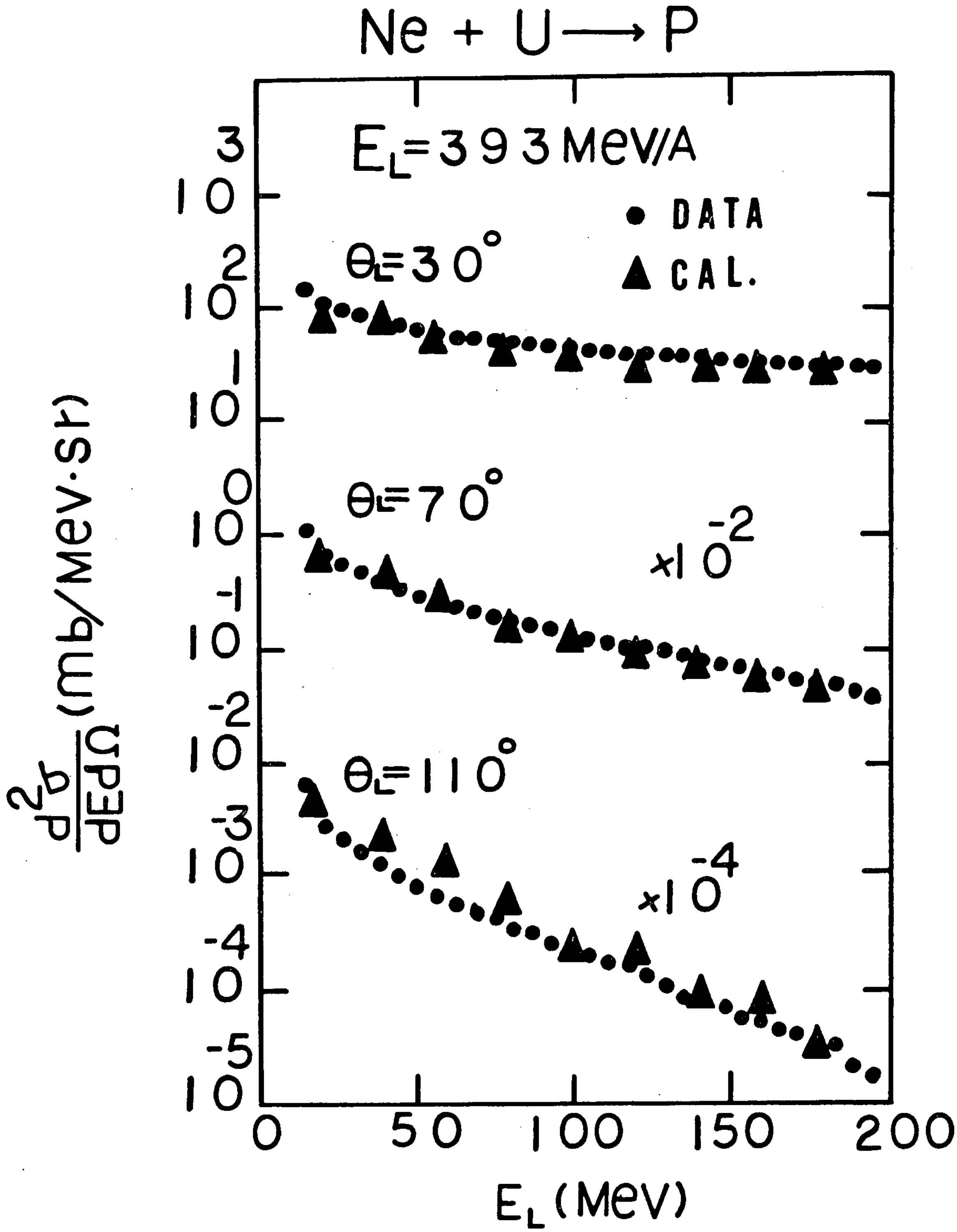

Fig. 2b

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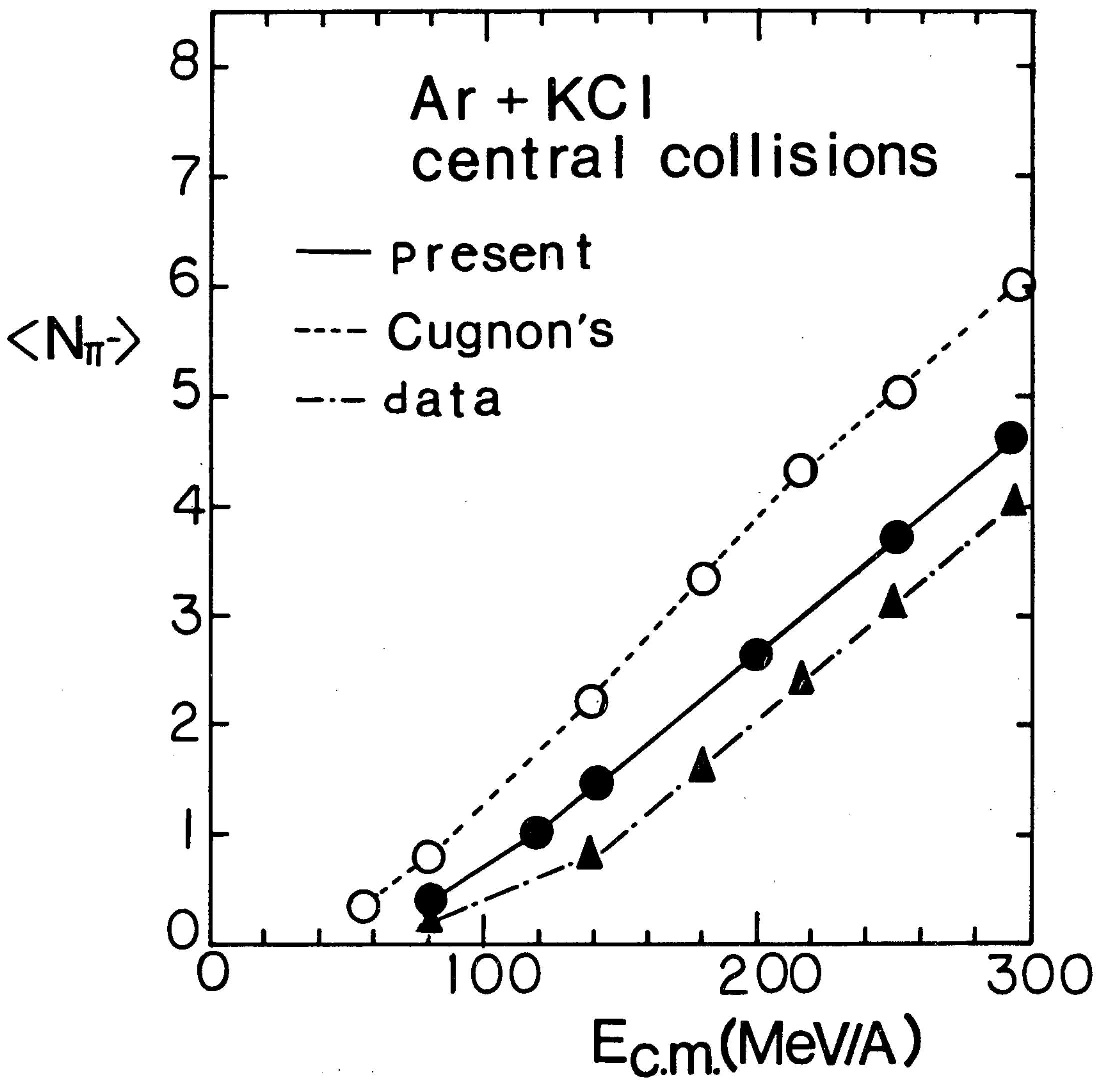

Fig. 3

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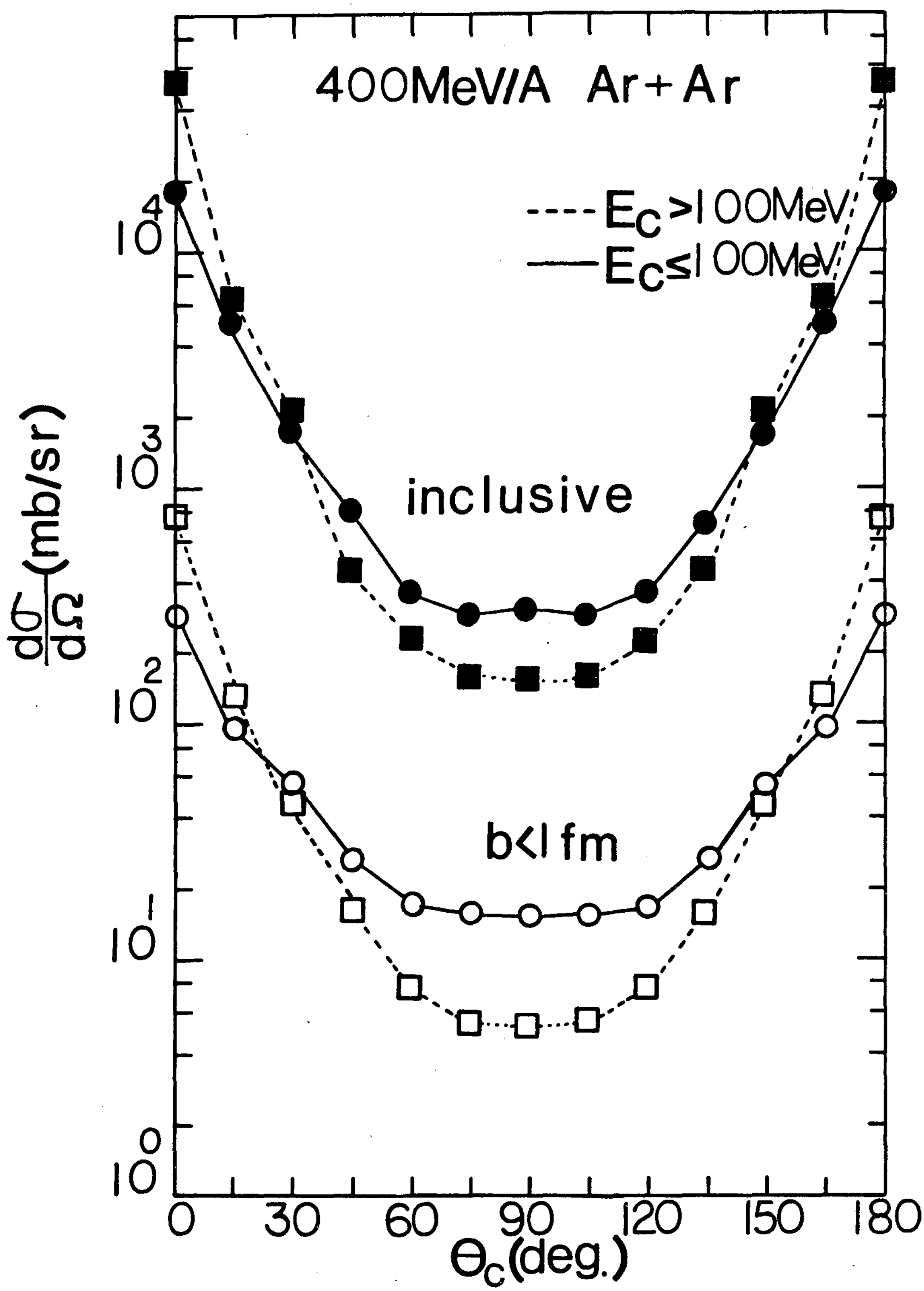

Fig. 4

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