LBL-9352 c.2
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Submitted to Physics Letters

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June 1979

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Prepared for the U. S. Department of Energy
under Contract W-7405-ENG-48

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Negative Pion Production by 800 MeV/A C, Ne, and Ar Beams

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ABSTRACT

Energy and angular distribution of π^- produced in relativistic heavy-ion collisions have been measured at 800 MeV/A incident energy. Cross sections for low energy pions ($E_{CM} \simeq 100 \sim 200$ MeV) are forward and backward peaked in the nucleon-nucleon C.M. frame. Such anisotropy becomes weaker for higher energy pions. The shape of the energy spectra at $\theta_{CM} = 90°$ is approximately exponential. Their slopes are steeper than those observed for protons. The data are discussed in terms of several models.

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In a previous paper [1] we reported proton inclusive spectra over a wide range of proton energies and angles in collisions between nuclei at a beam energy of 800 MeV/A. Several models such as hard scattering [2], cascade [3], and firestreak [4] can reproduce the proton spectra even though they are based on quite different assumptions. Pions may play a different role, complementary to that of protons, because of the energy threshold required for their production. Thus pion spectra are expected to give us different types of information to constrain the various models.

Up to now not very much experimental information on pion production in relativistic heavy-ion collisions has been collected. Forward pion emission has been studied by Papp et al. [5] and also by Schimmerling et al. [6]. Experiments using the streamer chamber [7] as well as emulsions [8] have given pion multiplicity distributions. However, no precise measurements of energy and angular distributions of pions emitted at large laboratory angles up to large transverse momentum were available. We have measured the pion inclusive spectra in collisions of C on C and Pb, Ne on NaF and Pb, and Ar on KCl and Pb, at a projectile energy of 800 MeV/A.

The experimental procedures and equipment are the same as those described in Refs. [1] and [9]. A magnetic spectrometer mounted on a rotatable platform was used to measure pions with energies of 80-1000 MeV at laboratory angles from 15° to 145°. Several corrections to the raw data have been applied in obtaining absolute cross sections. These are generally similar to those used in the case of the proton measurements [1]. Specific to pions was the decay-in-flight correction which amounted to 21% for E_π = 100 MeV and 6% for E_π = 400 MeV. The overall uncertainty of the cross section values is about 30%.

In most cases we measured both π^+ and π^- by using both polarities of the magnetic fields in the spectrometer. In collisions between nearly equal-mass nuclei, such as C + C, Ne + NaF, and Ar + KCl, the observed yield ratio $R \equiv \pi^-/\pi^+$ was such that $R \simeq 1$ for high-energy pions, while for low energy pions, especially in collisions of Ar on KCl, R is substantially greater than 1. It seems very likely that these deviations from R = 1 are due to Coulomb effects. It would certainly be interesting to study such effects in detail, but in the present paper we concern ourselves with other aspects of pion production and will limit ourselves to the π^- results only, since they have much better statistics.

Shown in Fig. 1 are typical results of π^- production for Ar + KCl and Ar + Pb collisions. The data are presented in the nucleon-nucleon center-of-mass frame, although this may not be the best choice in the case of Ar + Pb. Each contour line in the plane of parallel $(p_{\parallel}^*/m_\pi c)$ and transverse $(p_T/m_\pi c)$ momenta connects the same invariant cross sections $\sigma_I = (E/p^2)(d^2\sigma/dpd\Omega)$. Two adjacent thick solid curves differ by one order of magnitude in cross sections. Isotropic distributions in the nucleon-nucleon CM frame are expressed by semi-circular lines in this plane, which are indicated by dotted lines in Fig. 1. For pions with CM momentum higher than 200 MeV/c the shape of the cross section contours is almost independent of target and is centered around $p_{\parallel}^* = p_T = 0$. In the case of Ar on Pb, the centroid of the contour lines shifts toward the target frame as pion momenta decrease.

Energy distributions of pions at $\theta_{CM} = 90°$ are shown in Fig. 2. They are roughly exponential in shape, $\exp(-E_K^*/E_0)$ with the slope factor E_0 of 60-70 MeV, where E_K^* is the kinetic energy in the CM frame. It is interesting to compare this observation with the proton case. There the distribution for high-energy protons is also approximately exponential, with a slope factor E_0

of 70-90 MeV, but for low energy protons these distributions deviate substantially from such an exponential shape [1]. Thus, not only is the shape different for protons and π^-, but E_0 of protons is greater than that of π^-.

The predictions of the firestreak model [4] and single nucleon-nucleon scattering model [2] for the Ne + NaF system are compared with the experimental data on Fig. 2. The firestreak calculation fails to reproduce the data. It predicts almost the same slope for pions and protons and consequently overestimates the experimental cross-section by a factor of 10 at $E_K^* = 400$ MeV. In its present form the firestreak model assumes (a) complete thermalization within each tube, (b) no relative transverse momenta between two adjacent tubes. Therefore, at $\theta_{CM} = 90°$ a purely thermal component contributes to particle production, which implies that E_0 should be almost identical for protons and pions.

Noticing the difference in the slope factor E_0 between protons and pions, Siemens and Rasmussen [10] proposed a thermal model including the expansion motion of the system. This expansion model qualitatively explains the difference in E_0 between protons and pions. However, neither the absolute cross section nor the angular distribution have yet been predicted with this model. Another explanation of the thermal model is given by Sano et al. [11] who claimed that most of the pions are produced through Δ's. The slope for pions could then be steeper than that for protons, due to the motion and decay characteristics of Δ.

The prediction of the single hard scattering model which assumes a nucleon momentum distribution of the form $(p/p_0)/\sinh(p/p_0)$ is in reasonably good agreement with the data except at very low energies. This momentum distribution was chosen to approximate the effective momentum distribution of nucleons in nuclei including at least some distortions due to multiple scattering, absorption and scattering from correlated nucleons.

In Table I the ratios of invariant cross sections between $\theta_{CM} = 30°$ and 90° in the CM frame are compared for C + C, Ne + NaF, and Ar + KCl, at three pion momenta. The corresponding ratios for proton data are also listed there. We note three points. First, the angular distributions for pions are less anisotropic than those for protons. Since the pions generally have much higher velocities than the protons, it is expected that the emission of pions is less sensitive to the initial velocity of the beam. Second, the observed anisotropy at $p^*/m_\pi c \simeq 2$ is stronger than the anisotropies predicted by the firestreak or hard scattering models. Recently this tendency was observed also by Chiba et al. [12] in their measurements of low-energy π^+. The third point is that the observed anisotropy of pions of very high momentum, $p^*/m_\pi c \sim 4$, is very small, being smaller than that of $p^*/m_\pi c \sim 2$. This tendency is in contradiction with both the predictions of the firestreak model and the hard scattering model, and especially of the latter.

In summary, the present pion data provide new tests of the current theoretical models. The firestreak model is not able to reproduce the steep slope observed for the high momentum exponential tail of the pion spectra. The expansion model reproduces qualitatively the shape of the energy spectra at $\theta_{CM} = 90°$ for both pions and protons but lacks a quantitative estimation of the cross sections and angular distributions. The single nucleon-nucleon hard scattering model predicts fairly well the dominant feature of the shapes of the energy spectra for both pions and protons. However, this model does not reproduce the details of the CM angular distribution for low energy pions, and it predicts too large an anisotropy for high energy pions and protons. Clearly, better models are needed.

Finally let us compare our data with a simple calculation based on the use of proton + nucleon data. Because data for proton + C are available at E_p = 730 MeV [13], we compare our C + C → π^- data with them. The simplest assumption is that the projectile C nucleus is replaced by 6 individual protons and 6 neutrons. We then have

$$\sigma_{CC\to\pi^-} = 6\sigma_{nC\to\pi^-} + 6\sigma_{pC\to\pi^-} \simeq 6\sigma_{pC\to\pi^+} + 6\sigma_{pC\to\pi^-}. \tag{1}$$

Results obtained by this formula are indicated by curve I in Fig. 3. For low-energy pions the fit to the data is reasonable, but for high-energy pions a significant deviation from the data is observed. It is obvious that Eq. (1) is not symmetric between projectile and target, because Fermi-motion effects as well as absorption and rescattering effects are neglected for the projectile but not for the target. In order to achieve the symmetry between projectile and target, we artificially produced C (projectile) + p (target) data from p (projectile) + C (target) data by a simple transformation of the frame and then calculated the following cross sections:

$$\begin{aligned}\sigma_{CC\to\pi^-} &= \frac{1}{2}\left[(6\sigma_{nC\to\pi^-} + 6\sigma_{pC\to\pi^-}) + (6\sigma_{Cn\to\pi^-} + 6\sigma_{Cp\to\pi^-})\right] \\ &= \frac{1}{2}\left[(6\sigma_{pC\to p^+} + 6\sigma_{pC\to p^-}) + (6\sigma_{Cp\to p^+} + 6\sigma_{Cp\to p^-})\right].\end{aligned} \tag{2}$$

The results are indicated by curve II in Fig. 3, where the high-energy tail at forward angles is now in better agreement with the data. This is a simple reflection of the fact that the high-energy pions at forward angles are more sensitive to the Fermi motion of projectile nucleons. Of course, calculation (2) is still over-simplified and ignores the effects when both projectile and target nucleons have Fermi motion. Furthermore, because the comparison is made with pC data at 730 MeV and no comparable results are available at slightly

higher energies, we have neglected possibly important energy dependent effects. Still, such a simple calculation seems to explain quite well the dominant features of the the pion spectra observed at forward and backward angles in nucleus-nucleus collisions. The 56° spectra are not fit as well, possibly because multiple scattering and other effects involving both nuclei have been excluded in this simple picture.

We would like to express our thanks to Dr. L. Anderson and Dr. W. Brückner for their participation in the experiment at an initial stage. Thanks also go to Mr. R. Fuzesy for his technical support and to Prof. K. Nakai for stimulating discussions. This work was supported by the Nuclear Science Division of the U.S. Department of Energy under contract W-7405-ENG-48 and by the Yamada Foundation.

REFERENCES

[1] S. Nagamiya, L. Anderson, W. Brückner, O. Chamberlain, M.-C. Lemaire, S. Schnetzer, G. Shapiro, H. Steiner, and I. Tanihata, Phys. Lett. 81B (1979), 147.

[2] R. L. Hatch and S. E. Koonin, Phys. Lett. 81B (1979), 1.

[3] R. K. Smith and M. Danos (to be published).

[4] J. Gosset, J. I. Kapusta, and G. D. Westfall, Phys. Rev. C18 (1978), 844.

[5] J. Papp, J. Jaros, L. Schroeder, J. Staples, H. Steiner, A. Wagner, and J. Wiss, Phys. Rev. Lett. 34 (1975), 601.

[6] W. Schimmerling, K. G. Volburgh, K. Keopke, and W. D. Davis, Phys. Rev. Lett. 33 (1974), 1170.

[7] S. Y. Fung, W. Gorn, G. P. Kiernan, F. F. Liu, J. J. Lu, Y. T. Oh, J. Ozawa, R. T. Poe, L. Schroeder, and H. Steiner, Phys. Rev. Lett. 40 (1978), 292.

[8] B. Jakobsson, NORDITA Preprint 78/28 (1978), presented at 5th Int. Seminar on High Energy Physics Problems, Dubna, 1978.

[9] S. Nagamiya, I. Tanihata, S. Schnetzer, L. Anderson, W. Brückner, O. Chamberlain, G. Shapiro, and H. Steiner, Proc. Int. Conf. Nuclear Structure, Tokyo, 1977, J. Phys. Soc. Japan 44 (1978), Suppl. p. 378.

[10] P. Siemens and J. O. Rasmussen, Phys. Rev. Lett. 41 (1979), 880.

[11] M. Sano, private communication, 1979.

[12] J. Chiba, K. Nakai, I. Tanihata, S. Nagamiya, H. Bowman, J. Ingersoll, and J. O. Rasmussen, LBL-8699 (1979), submitted to Phys. Rev. C.

[13] D. R. F. Cochran, P. N. Dean, P. A. M. Gram, E. A. Knapp, E. R. Martin, D. E. Nagle, R. B. Perkins, W. J. Shlaer, H. A. Thiesson, and E. D. Theriot, Phys. Rev. D6 (1972), 3085.

Table I.

Ratios of invariant cross sections between θ_{CM} = 30° and 90°.

Numbers in parentheses indicate errors to the last decimal place.

The pion scale is referred to pion mass, the proton scale to proton mass.

	Pions (π^-)			Protons	
(p*/mc) =	2.0	3.0	4.0	1.0	1.3
Experiments:					
C + C	2.0(2)	1.8(4)	1.6(5)	5.3(7)	5(1)
Ne + NaF	2.1(3)	1.5(3)	1.2(4)	4.9(5)	5(1)
Ar + KCl	2.5(3)	2.0(5)	1.4(5)	3.8(10)	4(1)
Calculations for Ne + NaF:					
Hard Scattering[a)]	1.3	5	∿10	8	∿20
Firestreak[b)]	1.3	1.6	1.7	7	8

a) Ref. [2].

b) Ref. [4].

FIGURE CAPTIONS

Fig. 1. Contour plots of cross sections in the nucleon-nucleon CM frame for 800 MeV/A Ar + KCl $\rightarrow \rho^- + X$ (top) and 700 MeV/A Ar + Pb $\rightarrow \pi^- + X$ (bottom).

Fig. 2. Energy distributions of π^- at 90° in the nucleon-nucleon CM frame. Except for the case of Ar on Pb the yields are proportional to $\exp(-E_K^*/E_0)$. E_0 shown here has an error of ±5 MeV. For Ar on Pb the high-energy part is approximately expressed by such an exponential form. Two theoretical models are compared with the data of Ne on NaF: the firestreak model of Ref. [4] and the hard-scattering model of Ref. [2].

Fig. 3. Momentum spectra of π^- in collisions of 800 MeV/A C on C, as compared with the data of 730 MeV p + C $\rightarrow \pi^- + X$. As to estimations I and II, see the text.

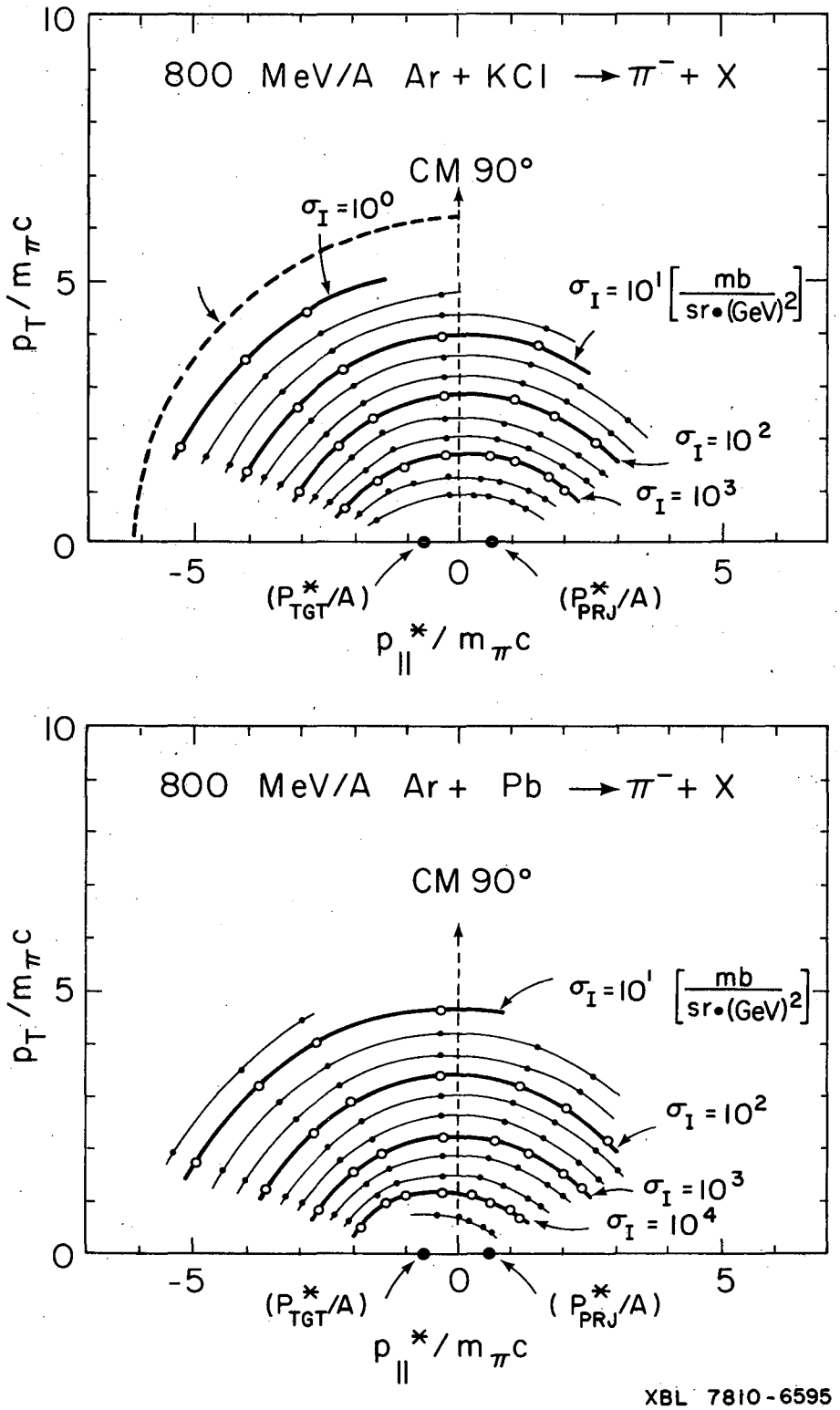
800 MeV/A Ar + KCl → π⁻ + X
CM 90°
σI = 10⁰
σI = 10¹ [mb / sr•(GeV)²]
σI = 10²
σI = 10³
pT / mπc
p∥* / mπc
(PTGT*/A)
(PPRJ*/A)
800 MeV/A Ar + Pb → π⁻ + X
CM 90°
σI = 10¹ [mb / sr•(GeV)²]
σI = 10²
σI = 10³
σI = 10⁴
pT / mπc
p∥* / mπc
(PTGT*/A)
(PPRJ*/A)
XBL 7810-6595

Fig. 1

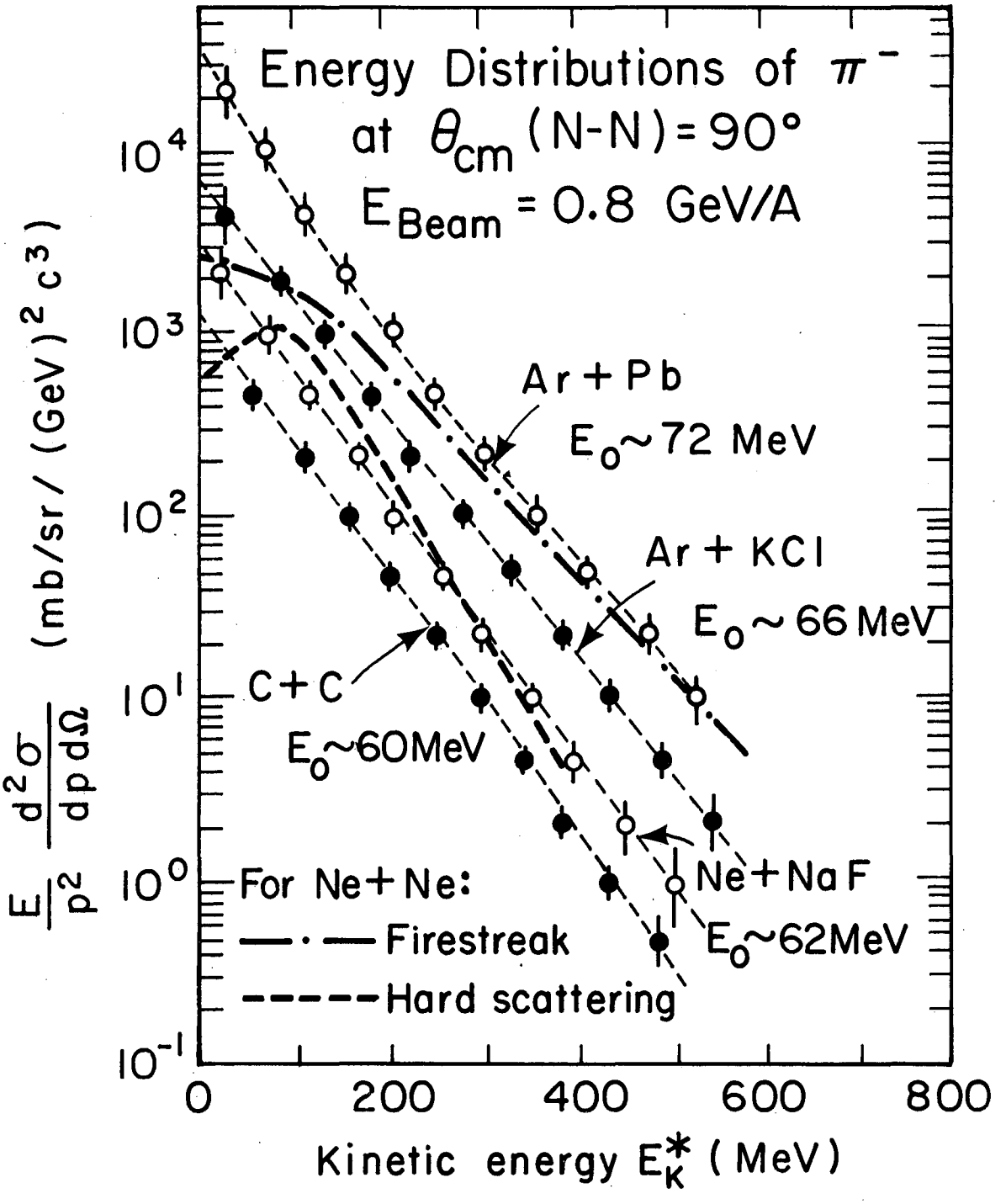

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Fig. 2

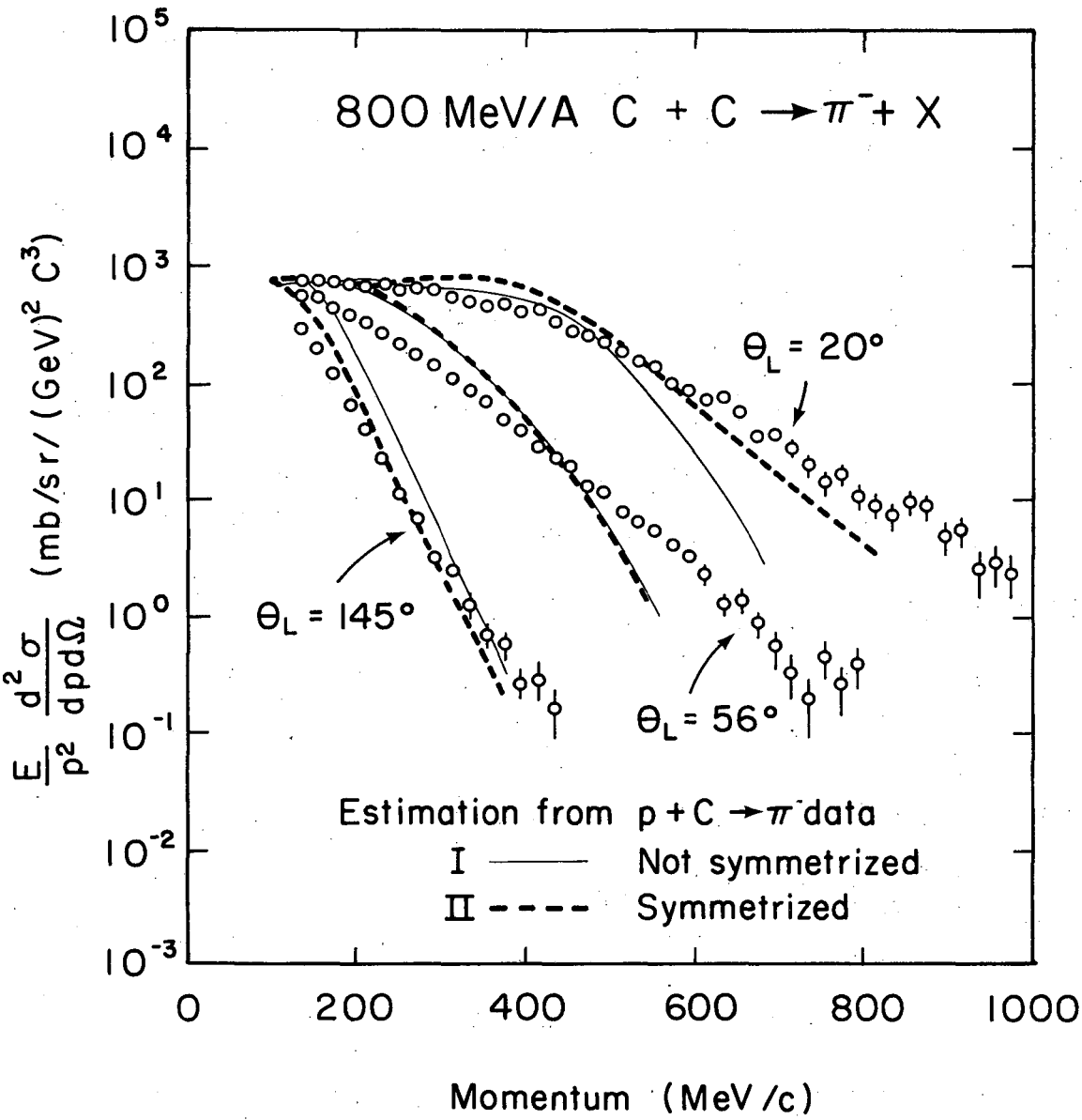

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Fig. 3

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