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Author
Nagamiya, S.

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S. Nagamiya, H. Hamagaki, P. Hecking, S. Kadota,
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Production of Negative Pions with 183 MeV/nucleon Ne Beams

S. Nagamiya,[a] H. Hamagaki,[b] P. Hecking, S. Kadota,[b] R. Lombard,[c]
Y. Miake,[d] E. Moeller,[e] S. Schnetzer,[f] H. Steiner,[g] and I. Tanihata[b]

Nuclear Science Division, Lawrence Berkeley Laboratory,
University of California, Berkeley, California 94720,

and

S. Bohrmann

Max Planck Institut fur Kernforschung, D-6900 Heidelberg, Germany

and

J. Knoll

Gesellschaft fur Schwerionenforschung (GSI), D-6100 Darmstadt, Germany

Abstract

Cross sections for negative pion production in 183 MeV/nucleon Ne + NaF and Ne + Pb collisions have been measured at laboratory angles from 20° to 90°. Almost isotropic angular distributions in the nucleon-nucleon c.m. frame are observed. The energy spectra in this frame are of an exponential type with an inverse slope of 25 MeV for NaF and 26 MeV for Pb. No evidence of a bump predicted to result from pionic instability is observed. Possible mechanisms for producing high-energy pions are discussed.

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In nucleus-nucleus collisions pion production at $E^{\mathrm{Lab}}_{\mathrm{Beam}}/A < 290$ MeV is of substantial interest, because it is beyond the kinematic domain accessible in free nucleon-nucleon (NN) collisions and therefore must involve either the nucleon Fermi motion and/or effects which involve more than two colliding nucleons. So far, detailed measurements of pion spectra with these low-energy beams have been done only at 0° and only for relatively low pion energies.[1] Clearly it is interesting to extend the measurements into regions of larger angles and much higher pion energies. The first goal of this experiment was to study the mechanism of subthreshold pion production for such large-angle high-energy pions. It is claimed in Ref. 1 (especially see the errata of this reference) that the observed 0° cross sections at $E^{\mathrm{Lab}}_{\mathrm{Beam}}/A = 80$ MeV cannot be explained by any conventional model,[2,3] and that they are a factor 5-10 larger than the predicted ones. We address a similar question with our data; namely, can conventional models explain the data over a wide kinematic domain of emitted pions?

The second goal of this experiment was to test a recent theoretical prediction of a pionic instability effect related to pion condensation. According to Gyulassy,[4] if this effect exists, then it should reveal itself in the inclusive pion spectra. Namely, the pionic instability induces an excess pion production at c.m. 90° and at a c.m. momentum around $2 - 3\, m_\pi c$. The predicted invariant cross section of these excess pions, $E(d^3\sigma/d^3p)_{90^\circ}$, is approximately equal to 1 (mb·GeV)/(sr·(GeV/c)^3) for Ne + NaF, and is almost independent of the beam energy. So far, pion production data that cover c.m. momenta of $2 - 3\, m_\pi c$ at c.m. 90° have been reported only at $E^{\mathrm{Lab}}_{\mathrm{Beam}}/A =$ 400, 800, and 2100 MeV.[5,6] There the yield of *normal* pions is much higher than that of the predicted *excess* pions. Thus, he emphasized the importance of experiments at much lower beam energies.

The experimental procedures are almost the same as those reported in Ref. 5. Neon beams of 200 MeV/nucleon were accelerated by the Berkeley Bevalac. Targets were NaF (approximately equal in mass to the projectile) and Pb (heavy mass) with thicknesses of about 0.5 g/cm^2. The beam energy at the center of the target was 183

MeV/nucleon. Negative pions were measured with a magnetic spectrometer[5] at angles from 20° to 90° in the laboratory frame and at momenta above 125 MeV/c. Absolute values of the cross sections are reliable to within ± 20 %.

Fig. 1 shows the observed momentum spectra. They are smooth as a function of the pion momentum. We obtained the highest statistics at $\vartheta^{\mathrm{Lab}} = 70°$, since this angle corresponds to about 90° in the *NN* c.m. frame for which the effects due to pionic instability are predicted to be the largest. Although spectrum shape is almost identical for the two targets, the absolute yield is larger for Pb than for NaF by a factor of 7 at $\vartheta^{\mathrm{Lab}} = 90°$ and by a factor of 3 at $\vartheta^{\mathrm{Lab}} = 20°$. Note that these factors are, respectively, slightly above and below the value of $(A_{\mathrm{Pb}}/A_{\mathrm{NaF}})^{2/3} \simeq 4.6$. Such a tendency is consistent with the A-dependence of the pion production from nuclear collisions at higher beam energies.[7]

When the data for Ne + NaF are plotted in the form of contour lines of invariant cross sections in the plane of parallel and transverse momenta in the *NN* c.m. frame, we note that the cross-section contours are almost circular especially for high-energy pions. This indicates that the angular distributions of these pions are almost isotropic in the *NN* c.m. frame. For low-energy pions the cross sections have a slight forward peaking. In the data for Ne + Pb, a slight forward-backward asymmetry is observed (within a factor of 2), but the gross features are more or less the same even for such a heavy-mass target.

In Fig. 2 the energy spectra of π^- at c.m. 90° observed for Ne + NaF collisions are displayed together with the previously published data[5,6] for the same projectile and target combination but at different beam energies. The spectra are approximately exponential with an inverse slope, $E_0 \simeq 25$ MeV at $E^{\mathrm{Lab}}_{\mathrm{Beam}}/A = 183$ MeV. As the beam energy increases the value of E_0 monotonically increases. When we plot the present data for Ne + Pb in the *NN* c.m. frame, the spectrum shape is again almost exponential with E_0 in this case being $\simeq 26$ MeV.

In Fig. 2 we notice two features in the data at $E^{\rm Lab}_{\rm Beam}/A$ = 183 MeV. The first one is that they do not show any evidence of the pionic instability effect predicted by Gyulassy. The observed pion yield is almost two orders of magnitude smaller than the predicted *excess* pion yield. It is of course possible that the Ne + NaF system contains too few nucleons for collective phenomena to occur. However, the data for Ne + Pb collisions also fail to show any evidence of the bump. Therefore, the present data do not support the theoretical prediction by Gyulassy.

The second feature of the data is the production of energetic pions. The kinetic energy of the observed pion extends up to 250 MeV in the *NN* c.m. frame, and the spectrum shape is almost purely exponential over the entire energy region. In order to create the highest-energy pions a total energy (including the 140 MeV rest mass) of 390 MeV has to be supplied. If we ignore the Fermi motion, a large number of nucleons (up to 9) would have to sum their kinetic energies, since each nucleon carries 45 MeV kinetic energy in this frame. In terms of single *NN* collisions a large Fermi momentum has to be assumed. For example, if both projectile and target nucleons carry the same Fermi momentum in opposite directions, then $p_{\rm F} \approx 350$ MeV/c for both nucleons would be needed. Some possible mechanisms for producing such high energy pions are discussed in the rest of the paper.

First, we discuss a phase space model,[8,9] which has been quite successful in fitting the existing pion data at higher beam energies, as shown in Ref. 9. The assumptions involved in this model are as follows: The nuclear collision is divided into several tube-tube collisions and the contributions from the various tubes are incoherently added. If one tube contains $n = n_{\rm P} + n_{\rm T}$ nucleons, where $n_{\rm P}$ originates from projectile and $n_{\rm T}$ from target, then the emission of the pions is governed only by phase space considerations[10] within this n-nucleon system. Here, the probability of finding $n_{\rm P}$ and $n_{\rm T}$ nucleons is calculated by the Glauber theory.[11] The momentum distribution of $n_{\rm P}$ nucleons inside the projectile (and that of $n_{\rm T}$ inside the target) is of a Gaussian type. The Gaussian widths were obtained from fits to the observed momentum spectra for projectile fragments.[12] This model contains one adjustable parameter related to the density of the n-nucleon system, which determines the absolute scale of the cross section. In our case the value of this parameter was chosen to be the same as that used in Ref. 9. Actual calculations were done for a beam energy of 200 MeV/nucleon, but the main features of the results (absolute value and slope) change only slightly when the beam energy is 183 MeV/nucleon. The cross section calculated with this model is shown by the dashed line in Fig. 2. The agreement with the data is reasonably good. According to this calculation, an average of $<n> \simeq 8$ nucleons are needed to create 250 MeV pions. This number is almost the same as what we guessed on the basis of simple energy considerations as described above.

Second, we examine a model in which the pions are produced in single *NN* collisions (hard-scattering model). According to the isobar model,[13] pions are created mostly through Δ_{33} resonances. At a nucleon energy of around 183 MeV, the probability of forming Δ_{33} is small, but as the beam energy increases this probability rapidly increases. One consequence of this fact is that even if the probability of finding high-momentum tails in the nuclear wavefunction is small, the contribution from these tails is likely to be important. Using the experimental data of $pp \to \pi$ and $pn \to \pi$, together with a Fermi energy distribution of the Woods-Saxon shape, $1/[1 + \exp(-(E-E_F)/\Delta E)]$, we have calculated the cross section for pion production. Here, $E_F = 36.5$ MeV, and the parameter value of ΔE was determined from fits to the (e,e') data[14] to be $\Delta E = 6.6$ MeV. The calculated pion spectrum is shown by the dotted curve in Fig. 2. In the low energy region the model overestimates the cross section by a factor of up to 10. Furthermore, the calculated slope in the high energy region falls off much more steeply than the data. We have tried to estimate effects due to both pion absorption and rescattering. For the pion absorption, the time dependence of the system was neglected and the calculation was done in a static geometry. The pion mean free path was taken from Ref. 15. This absorption effect reduces the pion yield by a factor of 2-5, depending on the pion energy. However, the calculated cross section is still too large and the slope in the high energy region is still too steep. The pion rescattering was treated using a cascade calculation. The pion-nucleon cross section in nuclear matter was assumed to be the same as that in free space. The result is shown by the dash-dot curve in Fig. 2. Although the overall cross section is overestimated by a factor of 2, the shape is now in reasonable agreement with the data. This calculation which includes both absorption and rescattering also agrees fairly well with data at 400 and 800 MeV/nucleon.

It is also interesting to compare the results of these two calculations with the existing data of subthreshold pion production at 0°.[1] We discuss the data for 80 MeV/nucleon Ne + NaF collisions, since there the previous conventional models[2,3] do not reproduce the data. The hard-collision model used in the present analysis reproduces the observed cross sections reasonably well.[16] On the other hand, the present phase-space model predicts a steeper slope in pion energy than the data. Also the absolute value of the cross section is underestimated, but it can be brought into agreement by readjusting the free parameter of the model. For a detailed comparison of the phase-space model, see Ref. 17. Finally, we point out the experimental fact that the observed cross section at 0° (with 80 MeV/nucleon beams) is about 300 times larger than the cross section of the present 90° data at $E_\pi^{\mathrm{c.m.}} \simeq 250$ MeV (with 183 MeV/nucleon beams).

In conclusion, we have observed high-energy pions at subthreshold beam energies in nuclear collisions down to cross section of $\approx 1\ (\mu\mathrm{b}\cdot\mathrm{GeV})/(\mathrm{sr}\cdot(\mathrm{GeV}/c)^3)$. We have found no evidence for the pionic instability effect predicted by Gyulassy. The production mechanism of high-energy pions has been studied using both hard-collision and phase-space models. A naive hard-collision model without rescattering effects does not explain the data when conventional internal momentum distributions are assumed. However, if both pion absorption and rescattering are included, then the model agrees to within a factor of about 2 with the data. For the production of high-energy pions it turns out that the πN rescattering is especially important. The phase-space model also fits the present data reasonably well. From the qualitative agreement of the data with both of these models it seems likely that processes involving more than two nucleons play an important role for producing energetic pions at subthreshold beam energies. The relationship between these two models is still not clear, but it may be that the microscopic rescattering and absorption effects can be effectively replaced by the statistical behavior of a rather large number of nucleons.

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a) Also, Department of Physics, Faculty of Science, University of Tokyo, Hongo, Bunkyo-ku, Tokyo, Japan.

b) On leave from Institute for Nuclear Study, University of Tokyo, Tanashi-shi, Tokyo, Japan.

c) Present address: DPhN/ME, CEN de Saclay, 91191 Gif-sur-Yvette, France.

d) On leave from Department of Physics, Osaka University, Osaka, Japan.

e) On leave from Institut für Theoretische Physik, Freie Universität Berlin, 1000 Berlin 33, Germany.

f) Present address: National Laboratory for High-Energy Physics (KEK), Oho-machi, Tsukuba-gun, Ibaraki-ken, Japan.

g) Also Department of Physics, Univerisity of California, Berkeley, California 94720.

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FIGURE CAPTIONS

FIG. 1 Pion momentum spectra for 183 MeV/nucleon Ne + NaF (left) and Ne + Pb (right).

FIG. 2 Energy spectra of π^- at $\vartheta^{c.m.} = 90°$ in Ne + NaF collisions at four beam energies, 0.18, 0.4, 0.8, and 2.1 GeV/nucleon. E_0 is the inverse slope factor when the cross sections are parametrized by $\exp(-E_\pi^{c.m.}/E_0)$. The solid curve is the predicted cross section for pionic instability as calculated by Gyulassy (Ref. 4). The dashed line is the result of a phase-space-model calculation for E_{Beam}^{Lab}/A = 200 MeV. The dotted line is the calculation of a simple hard-collision model and the dot-dash line is the result from the hard-collision model which includes both pion absorption and rescattering.

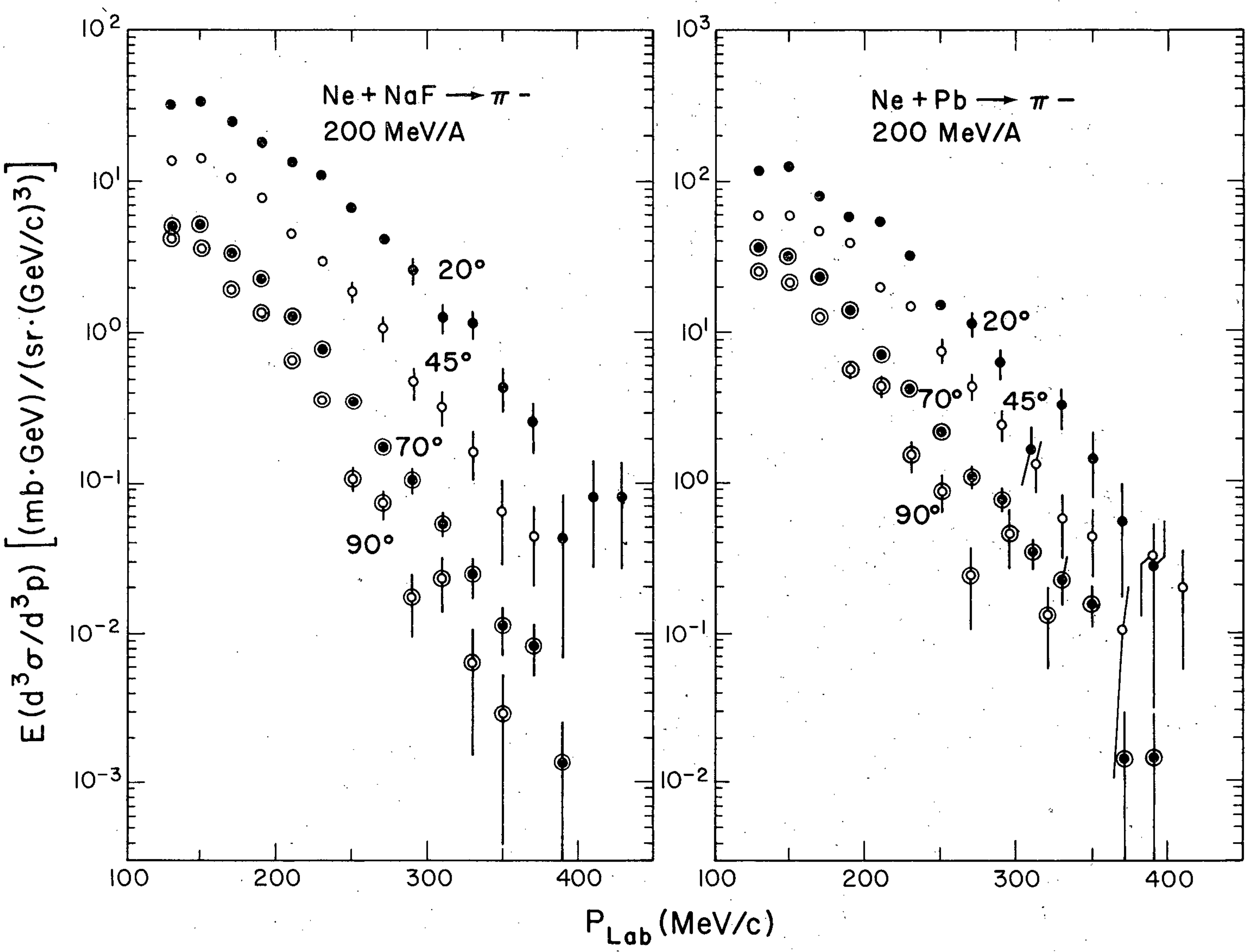

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Fig. 1

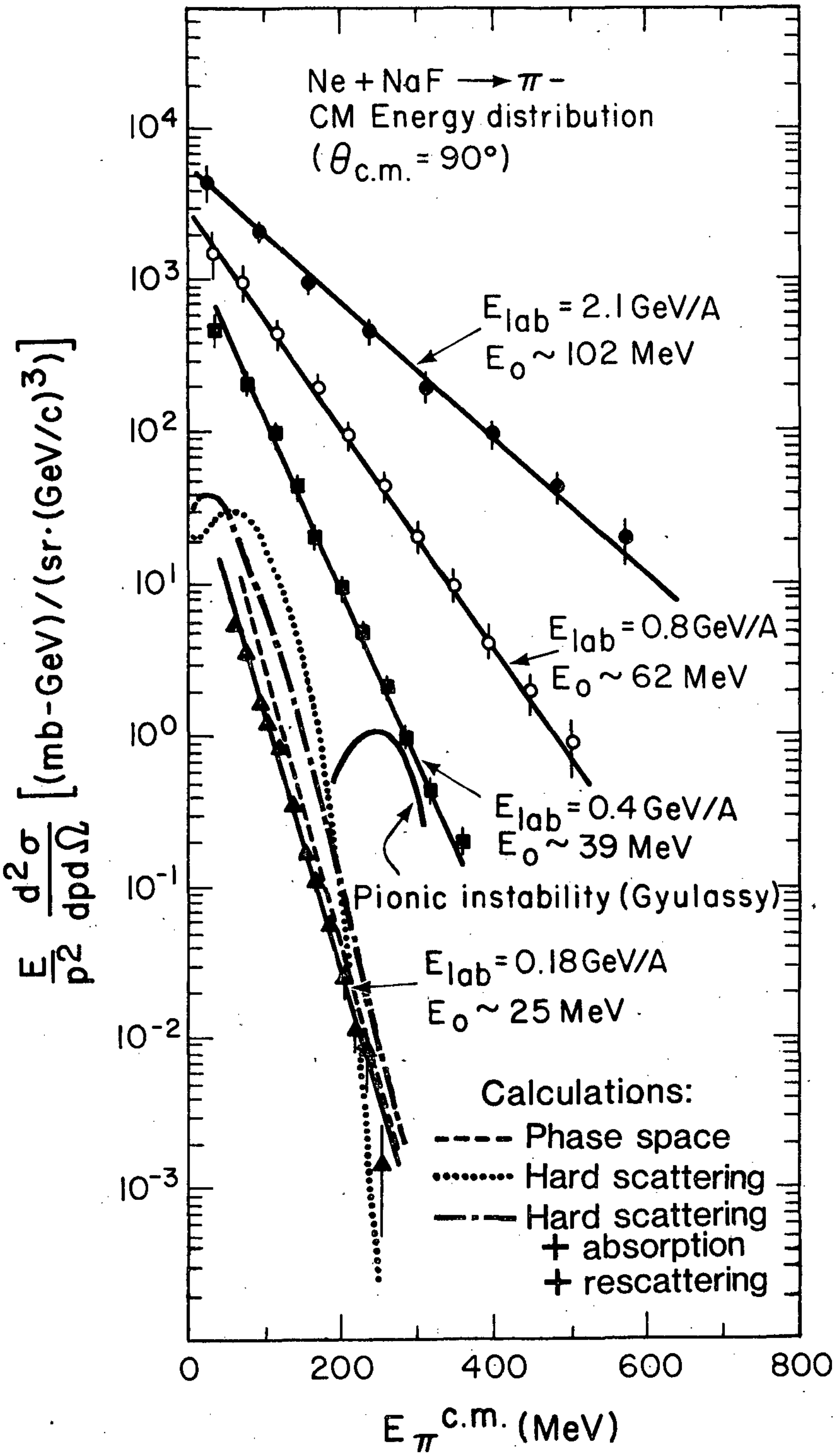

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Fig. 2

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