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Compression Effects in Relativistic Nucleus-Nucleus Collisions

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The negative-pion multiplicity is measured for central collisions of ^{40}Ar with KCl at eight energies from 0.36 to 1.8 GeV/nucleon and for ^{4}He on KCl and ^{40}Ar on BaI_2 at 977 and 772 MeV/nucleon, respectively. A systematic discrepancy with a cascade-model calculation which fits proton- and pion-nucleus cross sections but omits potential-energy effects is used to derive the energy going into bulk compression of the system. A value of the incompressibility constant of $K = 240$ MeV is extracted in a parabolic form of the nuclear-matter equation of state.

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Central collisions of nuclei at relativistic energies are predicted by dynamical models[1-3] to proceed via a compression-expansion cycle of hadronic bulk matter, with a first stage of interpenetration and pileup of the nucleon densities from target and projectile followed by expansion towards a final freezeout stage. While these models predict densities several times the nuclear ground-state density to be reached at the end of the compression stage, there has been no direct experimental evidence of such densities or of any new physical effects resulting from them. The reason is twofold: First, the compression is accompanied by heating manifested by chaotic kinetic effects which mask the collective motion[4]; second, a great deal of information about the compression stage is lost during expansion through final-state interactions, approach to chemical equilibrium, etc. Various approaches are being made to overcome these difficulties but none has so far yielded definitive results. These approaches include study of penetrating particles produced in the early stages of the collision,[5] and exclusive studies of all produced particles in the hope that analysis in terms of global variables may reduce chaotic effects relative to collective ones.[6] In the present work we propose the total multiplicity of produced pions as an observable linked to the high-density stage of the collisions. We present data on this variable for several colliding nuclear systems, demonstrate that the analysis in terms of nuclear density is consistent, extract values for the bulk compressional energy, and deduce a nuclear-matter equation of state.

The reason why such a simple variable as total pion multiplicity can be a good measure of the compression stage is an interplay of three considerations. First, the primary production yield in nucleon-nucleon collisions in the Bevalac energy range (up to 2.1 GeV/nucleon) is a rapidly rising function of energy. Second, the relative nucleon-nucleon energy in the nucleus-nucleus collision is degraded during the compression stage and is low by the time expansion begins. Thus, pion production is heavily weighted towards the compression stage. Finally, even though complex interactions during the expansion and freezeout stages strongly affect differential pion observables such as angular distributions and spectra,[7] it appears that the *total number* of pions and delta resonances, and hence the eventual pion yield, remains approximately constant.

These statements are best understood in the framework of an intranuclear cascade calculation. The cascade code used, that of Cugnon *et al.*,[3] was chosen because it is extensively described in recent publications and has input data in good agreement with pp, πp, and pn data that have recently been gathered[8] for the energy range of the Bevalac. Figure 1 shows the most important results for central collisions ($b_{\rm max} \leq 2.4$ fm) of ^{40}Ar +KCl at 977 MeV/nucleon. Figure 1(a) shows the baryon density in a sphere of 3 fm diameter about the origin of the center-of-mass coordinate system of the participant nucleons, expressed as a ratio to the ground-state nuclear density $\rho_0 = 0.17$ fm^{-3}. It peaks at about 7 fm/c of elapsed reaction time (in the laboratory system), corresponding to the end of the compression stage. Figure 1(b) shows that about half the baryon-baryon collisions occur during each of the stages, compression and expansion. Figure 1(c) shows that by the end of the compression stage the total number of pions and delta resonances $N_{\Delta+\pi}$ reaches a plateau where it remains approximately constant through expansion and freezeout. The three elementary processes, Δ decay into $\pi + N$, Δ absorption by the process $\Delta + N \to N + N$, and Δ formation both by $N + N \to N + \Delta$ and $\pi + N \to \Delta$, stabilize the value of $N_{\Delta+\pi}$ and hence the observed number of pions. Figure 1(d) shows the maximum density reached as a function of bombarding energy and also the mean density weighted according to the rate of $\pi + \Delta$ production. The latter, which reflects closely the maximum density, will be used in our subsequent analysis.

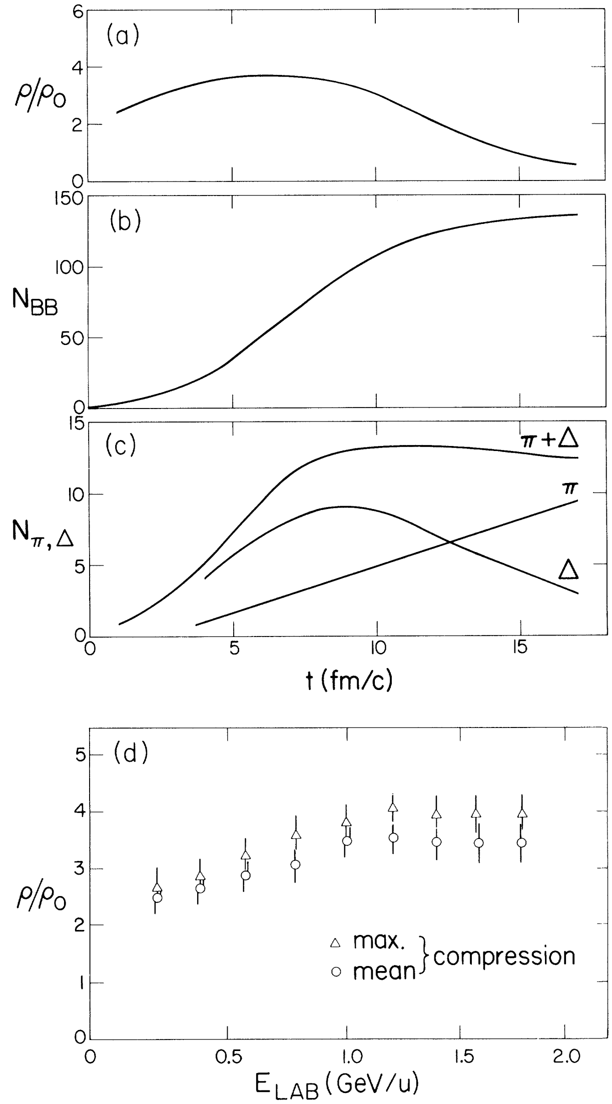

FIG. 1. Results of a cascade calculation for near-central collisions ($b \leq 2.4$ fm) of ^{40}Ar +KCl at a laboratory bombarding energy of 977 MeV/nucleon. The time dependence of the reactions is shown for (a) the baryon density, relative to the ground-state value, (b) the integrated number of baryon-baryon collisions, and (c) the instantaneous number of pions and Δ resonances. (d) The maximum baryon density attained as a function of bombarding energy and the mean density weighted by the rate of $\pi + \Delta$ production.

In our experiment, we used the Bevalac and the Lawrence Berkeley Laboratory Streamer Chamber facility to study the interaction of ^{40}Ar with KCl at bombarding energies from 0.36 to 1.8 GeV/nucleon. Between 4000 and 10 000 events were accumulated at each of the energies 360, 566, 722, 977, 1180, 1385, 1609, and 1808 MeV/nucleon in both inelastic and central trigger modes. In addition data were obtained for ^{4}He +KCl at 977 MeV/nucleon and ^{40}Ar +BaI$_2$ at 722 MeV/nucleon. Techniques and a part of the data have been presented elsewhere.[9] For ^{40}Ar +KCl the central trigger corresponded to a reaction cross section of 180 ± 20 mb, or impact parameters up to $b_{\rm max} = 2.4$ fm in a geometrical model. This value, when used in the cascade code, enables us to predict successfully many experimental quantities such as the proton participant multiplicity distribution.

Figure 2(a) shows the negative-pion multiplicity $\langle n_{\pi^-}(E)\rangle$ observed in ^{40}Ar +KCl collisions as a function of laboratory and c.m. energy. The cascade model prediction is also shown: It is systematically too high, with overestimates ranging from a factor of 4 at 360 MeV/nucleon to 1.35 at 1.8 GeV/nucleon. The overestimate also appears for the other systems studied. For example, consider a sequence of data at approximately constant incident energy, namely p +^{48}Ti (730 MeV), ^{4}He +KCl (977 MeV/nucleon), ^{40}Ar

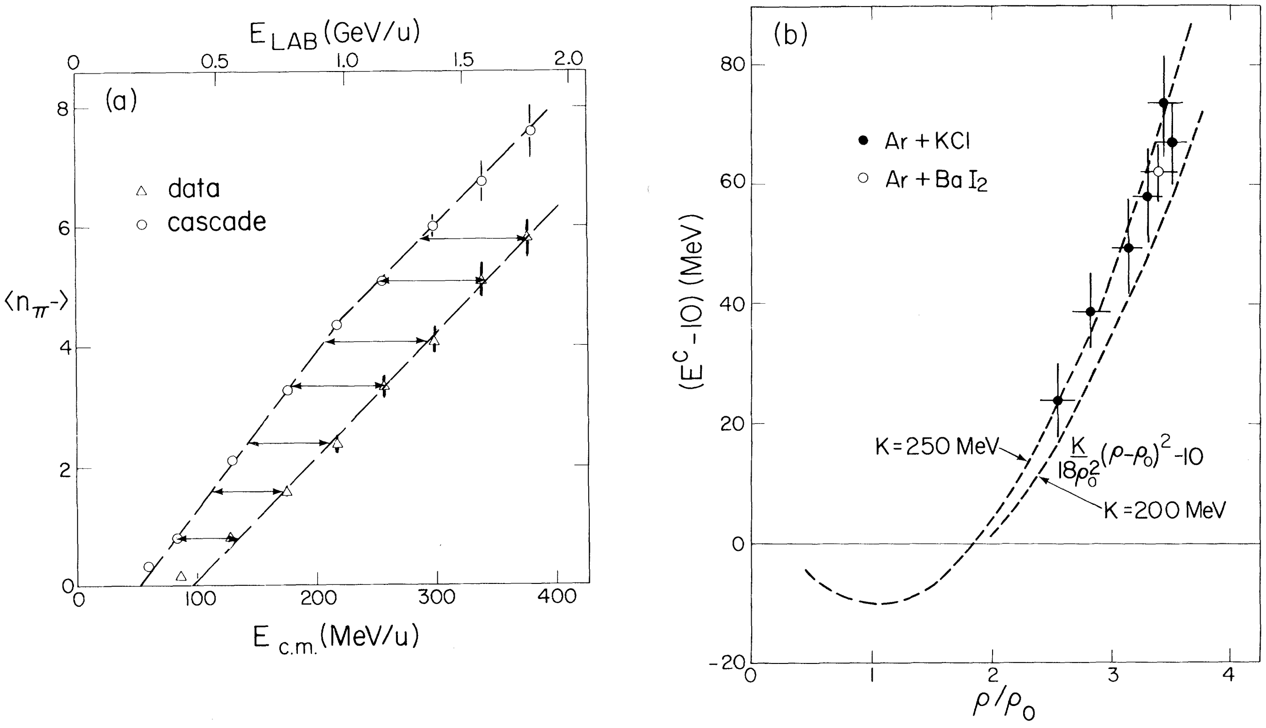

FIG. 2. (a) The mean π^- multiplicity as a function of bombarding energy for near-central collisions of ^{40}Ar + KCl. The triangles show the data. Open circles show the results of cascade calculations, where vertical lines at $E_{lab} \geq 1.4$ GeV/nucleon estimate the uncertainty due to multiple-pion production from single NN collisions, not included in the calculation. Horizontal arrows are the values of E_i^C, the compressional energy per nucleon determined at each experimental point. (b) The values of E_i^C as a function of the calculated mean baryon density. Points determined at 1.6 and 1.8 GeV/nucleon are not shown since values of E_C and ρ/ρ_0 are nearly identical to the results at 1.2 GeV/nucleon. The dashed lines represent equations of state with an incompressibility constant K of 250 and 200 MeV, respectively.

+KCl (772 MeV/nucleon), and ^{40}Ar +BaI$_2$ (772 MeV/nucleon), where the proton data are taken from Cochran *et al.*,[10] and the other results from our own measurements. The ratios of cascade-model predictions to the data are 1.2, 1.4, 2.1, and 2.4, respectively.

This discrepancy is not due to an inability of the cascade model to deal with pions. Several studies[11] have found it to work well for pion production in proton-nucleus collisions, for pion-nucleus scattering, and for pion absorption on nuclei. Despite the many ways in which the model appears as a rather crude approach to the real physics it takes into account many extremely important features of the collision process.[12] It appears to be a reasonable first-order approach to high-energy nuclear collisions in a normal nuclear-matter medium. The factor that is present in nucleus-nucleus collisions but not important in p-nucleus or π-nucleus collisions, where the cascade model was successful, is the feature of density increase, or compression.[13,14] We therefore examine, for the four interacting nuclear systems discussed above, the density reached as defined in Fig. 1(d). Such a definition is not useful for the p +^{40}Ti system, but for the other three systems the calculated density is given by $\rho/\rho_0 = 1.9$, 3.0, and 3.4, respectively. The overestimate ratios are almost exactly proportional to these densities, at roughly constant incident energy.

Now at a given c.m. energy E_i consider the measured multiplicity $\langle m_\pi(E_i)\rangle$. The same multiplicity is reached in the cascade model at a lower energy $E_i' < E_i$, as indicated in Fig. 2(a). As a crude approximation let us interpret the difference $(E_i - E_i')$ as that part of the c.m. internal energy per nucleon which goes into potential (compressional) degrees of freedom. This energy becomes inactive as far as pion production is concerned. By the time that it reappears in kinetic energy of the baryons, overall thermalization has reduced the mean energy of binary collisions to a point where pion production is no longer important. Reading the compressional energy per nucleon $E_i^C = E_i - E_i'$ from the graph of Fig. 2(a) at each experimental point and plotting it against the mean compression ρ/ρ_0 derived from Fig. 1(d) at the energy E_i, we obtain the nuclear-matter equation-of-state graph[15] shown in Fig. 2(b). It is noteworthy that above 1.2 GeV/nucleon where the density in Ar + KCl becomes constant, so are the values of E_i^C. Furthermore, the reaction ^{40}Ar + BaI$_2$ at 772 MeV/nucleon, for which the density prediction is $\rho = 3.4\rho_0$, leads to a value of E_i^C in agreement with that derived from ^{40}Ar + KCl at 977 MeV/nucleon, for which the density is also $3.4\rho_0$. The values of E_i^C plotted in Fig. 2(b) are offset by 10 MeV in order to allow for the ground-state binding energy of mass-40 nuclei. The dashed curve is a parabola representing an equation of state without phase transitions, corresponding to a compressibility constant $K = 250$ MeV, i.e., a "hard" equation of state. The value of 200 MeV extracted from excited nuclear energy levels yields the partial curve shown for comparison. The best fit to the data is found at $K = 240$ MeV. The horizontal and vertical error bars shown are statistical only. No estimate of the systematic errors implicit in our treatment has been made, as this should be the subject of more penetrating future theoretical studies, transcending the present simplistic approach.

In summary, we argue that the total pion multiplicity reflects the maximum density reached in central nucleus-nucleus collisions at Bevalac energies. We find that this assumption, taken with densities derived from a cascade calculation, serves to correlate data for different interacting systems at different energies. A systematic discrepancy between cascade calculations and experiment depends on the density and we attribute it to a bulk compressional effect not present in the calculation. A simple analysis of this effect yields an equation of state for nuclear matter which is somewhat harder than expected from low-energy nuclear excitations.

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[1] H. Stöcker *et al.*, Phys. Rev. Lett. 44, 725 (1980); J. R. Nix and D. Strottman, Phys. Rev. C 23, 2548 (1981).

[2] Y. Yariv and Z. Fraenkel, Phys. Rev. C 20, 2227 (1979), and 24, 488 (1981).

[3] J. Cugnon *et al.*, Nucl. Phys. A352, 505 (1981), and A379, 553 (1982).

[4] H. Stöcker, M. Gyulassy, and J. Boguta, Phys. Lett. 103B, 269 (1981).

[5] J. W. Harris *et al.*, Phys. Rev. Lett. 47, 229 (1981); J. Randrup and C. M. Ko, Nucl. Phys. A343, 519 (1980); S. Nagamiya, in Proceedings of the Fifth High Energy Heavy Ion Study, 1981, edited by L. S. Schroeder, Lawrence Berkeley Laboratory Report No. 12652 (unpublished), p. 144.

[6] R. Stock, in Proceedings of the Fifth High Energy Heavy Ion Study, 1981, edited by L. S. Schroeder, Lawrence Berkeley Laboratory Report No. 12652 (unpublished), p. 284; J. Kapusta and D. Strottman, Phys. Lett. 106B, 33 (1981); M. Gyulassy, K. A. Frankel, and H. Stöcker, Phys. Lett. 110B, 185 (1982).

[7] K. L. Wolf *et al.*, Phys. Rev. C, to be published.

[8] F. Shimizu *et al.*, to be published; G. Alexander *et al.*, Nucl. Phys. B52, 221 (1973); V. Flaminio *et al.*, CERN Report No. CERN-HERA 79-03 (1979).

[9] S. Y. Fung *et al.*, Phys. Rev. Lett. 40, 292 (1978); A. Sandoval *et al.*, Phys. Rev. Lett. 45, 874 (1980).

[10] D. R. F. Cochran *et al.*, Phys. Rev. D 6, 3085 (1972).

[11] M. Sternheim and R. Silbar, Phys. Rev. D 6, 3117 (1972); Y. Yariv and Z. Fraenkel, to be published. In calculations with the Cugnon code for pion absorption, quantitative agreement is obtained with the data of K. Nakai *et al.*, Phys. Rev. Lett. 44, 1446 (1980).

[12] J. R. Nix, Prog. Part. Nucl. Phys. 2, 237 (1979).

[13] I. Montvay and J. Zimanyi, Nucl. Phys. A316, 490 (1979).

[14] H. Stöcker *et al.*, Phys. Lett. 81B, 303 (1979).

[15] A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, New York, 1969), Vol. 1, p. 257.