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Abstract

The negative pion multiplicity is measured for inelastic and central collisions of ^{40}Ar with KCl at eight energies from 0.36 to 1.8 GeV/nucleon and for ^4He and ^{40}Ar on BaI_2 at 977 and 772 MeV/nucleon, respectively. A systematic discrepancy in central collision data 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 compressibility constant of $K = 240$ MeV is extracted in a parabolic form of the nuclear matter equation of state.

1. Introduction

In the study of nucleus-nucleus collisions at relativistic energy one of the main objectives is to determine the compressional energy of nuclear matter, over a wide domain of the density. The functional $\varepsilon(\rho, T=0)$ relating the internal energy per degree of freedom to the density of a zero temperature nuclear medium is known only in the vicinity of the ground state density of nuclear matter ($\rho=\rho_0 \approx 0.16$ nucleons/fm³). Ignoring Coulomb contributions, $\varepsilon(\rho_0, T=0) = -16$ MeV/u. From the excitation energies of the collective giant monopole vibrational states [1] we know that ε is parabolic in the vicinity of ρ_0 , and that the compressibility constant, $K = \delta^2 \varepsilon / \delta \rho^2_{T=0}$, has the value 200 ± 20 MeV. Thus, over the domain of a few percent in $\Delta \rho / \rho_0$, ground state nuclear matter exhibits a linear response to compression and expansion, similar to a macroscopic system. In such a system the pressure response may become non-linear for excursions far away from the stability point due to the occurrence of phase transitions. Similarly we are interested in the behaviour of nuclear matter far away from $\rho=\rho_0$. In the final stages of stellar evolution, densities of $0.1 \leq \rho/\rho_0 \leq 10$ are encountered, and the response to compression is fundamental towards the understanding of supernova dynamics [2] and neutron star stability [3]. From the study of the dilute surface regions of nuclei one would predict a phase transition, in isospin zero systems, to a gas of light clusters occurring towards the lower boundary of this density interval [4]. At high densities, another critical value

should be reached when the constituent baryon bags become tightly packed. This should occur at $\rho \geq 5 \rho_0$ if one assumes a bag radius of 0.8 fm. In this study we present first results for the "nuclear matter equation of state" in the interval $2 \leq \rho/\rho_0 \leq 4$, accessible through the study of central collisions of relativistic nuclei at Bevalac energies, $0.4 \leq E/u \leq 2$ GeV. In this interval of densities we expect to remain within the phase of "normal" nuclear matter.

Central collisions of nuclei at relativistic energies are predicted by dynamical models [5-8] to proceed via a compression-expansion cycle of hadronic bulk matter, with a first stage of interpenetration and pile-up of the nucleon densities from target and projectile followed by expansion towards a final freeze-out stage. The compression process is illustrated in Fig. 1 where two successive stages of nuclear matter interpenetration are shown for a central collision of equal-mass nuclei. In the interaction zone the relative motion of nucleons is slowed down due to the energy loss, in binary nucleon reactions, from longitudinal to transverse degrees of freedom, and to pion production. The external regions of nuclear matter in the target and projectile move ahead at their initial relative velocity ($\beta_{cm}^{rel.} \approx 0.8$), resulting at time step 2 in a pile-up in the interaction zone to densities higher than the instantaneous superposition density of $2\gamma_{cm}\rho_0$. At Bevalac energies this dynamical pile-up can be predicted a priori because

- a. The relative velocities β_{cm} are never getting close to $\beta \approx 1$. Thus the energy loss per binary nucleon collision leads to a significant slow-down in the cm system. Only about 3 generations of successive collisions are required in order to approximately thermalize the system in the cm frame. This is not so at truly relativistic energies, say at the ISR.
- b. On the other hand, the average transverse nucleon velocity components thus generated are of the order of $\beta_{\perp} \leq 0.5$. Thus $\beta_{\perp} \leq \beta_{||}$ and the piling up central density region can not escape sideways commensurate to the interpenetration process.

Fig. 2 gives a sketch of the reaction dynamics, in terms of the variables compression vs. internal energy per nucleon. The curve $\varepsilon(\rho/\rho_0, T=0)$, with a parabolic shape about ρ_0 , represents a guess of the ground state energy per nucleon [9] of extended nuclear matter: the functional that we hope to extract from the data. It is sloppily referred to as the nuclear equation of state in most of the literature although this term should be reserved to the derivative of ε with respect to ρ/ρ_0 at constant entropy, giving the non thermal part of the reaction pressure with respect to density.

In these variables, the reaction proceeds from point 1 where nuclei are not yet interacting, with their ground state internal energy of about - 16 MeV/u, and the relative cm system energy as given by the beam energy. At

point 2 the interpenetration is complete. Let us assume that the degree of thermalization, reached here, be sufficient in order for us to describe the system in terms of thermodynamical state variables. The "fireball" does not fall on the $\epsilon(T=0)$ functional because the interaction created heat: the internal energy now has a compressional (E_K) and thermal (E_T) component. The expansion stage then develops (3), towards $\rho=0$. Which reaction species will preserve the detailed information about the sharing among thermal and compressional energy at point 2? We will argue in the following that the total pion (K, Λ) yield, i.e. the rate of "radiation" of particles produced in the state of maximum total energy density, is best suited for an analysis of the compressional energy.

2. Pion Production Observables

While all dynamical 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: firstly, the compression is accompanied by heating manifested by chaotic kinetic effects which mask the collective motion [10]; secondly 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 [11], and exclusive studies of all produced particles in the hope that analysis in terms of global variables such as jets, thrust, etc., may reduce chaotic effects relative to collective ones [12]. 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. Firstly, 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. Secondly, 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 freeze-out stages strongly affect differential pion observables such as angular distributions, spectra, etc. [13, 14], it appears that the total number of pions and delta-resonances, and hence the eventual pion yield, remains approximately constant.

This statement is best understood in the framework of an intranuclear cascade calculation. Figure 3 shows the most important results of using a cascade model developed by Cugnon et al. [7] for central collisions ($b_{\text{max}} \leq 2.4$ fm) of $^{40}\text{Ar} + \text{KCl}$ at 977 MeV/u. Figure 3a shows the baryon density observed 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 $\rho_0 = 0.16 \text{ fm}^{-3}$. It peaks at about 7 fm/c of elapsed reaction time (in the laboratory system), corresponding to the end of the compression stage. Fig. 3b shows that about half the baryon-baryon collisions occur during the compression and expansion stages, respectively. Fig. 3c 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 freeze-out. The three elementary processes, Δ decay into $\pi+N$, Δ absorption by the $\Delta+N \rightarrow N+N$ process, and Δ formation both by $N+N \rightarrow N+\Delta$ and $\pi+N \rightarrow \Delta$ stabilize the value of $N_{\Delta+\pi}$ and hence the observed number of pions. Fig. 4 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. We note that the density does not increase beyond 1.4 GeV/nucleon for the $^{40}\text{Ar} + \text{KCl}$ system, which may reflect the onset of nuclear transparency in the cascade calculation, when the number of collisions per particle can no longer completely break down

longitudinal energy into random motion. For heavier colliding nuclei this will occur at a higher energy.

3. Data and Cascade Model Predictions

In our experiment, we used the Bevalac and the LBL Streamer Chamber facility to study the interaction of ^{40}Ar with KCl at bombarding energies from 0.36 to 1.8 GeV/nucleon. Between 4.000 and 10.000 events were accumulated at each of the energies 360, 566, 722, 977, 1180, 1385, 1609 and 1808 MeV/u in both inelastic and central trigger modes. In addition data were obtained for $^4\text{He} + \text{KCl}$ at 977 MeV/u and $^{40}\text{Ar} + \text{BaI}_2$ at 772 MeV/u. Techniques and a part of the data have been presented elsewhere [15]. Each event was classified according to its negative pion multiplicity, total charged particle multiplicity, and number of "leading" particles observed in the target and projectile fragmentation domains. The approximate number of protons from target and projectile participating in the reaction was obtained by subtracting from the total charged particle multiplicity for each event the number of created charges ($2\pi^-$) and the number of leading particles. For $^{40}\text{Ar} + \text{KCl}$ the central trigger corresponded to a reaction cross section of 180 ± 20 mb, or impact parameters up to $b_{\text{max}} = 2.4$ fm in a geometrical model.

Figure 5 shows for $^{40}\text{Ar} + \text{KCl}$ at 1.8 GeV/nucleon the distribution of observed proton participants compared with results of the cascade model calculation with the same value of impact parameter cutoff as was deduced from the cross section. The cascade code used, that of Cugnon et al. [7], 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 [15] for the energy range of the Bevalac. The comparison shown in Fig. 5 is typical of a wide range of successful predictions of the cascade model for straight-forward variables such as the above [6, 7].

Figure 6 shows the negative pion multiplicity $\langle n_{\pi^-}(E) \rangle$ observed in $^{40}\text{Ar} + \text{KCl}$ collisions as a function of laboratory and cm energy. The cascade model prediction is also shown: it is systematically too high, with overestimates ranging from a factor of 4 at 360 MeV/u to 1.35 at 1.8 GeV/u. 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), $^4\text{He} + \text{KCl}$ (977 MeV/u), $^{40}\text{Ar} + \text{KCl}$ (722 MeV/u) and $^{40}\text{Ar} + \text{BaI}_2$ (772 MeV/u), where the proton data are taken from Cochran et al. [17], 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 [18] have found it to work well for pion pro-

duction 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 the most important features of the collision process [19]. 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. We therefore examine, for the four interacting nuclear systems discussed above, the density reached as defined in Fig. 4. Such a definition is not useful for the $p + {}^{40}\text{Ti}$ system, but for the other three systems the calculated density is given by $\rho/\rho_0 = 1.9, 3.0, 3.4$, respectively. The overestimate ratios are almost exactly proportional to these densities, at roughly constant incident energy. Assuming, therefore, that the overestimate is a density dependent effect, we proceed further to examine the whole body of data to specify that result quantitatively.

At a given cm energy E_i the measured multiplicity is $\langle m_\pi(E_i) \rangle$. The same multiplicity is reached in the cascade model at a lower energy $E_i' < E_i$, as indicated in Fig. 6. As a crude approximation let us interpret the difference $(E_i - E_i')$ as that part of the cm internal energy per nucleon which goes into potential (compressional) degrees of freedom. This energy becomes inactive as far as pion production is concerned. It will govern

the collective part of the baryon pressure during expansion, i.e. it will be the energy source of the hypothetical hydrodynamical flow [5, 8, 10, 19]. By the time, however, 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 $E_i^C = E_i - E'$ from the graph of Fig. 6 at each experimental point and plotting it against the mean compression ρ/ρ_0 derived from Fig. 4 at the energy E_i , we obtain the nuclear matter equation of state graph shown in Fig. 7. It is noteworthy that above 1.2 GeV/u where the density in Ar + KCl becomes constant, so are the values of E_i^C . Furthermore, the reaction $^{40}\text{Ar} + \text{BaI}_2$ at 772 MeV/u, 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 $^{40}\text{Ar} + \text{KCl}$ at 977 MeV/u, for which the density is also $3.4 \rho_0$. The values of E_i^C plotted in Fig. 7 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 transition, 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 [1] 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 have been made, as this should be the subject of more penetrating future theoretical

studies, transcending the present simplistic approach. Let us point out, in particular, the lack of self-consistency in our use of the cascade model: the mean compression at each energy is taken from the model without attempting a correction for the population of potential energy degrees of freedom.

4. An Alternative Approach

The preceding treatment used on excitation function of the central trigger negative pion yield and assumed that the bombarding energy dependence of the cascade calculation was correct, except for an energy shift which may be open to some question, considering the large energy range covered, accross the delta resonance. Particularly, the pion absorption is uncertain at low energies. Also, one may have some qualms about the experimental method of maintaining central collisions, i.e. a constant trigger bias over a wide energy range, in spite of the good agreement of the participant number extracted from the data and the calculations in Fig. 5. Thus, a somewhat different approach was devised by taking advantage of the expected variation of ρ/ρ_0 with impact parameter, performing a cascade calculation at *one* energy for a comparison with pion multiplicity data taken with an unrestrictive "inelastic" trigger, and over a relatively narrow bombarding energy range, $1.0 \leq E/u \leq 1.8$ GeV. Concerning our aim to extract the compressional energy through comparison to the cascade calculation we note an important feature of the cascade model: the pion yield is insensitive to the treatment of Fermi motion and Pauli blocking in this energy domain, to a level of about 10 %. This is not so at the lower energies, covered by the data in Fig. 6.

Figure 8 shows five sets of pion multiplicity data taken from 1.0 to 1.8 GeV/u for Ar + KCl in the inelastic trigger mode, a sorted vs. the proton

participant number. The result of the cascade calculation at 1.2 GeV/u is superimposed with the dashed curve. The measured numbers of proton participants Q have been matched on the same scale to the cascade prediction of Q for impact parameter bins from 1-6 fm in 1 fm steps, denoted as b at the top of Fig. 8. It can be seen, for moderately peripheral collisions, $b = 6$ fm ($Q = 7.5$) that the cascade calculation predicts exactly the experimental value of the pion multiplicity. This good agreement is destroyed as more central collisions are considered. The calculated result (dashed curve) increases smoothly above the line interpolating the experimental 1.2 GeV/u result. The pion yields predicted in the cascade are enhanced in central collisions, relative to the experiment; the overestimate again correlates nicely with the baryon density. At large impact parameters only the diffuse surface regions of target and projectile overlap, and thus ρ/ρ_0 does not significantly exceed unity. The correct prediction of the pion yield by the cascade code, in that case, is in line with our general argument and lends credibility to the overall treatment of pion production by the cascade model at densities around ρ_0 . As the number of participant protons increases (with growing size of the interaction volume, towards smaller b), the predicted pion yield increases slightly slower than proportional to $Q^{4/3}$ but faster than linear. This behaviour is reasonable for a model of pion production from binary nucleon collisions: the total number of such collisions increases as $Q^{4/3}$ but the second, third etc. generations are at lower energy, producing less pions per collision. We would thus expect a dependence of $\langle m_\pi \rangle_Q$ somewhere

between $Q^{4/3}$ and Q , as is indeed exhibited by the theoretical results. The experimentally observed dependence is $\langle m_\pi \rangle \sim Q$, however, showing that a depression occurs towards higher Q (smaller b , higher compression) the mechanism of which is ignored in the cascade model.

At this point, a remark is necessary about the possible effect of "exotic" pion absorption mechanisms, setting in (or being enhanced) for higher densities. The cascade model removes pion degrees of freedom by the $N\Delta \rightarrow NN$ process, i.e. $\pi + N + N \rightarrow \Delta + N \rightarrow NN$: the conventional "absorption of a pion on two nucleons". The rate of this process is to first order linear in the nucleon density because of its independent two steps. If, on the other hand, there existed true multinucleon pion absorption mechanism [20], where the pion interacted simultaneously with n correlated nucleons, one would expect a steeper density dependence, ρ^n , and thus an enhancement of absorption with increasing compression. Such a mechanism can not, however, serve as an explanation of our observations: in the excitation function of the π -yield, Fig. 6, the compression increases from $\rho/\rho_0 \approx 2.5$ to 3.5 but the overestimate of the cascade model *decreases* from a factor of about four to the level of 1.3 at maximum compression. With multinucleon absorption processes at work, the most spectacular effects should occur at high energies. In our present interpretation, the loss of available kinetic energy to compressional (potential) degrees of freedom should, on the other hand, manifest itself most drastically at energies near the π production threshold.

Figure 8 can be used to extract compressional energy values, similar to the procedure used previously. We note the value of the laboratory bombarding energy which matches the cascade prediction for $\langle n_{\pi} \rangle$ at each impact parameter and interpolate the five experimental curves. Thus, at $b = 1$ fm, the 1.2 GeV/u cascade calculation ($E_{cm}/u = 263$ MeV) predicts pion multiplicities which are realized experimentally at 1.82 GeV/u ($E_{cm}/u = 378$ MeV), yielding a compression energy of $E_c = 115$ MeV/u, which is larger than all the E_c values obtained with the excitation function procedure. But one should note that the mean density predicted here is higher, $\rho/\rho_0 = 3.7$, due to the smaller 1 fm impact parameter, as compared to $b \leq 2.4$ fm for the central trigger. Averaged over a similar 2.4 fm b -range, the procedure using the inelastic trigger data yields values of E_c within 10 MeV of the values obtained from the excitation function at the corresponding density, providing a more than satisfactory consistency check of the two methods.

The impact parameter dependence shown in Fig. 8 predicts that only a small effect should be observed in inclusive measurements. This seems to be the case in careful comparisons of π^+ inclusive cross sections ratios for 1.05 GeV/u ^4He -, ^{20}Ne - and ^{40}Ar -induced reactions on ^{238}U targets [13]. There, the $^{40}\text{Ar}/^4\text{He}$ cross section ratio for π^+ was found to be depressed by 25 % from simple scaling or from predictions of the cascade calculation of Yariv and Fraenkel [6]. Both the lack of impact parameter restriction, and

comparison to ^4He -induced cross sections (where there may be a small compression effect already) lead to a reduction of the observed effect.

5. Summary

In summary, we argue that the total pion multiplicity reflects the maximum density reached in central nucleus-nucleus collisions at Bevalac energies. In the future, similar investigations will be extended to strange particle production. In either case, the observable *differential* quantities, such as angular distributions, energy spectra etc. are subject to rescattering during the expansion stage and thus reflect the final momentum/energy flux distribution of the nucleons, whereas the integrated yield refers to the high density stage.

We have compared cascade model calculations to three types of experimental data: the variation with target-projectile combination (p, ^4He , ^{40}Ar on light and heavy targets), the bombarding energy dependence and the variation with impact parameter. The ratios of calculated to experimental pion multiplicity values are well above unity, except for proton-induced reactions, and in grazing heavy-ion collisions. These ratios correlate with the predicted density increase in central and near-central heavy-ion collisions, but anticorrelate in the energy dependence. This latter factor argues against a multinucleon pion absorption mechanism; instead a

removal of available energy from the pion producing degrees of freedom at high densities explains all three types of comparisons. We determine this missing fraction of the free CM internal energy at various mean compressions, $2.5 \leq \rho/\rho_0 \leq 3.7$, and identify it with the bulk compressional energy of nuclear matter. In this simple approach, a functional dependence of the nonthermal part of the internal energy per nucleon on the compression results. Disregarding possible higher order corrections, which should be the subject of future systematic theoretical studies, we identify this functional with the "nuclear matter equation of state". Over the range of densities accessible to our study, it is approximately parabolic, with a curvature about $\rho = \rho_0$ as expressed by a compressibility constant of $K = 240$ MeV, somewhat higher than expected from low energy nuclear monopole excitations.

In concluding we note first that the present approach is a variation of a theme already conceived in several previous theoretical investigations of the compression process in central nucleus-nucleus collisions at high energy. However, the hydrodynamic theory [21] and the hadrochemical dynamics model [8] incorporate a guess of the equation of state and exploit its influence on the pion yield along with all other implicit assumptions about the dynamics. We use the simple cascade model in a subtractive manner, assuming that it treats the dynamics well to first order except for its total ignorance of potential energy degrees of freedom.

Secondly, we may comment on alternative methods conceived in order to identify the compressional collective part of the energy/momentum flux from an event by event analysis of the final state in momentum space. Our analysis suggests that at most only about one third of the center of mass energy is available in the form of potential energy that might act as the driving energy store for collective flux, with the majority of the available energy going into chaotic thermal motion. It will thus be a difficult task to disentangle the flux contributions in this way. However, systematic studies of this type are also in progress at the Bevalac.

References

1. Serr, F., Bertsch, G., and Blaizot, J.P., Phys. Rev. **C22**, 922(1980).
2. Bethe, H.A., et al., Nucl. Phys. **A324**, 487(1979).
3. Irvine, J.M., Progress in Particle and Nuclear Physics, Vol. 2, p. 201, Pergamon Press 1979.
4. Curtin, M.W., Toki, H. and Scott, D.K., Michigan State University Reprint MSUCL-373, 1982.
5. Stoecker, H., et al., Phys. Rev. Lett. **44**, 725(1980);
Nix, J.R. and Strottman, D., Phys. Rev. **C23**, 2548 (1981).
6. Yariv, Y. and Fraenkel, Z., Phys. Rev. **C20**, 2227(1979) and **C24**, 488(1981);
Gudima, K.K. and Toneev, V.D., Joint Institute for Nuclear Research E2-12621, Dubna, 1979.
7. Cugnon, J. et al., Nucl. Phys. **A332**, 505(1981) and **A379**, 553(1982);
the calculations presented in our work use a slightly modified version of the code of Cugnon et al.

8. Montvay, I. and Zimanyi, J., Nucl. Phys. *A316*, 490 (1979).
9. Bohr, A. and Mottelson, B.R., Nuclear Structure, Vol. I, Benjamin Publ. 1969, p. 257.
10. Stoecker, H., Gyulassy, M. and Boguta, J., Phys. Lett. *103B*, 269(1981).
11. Harris, J.W. et al., Phys. Rev. Lett. *47*, 229(1981);
Randrup, J. and Ko, C.M., Nucl. Phys. *A343*, 519(1980);
Nagamiya, S., Proc. 5th High Energy Heavy Ion Study, ed., Schroeder, L.S., LBL-12652, 144(1981).
12. Stock, R., Proc. 5th High Energy Heavy Ion Study, ed., Schroeder, L.S., LBL-12652, 284(1981);
Kapusta, J. and Strottman, D., Phys. Lett. *106B*, 33(1981);
Gyulassy, M., Fraenkel, K.A. and Stoecker, H., Phys. Lett. *110B* 185(1982);
Csernai, L.P., et al., Phys. Rev. *C25*, 1873(1982);
13. Wolf, K.L., et al., submitted to Phys. Rev. C.
14. Nagamiya, S., et al., Phys. Rev. *C24*, 971(1981).

15. Fung, S.Y., et al., Phys. Rev. Lett. *40*, 292(1978);
Sandoval, A., et al., Phys. Rev. Lett. *45*, 874(1980).
16. Shimizu, F., et al., University of Tokyo preprint (1982);
Alexander, G., et al., Nucl. Phys. *B52*, 221(1973);
Flaminio, V., et al., CERN-HERA 70-03 (1979).
17. Cochran, D.R.F., et al., Phys. Rev. *D6*, 3085 (1972).
18. Sternheim, M. and Silbar, R., Phys. Rev. *D6*, 3117 (1972);
Yariv, Y. and Fraenkel, Z., to be published.

In calculations with the Cugnon code for pion absorption, quantitative agreement is obtained with the data of Nakai, K., et al., Phys. Rev. Lett. *44*, 1446 (1980). For the $^{40}\text{Ar} + \text{KCl}$ reaction, these calculations indicate that about 45 percent of the produced Λ -resonances are annihilated.
19. Nix, J.R., Prog. Part. Nucl. Phys. *2*, 237 (1979).
20. McKeown, R.D., et al., Phys. Rev. Lett. *44*, 1033 (1980).
21. Stoecker, H., et al., Phys. Lett. *81B*, 303 (1979).

Figure captions

Fig. 1 Two successive stages of a high energy central collision of equal mass nuclei in the cms system (ignoring Lorentz contraction). The hatched area is the compression zone.

Fig. 2 Sketch of the functional $\varepsilon(\rho, T = 0)$ relating the internal energy of nuclear matter to the compression. The overall reaction cycle of a collision of relativistic nuclei is indicated by 1 (before interaction begins), 2 (maximum compression, highest energy density) and 3 (expansion towards freeze-out). Note the sharing, at stage 2, of the internal energy between thermal (E_T) and potential (E_K) energy.

Fig. 3 Results of a cascade model calculation for near central collisions ($b \leq 2.4$ fm) of $^{40}\text{Ar} + \text{KCl}$ at 977 MeV/u. The time dependence of the reaction is shown in units of fm/c for (a) the baryon density in the reaction zone, relative to the ground state value, (b) the integrated number of baryon-baryon collisions, and (c) the instantaneous number of pions and Δ -resonances.

Fig. 4 Maximum compression as a function of the incident energy predicted by the cascade model for $\text{Ar} + \text{KCl}$. The circles give the mean com-

pression as weighted with the instantaneous rate of pion plus delta production (i.e. with the derivative of Fig. 2c).

Fig. 5 The data points show the distribution of the number of proton participants measured with a central trigger for $^{40}\text{Ar} + \text{KCl}$ at 1.8 GeV/u. The curve is the cascade model result; an upper cutoff of 2.4 fm was assumed for the impact parameter, b .

Fig. 6 The mean π^- -multiplicity as a function of bombarding energy for near-central collisions of $^{40}\text{Ar} + \text{KCl}$. The triangles show the data. Open circles show the results of cascade calculations, where vertical lines at $E_{\text{lab}} \geq 1.4$ GeV/u 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.

Fig. 7 The values of E_i^C as a function of the calculated mean baryon density. Points determined at 1.6 and 1.8 GeV/u are not shown since values of E^C and ρ/ρ_0 are nearly identical to the results at 1.4 GeV/u. The dashed lines represent parabolic equations of state with compressibility constant K of 250 and 200 MeV, respectively.

Fig. 8 The mean π^- multiplicity observed in Ar + KCl reactions at 1.0, 1.2, 1.4, 1.6 and 1.8 GeV/u, plotted as a function of the observed number of proton participants, Q . Only interpolating straight lines are shown except for 1.0 and 1.8 GeV/u. The dashed curve gives the cascade multiplicity result for 1.2 GeV/u, plotted vs. Q as determined from the calculation. The mean values of the impact parameter $\langle b \rangle$ that correspond to sets of cascade events with given Q are shown on the upper scale.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8