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ABSTRACT

Negative pion multiplicity $\langle n_{\pi^-} \rangle$ was measured over the range of participant nucleon number $80 \leq A \leq 270$ for incident energies from 530 to 1350 MeV/n in the La + La system. The $\langle n_{\pi} \rangle$ is proportional to A and increases linearly with the c.m. energy. Thermal and potential energies, and temperatures of the maximum density phase of the collision are extracted from the data. The results require a stiff nuclear matter equation of state.

Determining the response of nuclear matter to extreme changes in temperature and density is important to understanding effective baryon-baryon interactions[1] as well as supernova explosions,[2] neutron star formation[3] and structure.[4] Recent studies of relativistic nucleus-nucleus collisions[5,6,7] have shown that particle production, in the form of pions and kaons, provides information on the amount of kinetic energy available in the high density stage of the reaction. The potential, and thus compressional, energy can then be determined using the total initial energy and energy conservation. Others[8,9] have studied the decompression stage of the reaction finding that some of the compressional energy reappears in asymmetric flow of matter. Since initial efforts[5,6] to extract the compressional energy from pion multiplicities employed the relatively light Ar + KCl system and led to a surprisingly stiff equation of state, it is important to extend this study to heavier nuclei to understand better the pion production and absorption mechanisms and investigate the degree to which surface effects and other size phenomena may affect the conclusions.

Negative pion production in collisions of $^{139}La + ^{139}La$ was studied in the Bevalac Streamer Chamber at LBL at incident laboratory energies of 530, 740, 990, 1200, and 1350 MeV/n. Minimum bias, semi-central, and central trigger configurations[10] were employed at each incident energy. In a geometric model these triggers correspond to impact parameter values of $b < b_{max}$, $b < 0.73\, b_{max}$, and $b < 0.24\, b_{max}$, respectively. Extrapolation to zero impact parameter as done previously[6] with the lighter Ar + KCl system is difficult for the heavy system due to the presence of a larger number and variety of nuclear fragments. Only after implementation of a 384 element scintillator array, covering angles $\theta_{lab} < 18$, was this extrapolation possible. It provided position, charge, and time-of-flight information which allowed extraction of the total projectile spectator charge and, by subtraction, the number of participant protons in each event. The negative pion multiplicities were determined by scanning and measuring tracks on film. The participant and pion information were then correlated event-by-event.

Projectile spectators were identified in the array by the pulse height, emission angle, and time-of-flight. The minimum bias trigger, which selects mostly peripheral collisions dominated by spectator emission, was used at each incident energy to determine the spectator windows on these quantities for each scintillator element:

a) The dE/dx spectrum which yields the projectile spectator charge was calibrated with fragmentation products from Ne and La beams. Unit charge identification was achieved for fragment charges $1 \leq Z \leq 10$.

b) The projectile spectator angle window was defined to be the region centered about beam velocity Z=1 and 2 fragments containing 90 percent of the charged particles in the minimum bias data. The Fermi momentum of the projectile nucleons implied by this procedure was approximately 240 MeV/c.

c) The projectile spectator time-of-flight window was defined to correspond to 90 percent of the time-of-flight spectrum of charged particles observed in the scintillators in the minimum bias data.

Since there is no complete separation in phase space of participants and spectators at these incident energies, a Monte Carlo simulation was carried out to ascertain the efficiency of this procedure for selecting spectators in the semi-central and central data. A cascade code[11] was used to generate events corresponding to the three trigger modes. The participants and spectators, which are distinguished in this microscopic model, provided characteristic position and time-of-flight distributions at the downstream scintillator array after simulation of their trajectories through the Streamer Chamber magnetic field. By this procedure, a final efficiency factor was determined and applied to the data.[12] The projectile spectator charge was transformed to participant nucleon number by assuming: a) the total (projectile + target) spectator charge Q_{spec} to be twice the measured projectile spectator charge (A+A collisions), and b) the total participant nucleon number to be (A/Z) (2Z-Q_{spec}) where Z and A are the nuclear charge and mass of La.

The Streamer Chamber π^- data were corrected for losses due to the beam entry pipe ($\Theta_{lab} > 130$ degrees), identification losses along the magnetic field direction, losses due to stopping in the target ($p < 50$ MeV/c), and for target conversion of gammas (from neutral pion decay) into electron-positron pairs where electrons are misidentified as negative pions. These corrections were + (3.1 to 4.5)%, + (13 to 15)%, + (1.4 to 2.5)% and - (5.8 to 6.3)%, respectively, depending upon incident energy.

The observed negative pion multiplicity $\langle n_{\pi^-} \rangle$ is displayed in Fig.1 as a function of participant nucleon number for the semi-central and central trigger modes at three different incident energies. It is proportional to the participant nucleon number A at each incident energy and the slopes are the same as those observed[6] for Ar + KCl at the same incident energies.

The total pion multiplicity was derived from $\langle n_\pi \rangle = 2.35 \langle n_{\pi^-} \rangle$, where the factor[13] accounts for the isospin asymmetry of ^{139}La. The energy dependence of the ratio $\langle n_\pi \rangle$/A is displayed in Fig. 2. In addition to the data at 530, 740 and 1350 MeV/n, shown in Fig.1, the results of central trigger runs at 990 and 1200 MeV/n are plotted from an earlier run when the downstream scintillator array was not available. The mean numbers of participant nucleons at these two energies were interpolated from the 740 and 1350 MeV/n data where identical central trigger cross sections were maintained. Also shown in Fig. 2 are our previous results[6] for the Ar + KCl system. The $\langle n_\pi \rangle$/A ratio is a linear function of the incident energy in the c.m. frame which, for the domain covered here, corresponds to 530 - 1800 MeV/n incident laboratory energy. No significant difference between the Ar + KCl and La + La data is observed. The constancy of $\langle n_\pi \rangle/A$, both as the mass of the interacting nuclei is changed from Ar + KCl to La + La and as the interaction volume is changed by varying the trigger conditions, demonstrates that pion production is a bulk nuclear matter probe rather than a surface probe. An $A^{2/3}$ dependence[14] of $\langle n_\pi \rangle$ is strictly ruled out by these data.

In the past we have suggested[6] that the pion abundance per participant $\langle n_\pi \rangle/A$ is determined at the end of the high density stage of the reaction at the time of chemical freezeout before expansion, rendering $\langle n_\pi \rangle/A$ a sensitive probe of the compressed fireball, unaffected by the expansion phase. The present result, mass independence of $\langle n_\pi \rangle/A$, supports that assumption since the expansion dynamics should depend strongly on mass. For example, the expansion rate, or volume doubling time, should increase as $A^{1/3}$. If the pion yield were to readjust during expansion, a reduced $\langle n_\pi \rangle/A$ ratio would be expected in heavier systems,[15] contrary to what is observed.

Assuming that the pion abundance reflects the thermal energy per baryon of the high density stage, our results can be used to determine the thermal energy in a way that is independent of the dynamics of the collision process. Fig. 2 includes the result of thermal model calculations,[16] for an equilibrium mixture of nucleons, deltas and pions. The $\langle n_\pi \rangle/A$ ratio increases with the c.m. energy per nucleon, but with a steeper slope than the data. The reduced pion yield results from excitation of non-thermal degrees of freedom of the nuclear medium such as the potential energy stored in compression, and from the off-shell behaviour[17] of the nucleon, pion and delta resonance masses. Medium influences on the observed pion yield are presently under investigation.[18] Pending results of those studies, let us examine further the consequences of the simple assumption that the major influence stems from conversion of kinetic into potential energy, which was implicit in our previous efforts[5,6] to link the $<n_\pi>/A$ ratio to the nuclear matter equation of state.

The "missing" potential energy, inactive as far as particle production is concerned, can be determined from Fig. 2. It is the difference between the c.m. energy of the experiment, which is the total available energy, and the thermal energy which is the energy necessary in the thermal model to create the observed $<n_\pi>/A$ ratio. The results are displayed in Fig. 3a. Plotted is the "missing" energy per nucleon, E^{pot}/A, at each incident c.m. energy of the Ar + KCl and La + La experiments. E^{pot}/A is the increase of potential energy per participant nucleon expended in going from initial ground state nuclear density ρ_0 to the density ρ reached at each of the incident energies. In dynamical models this density $\rho\,(E_{cm}/A)$ is a monotonically increasing function of E_{cm}/A. Note that the fraction of initial c.m. energy that is transformed into potential energy rises from 13 % at 125 MeV/n to 33 % at 380 MeV/n.

It is of specific theoretical interest to relate the potential energy to the nuclear density at each c.m. energy, within the limitations of the present first order approach. The cascade[5] and the one-dimensional Rankine-Hugoniot shock compression[6] models have previously been employed to ascertain density (ρ/ρ_0) at each bombarding energy. E^{pot}/A can be determined from the data, as shown above. The nuclear matter energy-density relation is

$$W(\rho/\rho_0) = \frac{E^{pot}}{A}(\rho/\rho_0) + 21((\rho/\rho_0)^{2/3}-1) + W(\rho/\rho_0=1) \qquad (1)$$

where the second term approximates[19] the Fermi energy contribution to the ground state energy and the third, constant term is the binding energy at $\rho/\rho_0=1$. As dynamical models contribute additional uncertainty to the determination of

W (ρ/ρ_0) we do not pursue this result in detail. It is sufficient to note that all dynamical models[7,11,16,19] predict the nuclear density to reach a value of ρ/ρ_0 = 3.5 +/- 0.5 at the top Bevalac c.m. energy of 400 MeV/n. From Fig. 3a and Equ. 1 we then obtain the estimate W = 145 +/- 35 MeV at $\rho/\rho_0 = 3.5$, which corresponds to an extremely "stiff" nuclear matter equation of state.

In comparing the above result with nuclear matter calculations at T = 0, where a much softer equation of state with W ($\rho/\rho_0 = 3.5$) = 40 MeV is predicted,[20] one must be aware of the high temperatures at which nucleus-nucleus collisions proceed. From Fig.2 the thermal energy per nucleon was obtained as a function of the c.m. energy. The temperatures, corresponding to this thermal energy, are displayed in Fig. 3b. They increase monotonically from 55 to 80 MeV over the energy range of the present experiment and up to 95 MeV for Ar + KCl. A similar result has recently been reported by Hahn and Stöcker.[21] These temperatures are to be distinguished clearly from "temperatures" extracted from the energy spectra which are affected by expansion dynamics, including flow, and for the pion by decay kinematics of the delta resonance. The above temperature determinations should be important for the nuclear matter equation of state (EOS). Brown and coworkers[1] have recently argued that a significant fraction of the apparent stiffness of the EOS in nuclear collisions should result from the high relative baryon velocities, characteristic of high densities and temperatures in the fireball.

In summary, we have investigated the pion production for La + La and found a linear dependence both on the participant nucleon number, which reflects fireball size, and on the incident energy. The relative pion abundance, $\langle n_\pi \rangle/A$, is the same for 140 +140 and 40 + 40 collisions over the Bevalac energy range. This A-scaling of the pion multiplicity contradicts intuitive arguments concerning size-dependent absorption losses and effects of flow energy generation[23] on pion production and permits use of the $<n_\pi>/A$ ratio as a thermodynamic quantity referring to the high density stage of the reaction, before expansion and thermal freeze-out. In particular, an estimate of the fireball temperatures can be made using the "pion thermometer". The estimate of the potential part of the compressional energy, which also contains Fermi degeneracy energy, leads to the prediction of a very stiff nuclear matter equation of state, in apparent contradiction to the softer EOS resulting from $T = 0$ nuclear matter theory[20] and from recent attempts to understand supernova dynamics.[1,2] However, these two groups of results may be reconciled by taking into proper consideration the effects of the temperatures which are extracted in this Letter.

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FIGURE CAPTIONS

1. The mean pion multiplicity as a function of the number of participant nucleons A in the La + La reaction at three incident laboratory energies. The lines are straight line fits to the data points.

2. The ratio of the mean pion multiplicity to the number of participant nucleons as a function of incident c.m. energy (bottom scale) and laboratory energy (top scale). Plotted are the La + La data points (open circles) and data from Ref.6 for Ar + KCl (dots). Also displayed is a thermal model prediction,[16] which does not incorporate potential degrees of freedom.

3. a) The potential energy as a function of c.m. energy derived from Fig.2 as described in the text. b) The fireball temperatures derived from the pion multiplicity data and the thermal model.[16]

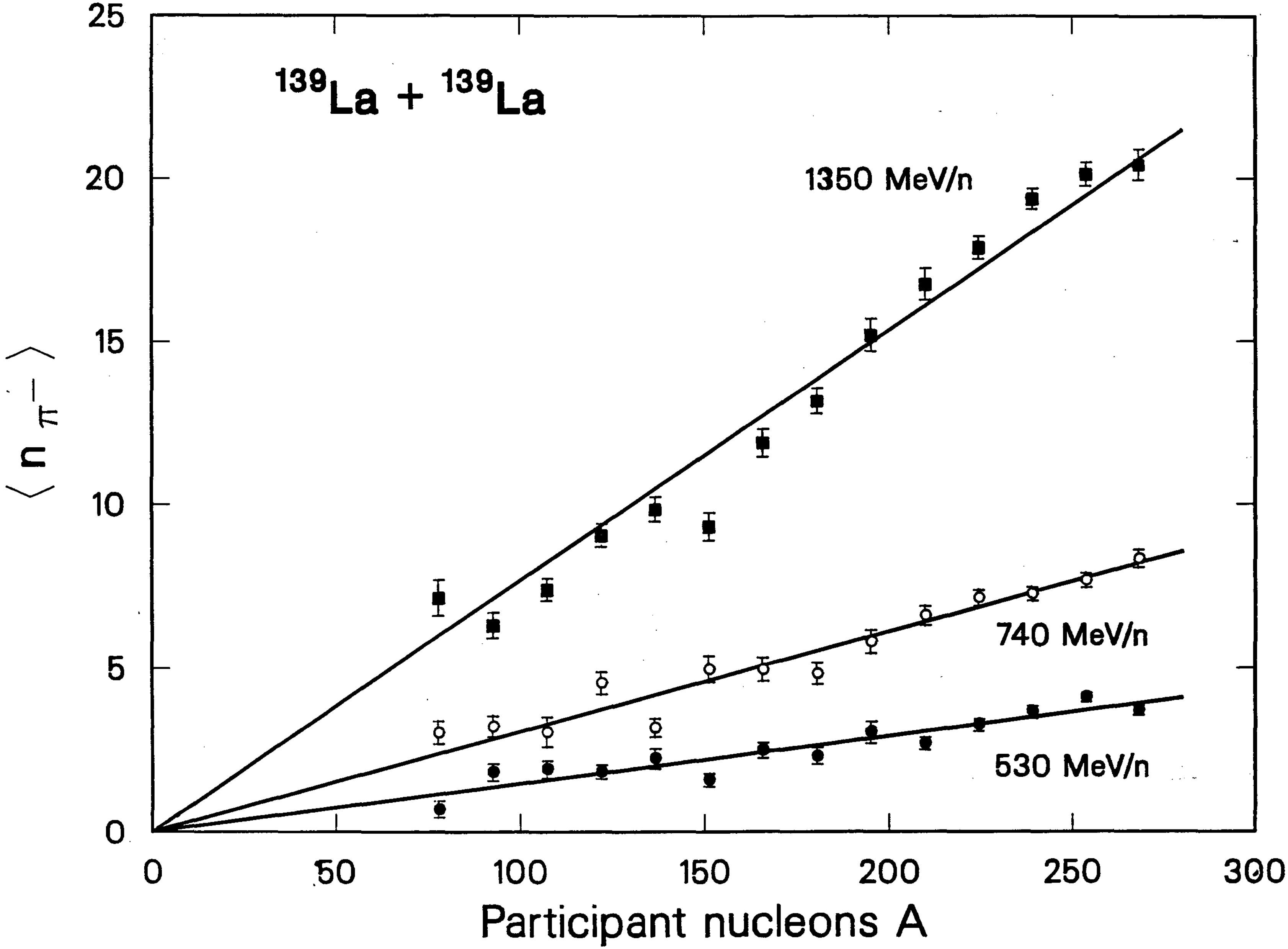
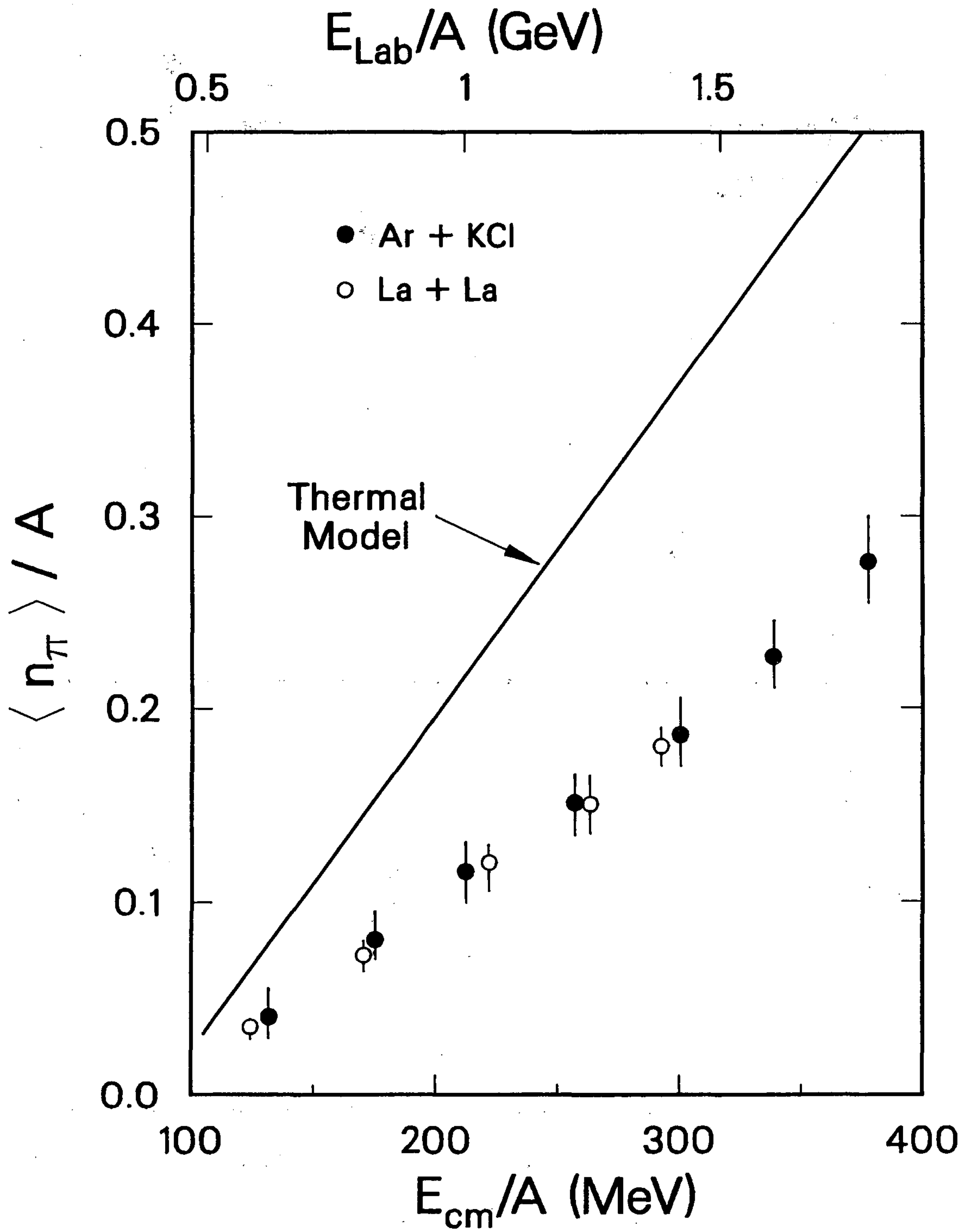


Fig. 1

XCG 865-7231 A



XCG 866-7280 B

Fig. 2

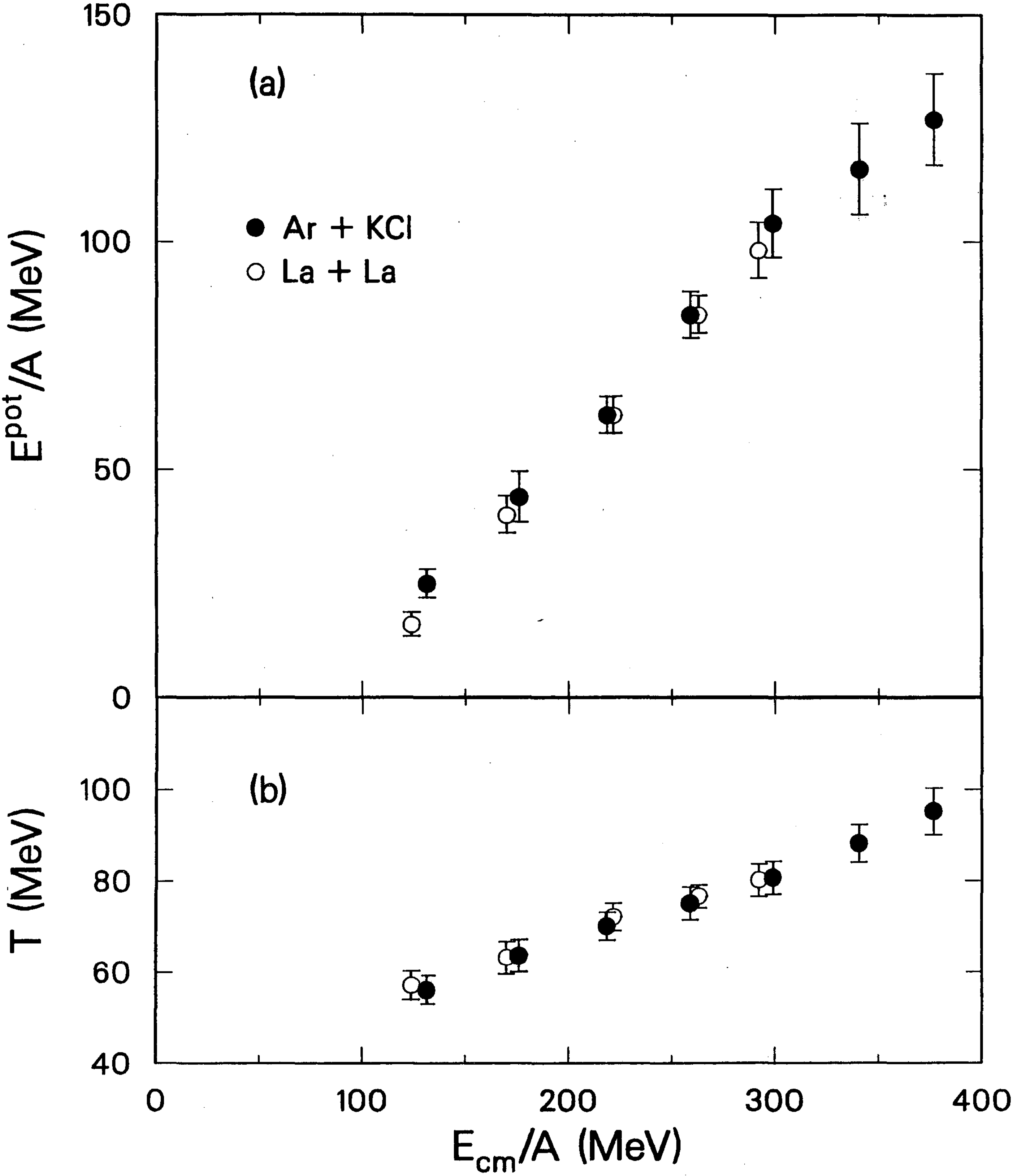


Fig. 3

XCG 867-7343 A

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