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Author

Gyulassy, Miklos

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UNIVERSITY OF CALIFORNIA

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Miklos Gyulassy

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Relativistic Nuclear Collisions in Perspective*

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

Abstract: Current attempts to deduce the nuclear matter equation of state and to search for new phases at high densities via nuclear collisions are discussed.

1. Introduction

One of the fastest growing new branches of nuclear physics is relativistic nuclear collisions. In the past few years a tremendous amount of data[1] have been taken on inclusive reactions of the type

$$A_P + A_T \to F_1 + F_2 + X_M \quad .$$

Projectiles as heavy as Fe have been used in those studies incident on target nuclei spanning the periodic table. The beam kinetic energies have been in the range 0.2-2.0 GeV/nucleon.

Most of the data involve the <u>inclusive</u> measurement of the momenta of only one or two of $\sim$100 fragments $F_i = \{\pi, K, p, n, d, \alpha\}$ produced in each event. However, in the latest experiments[2], the associated charged particle multiplicity, M, accompanying the fragments F_i was also measured. In this way, the

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inclusive fragment distributions in central collisions could be isolated for the first time by requiring high M per event.

Now, why are we interested in such complicated and violent reactions? The old Swiss watch analogy comes to mind. Nuclear collisions at these high energies have been compared to smashing a delicate Swiss watch with a sledge hammer! The intricate and subtle properties of ground state nuclei and Swiss watches surely cannot be studied by such "brutus forcus" methods. However, the aim is not the study of ground state nuclei--the focus of nuclear physics for over 50 years--but rather the exploration of the properties of highly excited and dense nuclear matter. At the present, we know nothing about the properties of nuclear matter at high densities, $n > n_o = 0.15\ \mathrm{fm}^{-3}$, and/or high temperatures, $\tau > E_F \approx 35$ MeV. While supernova explosions and the early history of the Big Bang hold the secret of those properties, relativistic nuclear collisions offer us a means to probe that high (n,τ) domain for the first time in the laboratory.

The range of n and τ that can be reached in such collisions is shown in Fig. 1. Based on an intranuclear cascade model, Gudima and Toneev[3] computed the maximum compression and temperature as a function of time for several typical reactions. Their results show that for times $\sim 5 \times 10^{-23}$ sec, high densities $n \gtrsim (2-4)n_o$ along with high temperatures $\tau \gtrsim 50-100$ MeV can be reached in such collisions due to multiple, incoherent NN scatterings. By varying the projectile-target combination and the bombarding energy, a large domain of the unexplored (n,τ) plane can thus in principle be investigated. Similar conclusions about the (n,τ) range accessible via relativistic nuclear collisions have been obtained via hydrodynamical calculations[4].

The most fundamental property that we ultimately wish to learn from such reactions is the nuclear matter equation of state, $W(n,\tau)$ = energy per baryon at fixed (n,τ). Incredibly, our current knowledge of W is limited to its value at the saturation density, $W(n_o,0) = -16$ MeV. Even the curvature, $K = 9n_o^2\partial^2W/\partial n_o^2 = 200 \pm 100$ MeV, around n_o is rather uncertain. The thermal properties of nuclear matter are unknown.

A second important goal (not independent of the first) is to search for new collective degrees of freedom or new phases of nuclear matter at high (n,τ). Theoretically[5], pion condensate, density isomeric, and even quark plasma states could be produced at sufficiently high densities. As an example, two calculations (RGG[6] and B[7]) of the pion condensation phase transition boundary are shown in Fig. 1. The range of densities and temperatures generated in nuclear collisions thus lies in a region where new collective phenomena could indeed occur.

Of course, it is by no means obvious how W can be deduced from actual data or what the signatures of a phase transition would be. The basic reaction mechanism in such collisions is rather complex with initial and final state interaction distortions and nonequilibrium (direct) processes competing with the equilibrium (hydrodynamic) processes. However, with the new data and extensive model calculation[1], many of the complex details of that reaction mechanism have been sorted out. In terms of Swiatecki's metaphor[8], we have cleared away many of the "weeds" in such reactions and are finally beginning to address the "heart of the matter". Although the most impressive progress in the past few years has been on the weeding front, I will concentrate in this comment on some current attempts to get at the "heart of the matter".

2. $A + B \rightarrow W(n,\tau) + X$

The most recent attempt to deduce $W(n,\tau)$ from inclusive data[2] involves the hydrodynamic calculations of Nix, et al.[9] The input for hydrodynamics is, of course, the pressure $P = n^2\partial W(n,\tau)/\partial n$ (at constant entropy). By solving the Euler equations for various models of $W(n,\tau)$ and comparing with data, the hope is that some constraints on the form of $W(n,\tau)$ can be obtained. In those calculations, W was assumed to be of the form $W(n,\tau) = W_o(n) + W_T(n,\tau)$, where W_o is the compression energy per baryon at $\tau = 0$, and W_T is the thermal energy. The pressure is thus the sum of a compression and a thermal part. For the thermal part an ideal Fermi gas form has been assumed. However, for the compression part, three different models were tested: one with a high incompressibility K = 400 MeV, one with K = 200 MeV, and one with a density isomer state at $n = 3n_o$.

The first comparison with data[10] was with the impact parameter averaged, charged particle inclusive double differential cross section, $d^2\sigma_{ch}/dEd\Omega$. This $d^2\sigma_{ch}$ is obtained by summing the inclusive cross sections for composite fragments with the same energy per nucleon, weighted by the charge of that composite. Physically, $d\sigma_{ch}$ is thought to represent the primordial proton distribution, before coalescence[1] into composites occurs. The comparison in Fig. 2a shows that while hydrodynamics provides a fair description of the data, there appears to be little sensitivity to variations in the compression part of $W(n,\tau)$. Variations in the thermal part were not tested in these calculations. We should note, however, that differences in the results less than a factor of 2-3 cannot be resolved because of the large numerical uncertainties. Therefore, the technical numerical problems associated with solving the hydrodynamic equations present a major obstacle at this time in placing constraints on W_o from impact parameter averaged data.

Given our limited theoretical resolution power, we must turn to more detailed observables for which the sensitivity to W_o is amplified. An important step in this direction was made possible by the new data[2] on central collisions. To isolate central collisions, the associated multiplicity, M, was measured in each event. An event was classified central if M belonged to the highest 15% of the multiplicity distribution. From intranuclear cascade calculations[11] such a selection corresponds to restricting the range of impact parameters to $b \lesssim 4 \pm 1$ fm. For this restricted range of impact parameters the hydrodynamic results[9] are indeed more sensitive to W_o as seen in Fig. 2b. However, there now appears to be a rather serious discrepancy between the data and calculations at forward angles.

The following factors are now thought to account for that discrepancy. First, the impact parameter range is not certain. In the highest 15% of the multiplicity there are contributions[11] from impact parameters $b > 4$ fm, which do not lead to complete geometrical overlap of Ne and U. These more peripheral collisions would clearly lead to more high-energy fragments in the forward direction. Second, even at $b = 4$ fm, a few nucleons in the Ne will traverse regions of U less than three mean free paths thick. From those regions direct, nonequilibrium processes, which are forward peaked, will contribute significantly to the cross section. Finally, technical details of the numerical calculations, especially the neglect of thermal averaging over fluid cells at the freezeout time, can result in too few high-energy fragments and too many low-energy fragments at 30°.

At larger angles (70°, 110°) the discrepancy is reduced, but, unfortunately, so is the sensitivity to $W_o(n)$. We must conclude then that $d^2\sigma_{ch}/dEd\Omega$, even triggered on high multiplicity, cannot be used to place stringent constraints on the compression energy.

What must we do in the future to gain sensitivity to $W_o(n)$? One obvious step is to use heavier projectiles in order to reduce the nonequilibrium component. By 1983 experiments with U + U up to 1 GeV/nucleon will be feasible at the Bevalac. A second step, proposed in Ref. 12, is to look for jetting phenomena in the <u>triple</u> differential cross section, $d^3\sigma/dEd\mu d\phi$.

To measure this triple differential cross section, the reaction plane must be determined event by event by studying the azimuthal distribution of the associated fragments. In Fig. 3 contour plots of the calculated $d^3\sigma$ for Ar(400 MeV/n) + Ca at b = 2 fm are shown as a function of the rapidity, y, and transverse velocity, P_T/m for different azimuthal angles . The peaks at $\phi = 0^{\circ}$ and $\phi = 180^{\circ}$ (in the reaction plane) correspond to jets of projectile and target fragments. For $\phi = 90^{\circ}$, two more jets are predicted, oriented perpendicular to the reaction plane in the cm frame. It is important to note that in the ϕ averaged double differential cross section labeled $<\phi>$, these jet signatures are washed away. Such conspicuous jetting phenomena, moreover, seem to be a unique signature of hydrodynamics. The intranuclear cascade calculations of Cugnon[11] lead to much smaller momentum transfer to the projectile fragment. Most likely, this difference is due to finite mean free path effects, which lead to considerable transparency for Ar and Ca.

A detailed experimental study of jetting phenomena will be important in assessing the real stopping power of nuclear matter at high densities. In the absence of collective phenomena, the four momentum transfers to the projectile jet could be small[11]. On the other hand, collective effects such as critical scattering phenomena[13] could lead to the rapid local equilibration necessary for the validity of hydrodynamics, which in turn leads to substantially larger momentum transfers. The experimental study of jetting will be possible in the near future as the HISS and Ball-Wall devices[1], that measure the four momentum of most charged fragments, come into operation.

If large momentum transfer jetting[12] is eventually observed, say via U + U collisions, what will that teach us about W? The average momentum transfer[12] (or the event shape[14]) is apparently not sensitive to K. We can estimate from the Rankine-Hugoniot equation that the total pressure $P = P_C + P_T$ typically varies by less than 20% as K is varied between 100 and 400 MeV, although P_C and P_T can vary by a factor of two individually. Jetting phenomena place then a constraint only on the time integrated <u>total</u> pressure.

To get information on P_C and P_T separately will require the measurement of additional thermodynamic variables. One important independent quantity is the entropy per baryon, $S(n,\tau)$. An exciting proposal made in Ref. (15) is that $S(n,\tau)$ could be determined by a composition analysis of the final fragments. In particular, the deuteron to proton, d/p, and the pion to proton, π/p, ratio could be used to determine $S(n,\tau)$ <u>if</u> chemical equilibrium were established. While there is current theoretical controversy over chemical equilibration and isentropic expansions in nuclear collisions, this idea clearly deserves careful further study. If indeed the total pressure, $P(n,\tau)$, and the entropy, $S(n,\tau)$, could be determined by a combination of jet analysis[12] and composition analysis[15], then the goal of mapping out the properties of dense nuclear matter would be finally in sight.

3. New Phases of Nuclear Matter?

Among the possible properties of dense nuclear matter could be phase transitions[5] involving new collective degrees of freedom (meson or gluon fields). In this section I will comment on some current attempts to find experimental signatures of such exotic states of nuclear matter.

One puzzling observation[16] was recently made concerning anomalous properties of projectile fragments produced in nuclear collisions. It appears that some fraction ($\sim 6\%$) of projectile fragments have an anomalously high ($\sim 10\sigma_{geom}$) reaction cross section in emulsions. The reaction cross sections of primary nuclei with $2 \leq Z \leq 26$ and energies between 0.2 and 2.0 GeV/nucleon have, on the other hand, been well established to follow simple geometrical formulas, $\sigma_{geom} \approx \pi(R_1 + R_2 - d)^2$. By measuring the number dN/dx of secondary fragments that react within a distance x of the primary vertex, a significant excess of events with x less than a tenth of the geometrical mean free paths were observed. Such observations were already made in early cosmic ray studies. However, only the latest experiment[16] had the necessary statistics to quantify this effect.

Many conventional possibilities such as pionic atoms, hyperfragments, isotopic effects, etc. have been ruled out. Of course, systematic experimental biases using emulsions are more difficult to evaluate. There is the exciting possibility that these observations could result from the production of some new state of nuclear matter. However, that state would have to be quite exotic indeed. Its lifetime would have to be at least 10^{-10} sec, since these "anomalous" nuclei travel at least a few centimeters in the emulsions. In addition, it would have to have a force range ∿3 times nuclear radii. Corridor and coffee lounge speculations have toyed with color polarized nuclei with long-range color dipole fields as possible candidates. For example, a color polarized deuteron would consist of two-color octet baryons in an overall color singlet state. Such ideas meet with difficulty in accounting for the long lifetimes of these states and the empirical absence of long range van der Walls forces between hadrons. However, these speculations incidentally point to a healthy new trend in nuclear physics to come to grips with the ever increasing reality of Quantum Chromodynamics.

To establish that the anomalous fragments indeed correspond to a new type of excitation of nuclei, it will be necessary to measure the invariant mass of projectile fragments. A narrow bump in that invariant mass distribution above the ground state mass could constitute proof of their existence. Fortunately, such an invariant mass distribution is a natural by-product of the jet analysis described in the last section. In particular, the HISS spectrometer[1] would be ideal for such studies. Resolving these puzzling observations will be one of the hot topics in the next few years.

Another search for signatures of new states produced in nuclear collisions has focused on pion production. As we saw in Fig. 1, nuclear collisions could explore a (n,τ) domain where pion condensation could occur. In nuclear collisions, pion condensation would be a transient, nonequilibrium phenomenon analogous to the two stream instability in plasmas[13]. It would be characterized by an instability toward the growth of a collective spin-isospin wave perpendicular to the beam. Therefore, if such an instability occurs, the expectation value of the spin-isospin current $\underset{\sim}{J}_{\mu 5} = \langle \bar{\psi} \gamma_\mu \gamma_5 \underset{\sim}{\tau} \psi \rangle$ becomes time dependent. Since $j(x) = g_\pi \partial^\mu J_{\mu 5}(x)$ is a source of the pion field

$$(\Box + m_\pi^2)\pi(x) = j(x) \quad ,$$

a time dependent $J_{\mu 5}(x)$ will lead to pion radiation. The number and sectrum of those pions depends[17] on the on-shell Fourier transform $j(\underset{\sim}{k},\omega_k)$ of $j(\underset{\sim}{x},t)$. Of course, at these energies pions are produced dominantly by incoherent inelastic $(NN \rightarrow N\Delta)$ processes that can be characterized by a chaotic current[17] $j_{ch}(x)$. The question then is how an additional coherent source, $j_o(x)$, due to pionic instabilities could show up in pion data.

To construct a model for j_o, the growth rate $\gamma(\underset{\sim}{k})$ of the instability in mode $\underset{\sim}{k}$ must be determined from the singularities of the pion propagator[13]. Then, initially, $j_o(\underset{\sim}{x},t) \propto \gamma(\underset{\sim}{k})t \exp(i\underset{\sim}{k}\underset{\sim}{x})$. The magnitude can be estimated from the $t \rightarrow \infty$ asymptotic form[18]. The result of the calculation[19] is that the number of coherently radiated negative pions per nucleon is very small $n_o/A \sim 10^{-4}$. Experimentally[20], $n/A \gtrsim n_{ch}/A \gtrsim 4 \times 10^{-2}\ E_{lab}/m_N \gg n_o/A$. Even at lower bombarding energies, $E_{lab} \sim 200$ MeV/nucleon, the chaotic pions outnumber

References

1. Proc. Symp. on Relativistic Heavy Ion Research, March 1978, GSI, Darmstadt, West Germany; Fourth High Energy Heavy Ion Summer Study, LBL-7766, Conf-780766, July 1978; Proc. of INS Kikuchi Summer School on Nuclear Physics at High Energies, K. Sagimoto (ed.) INS, Tokyo, Japan, July 1, 1980.
2. R. Stock, et al., Phys. Rev. Lett. 44 (1980) 1243.
3. K.K. Gudima, V.D. Toneev, Dubna JINR preprint E2-12624 (1979).
4. J.R. Nix, Prog. Part. Nucl. Phys. 2 (1979) 237;
   H. Stöcker, et al., Prog. Part. Nucl. Phys. 4 (1980) 133.
5. A.B. Migdal, Rev. Mod. Phys. 50 (1978) 107;
   T.D. Lee, Rev. Mod. Phys. 47 (1975) 267;
   E.V. Schuyak, Phys. Rep. C61 (1980) 72.
6. V. Ruck, M. Gyulassy, W. Greiner, Z. Phys. A277 (1976) 391.
7. G.G. Bunatjan, Sov. J. Nuc. Phys. 30 (1979) 131.
8. Second High Energy Heavy Ion Summer Study, LBL-3675, July 15 (1974), 349.
9. J.R. Nix, D. Strottmann, A. Sierk, Preprint LA-UR-80-1280 (April 1980), in Proc. of Kikuchi School, ibid.
10. A. Sandoval, et al., Phys. Rev. C21 (1980) 1321.
11. Y. Yariv, Z. Fraenkel, Phys. Rev. C20 (1979) 2227;
    J. Cugnon, Phys. Rev. C (in press).
12. H. Stöcker, et al., GSI preprint 9, 22, LBL-11774 (1980).
13. M. Gyulassy, W. Greiner, Ann. Phys. 109 (1977) 485.
14. G. Bertsch, A. Amsden, Phys. Rev. C18 (1978) 1293.

15. P.J. Siemens, J.I. Kapusta, Phys. Rev. Lett. **43** (1979) 1486;

J.I. Kapusta, D. Strottman, LA-UR-80-1831 preprint.

16. E.M. Friedlander, et al., Phys. Rev. Lett. **45** (1980) 1084.

17. M. Gyulassy, S.K. Kauffmann, L.W. Wilson, Phys. Rev. **C20** (1979) 2267.

18. B. Banerjee, N.K. Glendenning, M. Gyulassy, Nucl. Phys. A (in press).

19. M. Gyulassy, LBL-10883 and LBL-11556 preprints (1980).

20. A. Sandoval, et al., Phys Rev. Lett. **45** (1980) 874.

Figure Captions

1. Time evolution in steps of 10^{-23} sec of the average density n and temperature τ obtained via the intranuclear cascade calculations of Gudima and Toneev[3]. Two typical nuclear reactions are shown. The critical temperature curves for pion condensation from two model calculations RGG[6] and B[7] are also shown.

2. a) Hydrodynamical calculations[9] (histogram) for Ne + U at 393 MeV/nucleon are compared with charged particle inclusive data[10]. Three models for the compression energy, $W_o(n)$, were tested showing the insensitivity to W_o modulo large numerical uncertainties.
   b) As in (a) but now central trigged data[2] are compared to hydrodynamical calculations integrated from $b = 0$ to 4 fm.

3. Contours of triple differential cross sections of Stöcker, et al.[12] showing jet phenomena for Ar + Ca at 400 MeV/A and $b = 2$ fm. Azimuth $\phi = 0, 90, 180^o$ as well as $<\phi>$ cross sections are shown as function of rapidity, y, and transverse momentum, p_T/m.

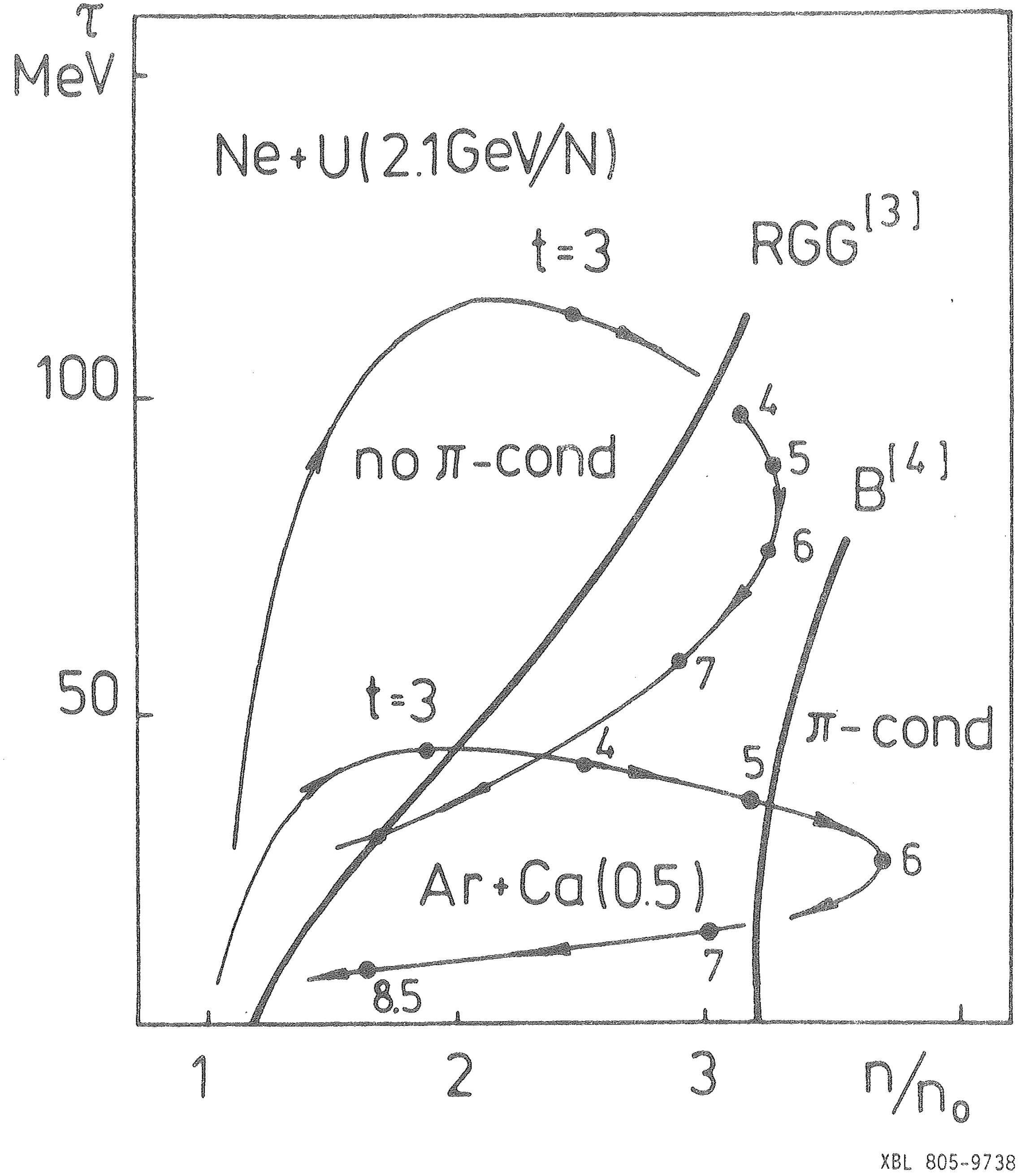
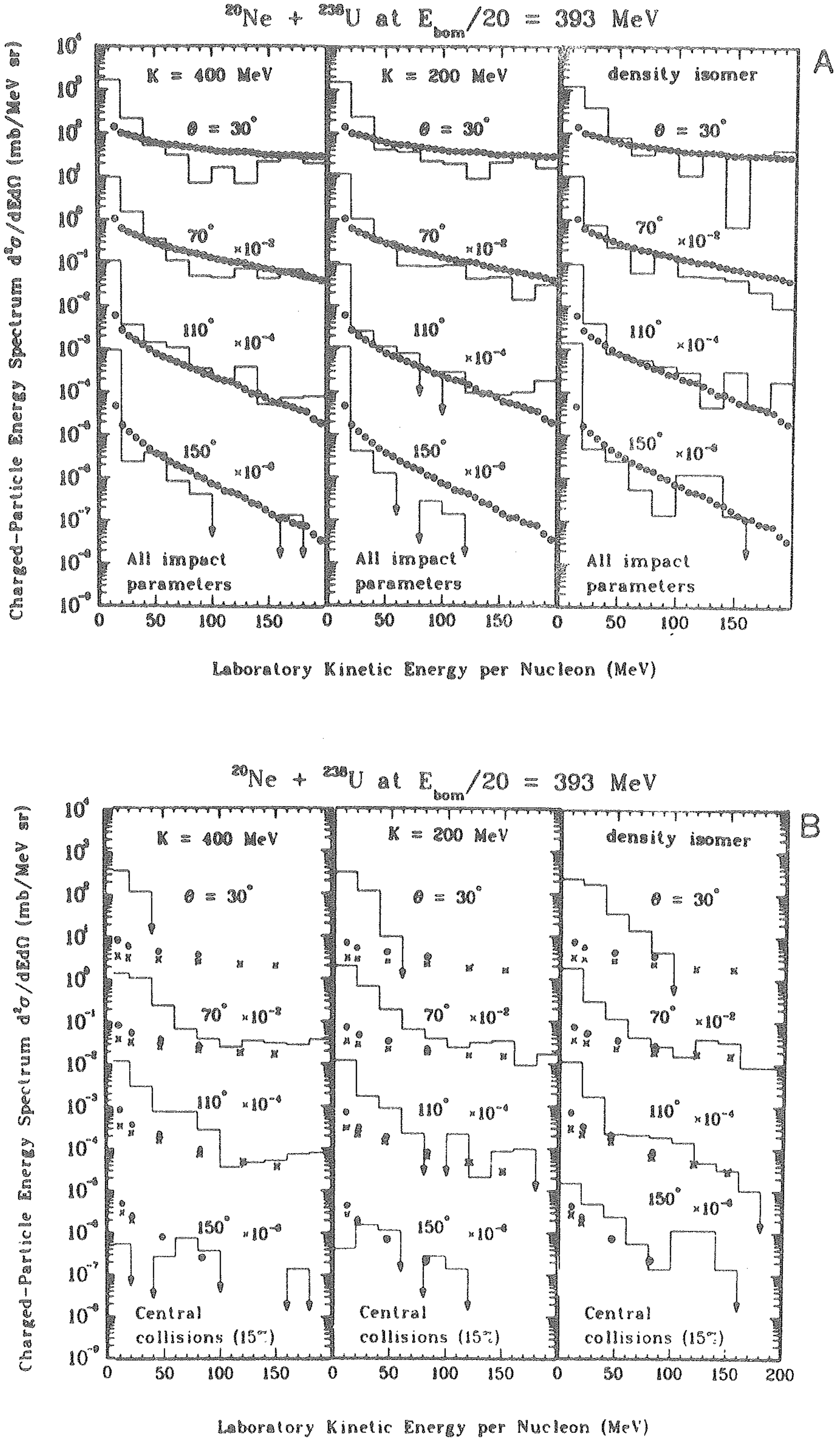

τ
MeV
100
50
1
2
3
n/n₀
Ne+U(2.1GeV/N)
t=3
RGG[3]
no π-cond
4
5
6
7
B[4]
t=3
4
5
6
π-cond
Ar+Ca(0.5)
7
8.5
XBL 805-9738

Fig.1



XBL 806-10460A

Fig.2

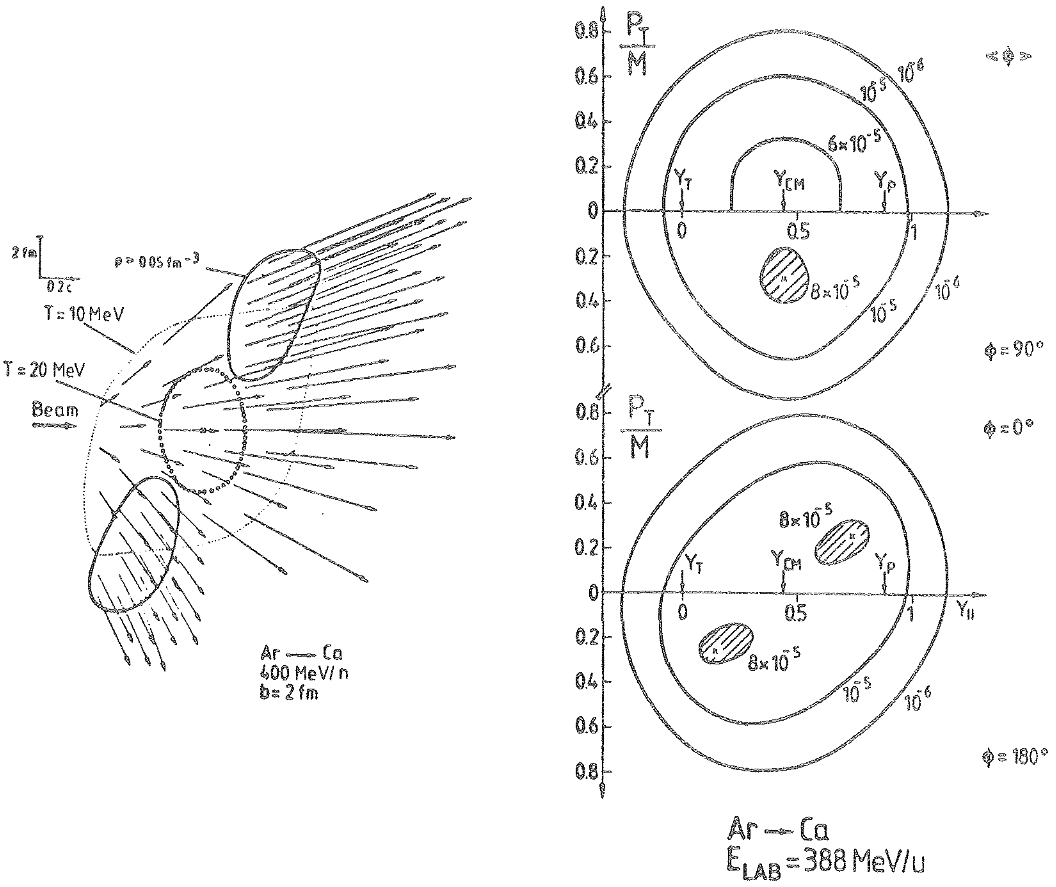


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Fig.3