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MACROSCOPIC NUCLEON-NUCLEON CORRELATIONS CAUSED BY THE BOUNCE-OFF PROCESS IN ENERGETIC COLLISIONS OF HEAVY NUCLEI[*]

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Abstract:

Two - particle correlation data are presented for the reaction Ar (800MeV/A) + Pb. The experimental results are analysed in the nuclear fluid dynamical and in a linear cascade model. We demonstrate that the collective hydrodynamical correlations dominate the measured two - particle correlation function for the heavy system studied. We discuss the transition from the early stages of the reaction which are governed by few nucleon correlations, to the later stages with their macroscopic flow which can only be reached using heavy colliding systems. The sensitivity of the correlation data on the underlying compressional and dissipative processes is analysed.

Keyword abstract: NUCLEAR REACTIONS, Ar + Pb (800 MeV/A)
relativistic heavy ion reactions,
two - proton correlations.

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I. Introduction

We present an extension of a recent experimental study of two - particle correlations[1] in relativistic heavy ion reactions towards heavier collision systems. Alongside theoretical aspects of the correlations[2,3] are discussed that cover two extremes of the reaction dynamics, namely the microscopic preequilibrium regime for which the linear cascade model is used and the collective macroscopic regime as accomodated by a fluid dynamical model.

Hydrodynamical models[4,5] predict a prefered sideward emission of nuclear matter in central collisions of heavy nuclei as a result of the macroscopic matter flow caused by the strong pressure that builds up in the interaction zone. Such predictions find a support by the emission patterns of α - particles and protons that have been observed in high multiplicity selected events of particle track detector[5,6] and counter data[7,8], respectively. At intermediate impact parameters a different phenomenon is predicted in the hydrodynamical model[4,9]: the projectile matter as a whole essentially gets deflected by the target as a whole, the bounce-off effect[10]. Cascade calculations on the other hand do not predict such an effect. The 180^0 azimuthal correlation observed between light and heavy fragments [9,13] has been the first experimental indication of this process. Here we want to investigate this phenomen with an independent experiment, using nucleons as a probe. The latter have the distinct advantage that they do not significantly influence the overall balance of the conservation laws.

Studies with nucleon-nucleus (n-N) collisions and with small nuclei showed that only limited thermalization may be reached in the light systems[1]. The mean free path of an impinging proton in the nucleus was estimated[14] to be approximately 2.4 fm. However, this value can be much smaller (around 1.5 fm [14]) in nucleus-nucleus (N-N) collisions due to the increasing temperature and density. Thus, while the lighter systems exhibit mainly the signatures of quasi elastic nucleon - nucleon (n-n) scattering[2], it is expected[3] that in the heavier systems macro correlations such as the bounce - off process[4] may dominate the observed correlations.

The observation of nucleon-nucleon correlations that cannot be explained by quasi-free n-n scattering but require collective macroscopic flow of matter deserves particular interest. It is the aim of this paper to show that for the heavy systems studied the observed coincidence between two nucleons indicate the existence of such macroscopic correlations.

The paper is organized in the following way. We briefly recall the experimental set-up in the next section. Subsequently we dicuss the priciple form of the two-particle coincidence cross-section in the two dynamical regimes with reference to the two models employed. A discussion of the experimental results together with the theoretical predictions is given at the end.

II. The two - particle correlation experiment

Two - particle correlations have been measured in the reaction Ar (800 MeV/nucl.) + Pb at the Berkeley Bevalac, completing the experimental study done previously[1] for lighter systems. In this section we do not repeat all the detailes of the experimental set-up; only basic features are presented which are necessary for the further discussion. For more detailes see Refs. [1,15].

The experimental system consisted of a magnetic spectrometer (S) and three sets of counter telescopes (R,U, and D). These telescopes were set at scattering angles $(\theta,\Phi) = (40^\circ,180^\circ)$, $(40^\circ,90^\circ)$ and $(40^\circ,270^\circ)$, respectively. The spectrometer (S) was located at $\Phi = 0^\circ$ and was rotated between $\theta = 15^\circ$ and 110°. Although it was impossible to identify particles with the telescopes it was known from the single particle inclusive data that the dominant yield at $\theta = 40^\circ$ is protons. In the experiment presented here the telescope energy has been confined to $E_{proton} \geq 200$ MeV.

An azimuthal (or coplanar) correlation function $C(y_{\parallel},p_T/m)$ has been measured which is defined as

$$C(y_{\parallel},p_T/m) = \frac{2 \times [S(y_{\parallel},p_T/m)\bullet R] / R}{[S(y_{\parallel},p_T/m)\bullet U]/U + [S(y_{\parallel},p_T/m)\bullet D]/D} , \tag{1}$$

where $y_{\parallel}$ and $p_T/m = y_T$ are the rapidity coordinates of the particle detected by the spectrometer. The quantity $[S(y_{\parallel},p_T/m)\bullet R]$ indicates the coincidence counts between the spectrometer and the R telescope ($\Delta\Phi = 180^0$). The coincidence rates with the other two telescopes give the $\Delta\Phi = 90^0$ correlations. At $\theta = 0^0$ or 180^0 ($P_T=0$) all these coincidence rates should be equal by definition, so that $C(y_{\parallel},0)=1$ there. It has a maximum ($C > 1$) at the rapidity where most of the inplane coincidences are observed. Out of plane correlations yields $C < 1$.

The relative accuracy of the measured correlation function points is about $\Delta C = 0.05$-0.1, but a slight difference between the sensitivities of the three telescopes could cause an overall normalisation error of about $\Delta C=0.1$-0.3. This error could have been eliminated only by the measurement of $C(y_{\parallel},0)$ values, but the available polar angle range ($\theta = 15^0 - 110^0$) did not allow this.

III. Microscopic two - particle correlations and the transition from micro- to macro- dynamics

In this section we describe the principle theoretical form the two particle cross section attains in going from the micro dynamical regime towards the macro regime.

At early times of the reaction only a few nucleons of both nuclei suffer only a few interactions. If one were to observe the nucleons at this early stage, the only strong correlations arise from such quasi-free n-n scattering contributions. Thus, the respective two - particle distribution function at a fixed impact parameter b attains a form containing two terms[16]

$$^2f(p_1,p_2,b) = \Sigma_c {}^2f_c(p_1,p_2)|_b + \Sigma_{c^1\neq c^2} {}^1f_{c^1}(p_1)\,{}^1f_{c^2}(p_2)|_b, \tag{2}$$

where c, c^1, c^2 denote all the possible subsystems (clusters) that were in interaction contact so far [17]. Besides the possibility that both observed nucleons result from the same cluster c with a correlated spectrum ^2f_c they can also result from two different clusters described by the uncorrelated product of the respective single particle momentum distributions ^1f_c. In the sense of the micro regime discussed so far the latter term represents an uncorrelated background. During the later stages of the collision, however, this goes over into the macroscopic correlation term. By integrating over all impact parameters we obtain the two particle coincidence cross section:

$$d^2\sigma/d\,p_1 dp_2 \equiv {}^2\sigma_C(p_1,p_2) = \int d^2b\ {}^2f(p_1,p_2,b). \tag{3}$$

The micro correlations prevail in light systems or at peripheral impact of heavy nuclei. However, in nonperipheral collisions of heavy nuclei the above clusters may attain a local (micro) equilibrium. Then the clusters turn into local fluid elements at position r and the forthcoming interactions serve the relaxation on the macro scale, for which the fluid dynamical model may give an appropriate description. In the fluid dynamical model the clusters or infinitezimal fluid elements are assumed to be in local equilibrium. Therefore microscopic correlations do no longer appear, the second term in eq.(2) becomes dominant. Then the two - particle spectrum has the form

$$^2F_H^{cell}(p_1,p_2,r) = {}^1F_H(p_1,r)\,{}^1F_H(p_2,r)\ . \tag{4}$$

where we use capital letters to recall for the macro dynamics and the subscript H stands for hydrodynamics. In a collision at fixed impact b the total two - particle distribution contains the correlations arising from the collective flow: the neighbouring cells are correlated to one another in the momentum space. The two particle distribution is still separable:

$$^2F_H(\,p_1,p_2,b) = \int d^3r_1 d^3r_2\ {}^1F_H(\,p_1,r_1)\,{}^1F_H(\,p_2,r_2)|_b$$
$$= {}^1F_H(\,p_1,b)\,{}^1F_H(\,p_2,b). \tag{5}$$

The integration of eq. (5) over all impact parameters b, $\int d^2b$ breaks this factorisation and leads to the respective two - particle cross section

$$^2\sigma_H(\,p_1,p_2) = \int d^2b\ {}^2F_H(\,p_1,p_1,b). \tag{6}$$

Thus observing one nucleon with momentum p_1 introduces a bias in impact parameter, so that the second nucleon attains a spectrum other than the inclusive cross section (see also the appendix and Fig. 5).

Hence, the cascade and hydrodynamical models both are describing correlations but of different origin. In the preequilibrium regime, as adequately described by the cascade picture, the correlations between different clusters may be neglected , while the microscopic correlations are taken into account. Just on the contrary in the hydrodynamical model microscopic correlaions within one local cluster (fluid element) are neglected while strong macroscopic correlations between different clusters (different regions) are considered.

It was one of the goals of the classical equation of motion approaches to study microscopically the transition from micro to macro (collective) dynamics. In order to achieve a separation of these two regimes *Bodmer* et al.[18] for instance suggested to devide the n-n force into long and short range parts: the long range part governing the macro dynamics in terms of an averaged force (*Vlasov* equation) while the short range force enters the stochastic collision term. In this type of unified models there would be a possibility to study the gradual change of the correlation function in the transition region. In order to accomodate both, the micro and the macro regime, in a more simple way one might think of a phenomenological model that retains the micro correlations from eq. (2) and replaces its second (back-

ground) term by the respective hydrodynamical spectrum. Thus integrating over all impact parameters we obtain the coincidence cross section

$$^2\sigma(p_1,p_2) = \int d^2b\ [^2f(p_1,p_2,b) + {}^2F_H(p_1,p_2,b)] \tag{7}$$

This composition (7) physically means that we take into account the correlations arising in a single fluid cell due to the limited number of nucleons in the cell (first term of (7)). The usual hydrodynamical descriptions neglect this effect. Such a unified model may enable the description of a smooth transition from the micro regime prevailing in the early stage of the collision to the macro regime in the later stage.

The models actually employed for the two dynamical regimes are the linear cascade model and the hydrodynamical model, respectively. Compared to three-dimensional cascade calculations in the linear cascade model[2] special simplifying assumptions are made for the type and weights of the various possible contributions to (2). For further details we refer to ref. [2], where also a systematic study of the correlations in light systems is given. The hydrodynamic model[4], that describes the violent stage of the reaction following the preequilibrium regime is supplemented by an evaporation calculation[19]. The latter decribes the transition from the fluid phase (hot nuclear matter) to separate nucleons and nuclei by a sudden break-up at the late stage of the expansion. Since this calculation includes the production of composite particles only a fraction of the nucleons leave the interaction zone as free nucleons. A detailed description of the fluid dynamical model with evaporation is given in refs.[19,20], and summarized in the Appendix.

IV. Results and Discussion

Let us first recall the kinematical situation of the experiment. Fig. 1 explaines the circumstances in the rapidity plane. The hatched area indicates the sensitivity range of the telecopes while for the in - plane coincidence the spectrometer maps out the lower part of the rapidity plane. By intend the chosen angle and energy cuts of the telescopes favour an analysis

of the quasi - free scattering process (knock-out). It leads to rapidities close to the dashed kinematical curve (a circle in non-relativistic kinematics) with a near back to back emission relative to the n-n c.m. frame. The isolation of this process which in fact leads to the most pronounced micro correlation was one of the major motivations for the present experimental set-up.

In fact, earlier coincidence experiments on light systems[1] showed an enhancement of the in-plane coincidence yield in line with the expectations from the quasi-free scattering process. A detailed discussion of these data by a phase space model[16] and the simplified cascade picture[2] further showed that besides the knock-out part there is also a sizeable correlation among the cluster nucleons due to the common share of energy and momentum, if mainly small clusters contribute. The latter effect gives rise to an in-plane correlation dominating at large momenta[2].

The above described effects are evidently not the ones that we see in the coincidence rates of the present experiment, as shown in Figs. 2a and 2c. Rather, for this heavy collission system we do observe a disfavour of the in-plane coincidence rate at large spectrometer momenta alongside with an in-plane enhancement at moderate momenta (with respect to the target frame). The correlation function C (eq.(1)) calculated in the framework of the linear cascade model in fact shows a qualitative disagreement with the experimental result. In this cascade model an enhancement is obtained around the quasi elastic n-n peak, as in lighter systems. However, here this increase is rather weak, $C \approx 1.1$. This points towards the expectation that in large systems the background term (second term in (2)) becomes so large that the correlation part of the model (first term in (2)) reaches the 15% level of the total coincidence yield at most. The fact that the obtained C- function does not resemble the experimental one shows the influence of effects other than microscopic two- or few- particle correlations. How can we understand the structural change in going from the light to the heavy systems?

What are the effects that are left out in the simplified cascade approach? The different clusters of interacting nucleons are treated as independent in this model. Thus, the contact of the clusters with the surrounding matter is neglected. This has essentially two effects: First, nucleons emit-

ted from a certain cluster may rescatter. This leads to shadowing effects that distort the predicted correlations. Secondly, as already discussed in sect. III, the forthcoming interactions serve a transport of energy and momentum across the different clusters and one enters the regime of macro motion. Thus, the data may draw attention towards collective effects.

First let us recall the the earlier discussions of shadowing effects[1,15,21]. The shadowing (rescattering) by the spectator nuclei suppresses the in plane coincidence rate as compared to the out of plane coincidence rate. We therefore expect $C < 1$. A simple calculation based on the geometry and mean free path, however, can only reproduce the data at high forward momenta due to this shadowing effect. It fails completely at large angles where the value of C is larger than 1. We therefore have to look for a different mechanism.

Returning to the kinematical situation depicted in Fig. 1, if the projectile and the target act as a whole with their total inertias, then (ignoring inelasticity effects for the moment) one expects nucleons resulting from the decay of the deflected projectile and target fragments to occupy the kinematical regimes around the dash-dotted lines. This is essentially the physics of the bounce-off process seen in hydrodynamical calculations. As it was shown qualitatively in the bounce-off model[3] this process may lead to a correlation function similar to the experimental one. Now on a detailed three dimensional hydrodynamical and evaporational[22] model the triple differential proton cross section was evaluated (Fig. 3) and the two-particle correlation function is calculatedon the basis of eqs.(1,6) (see also the Appendix).

The coincidence function is in good qualitative agreement with the experimental observations (Fig. 2d). The maximum around the zero rapidity is caused by the target evaporation which anticorrelates azimuthally with the higher energy projectile evaporation detected by the telescopes. The position of the maximum agrees with the experimental observations. The maximum of C is somewhat lower (≈ 0.2) than in experiment but this difference is withinthe systematic experimental normalisation error. The difference between the maximum and minimum values is only slightly higher than in the experiment. This shows that additional effects may influence the coincidence function, and the structure of the C function should be smoother by 10-20%.

In the framework of the fluid dynamical model extremely soft equation of state (phase transition) could cause stronger dissipation and so a stronger thermal smearing. However, finite particle number effects, i.e. non thermal fluctuations and the microscopic nucleon-nucleon correlations[2] or quantummechanical correlations[21] can cause similar smearing effects.

If we assume that the local nucleon clusters within the nuclear fluid have the sizes and momentum distribution similar to the ones predicted by the linear cascade model, we can evaluate the modifying effects arising from the microscopic correlations. The C function obtained in a joint hydrodynamical and cascade model (eq.(7)) resembles mainly the features of the hydrodynamical model (Fig. 2b) now the experimentally observed slope between the maximum and minimum is also reproduced. This shows that the consideration of the finite nucleon cluster effects within the nuclear fluid may extend the validity of such a unified model to the intermediate mass regions where neither the cascade nor the hydrodynamical model is sufficiently accurate.

V. Conclusions

It is important to note what type of underlying physical effects can be studied in this experiment in heavy N-N systems. As it was shown on Fig. 1 the two - particle correlations measure the N-N kinematics. As we have seen, the crucial point in the experiment is the lower energy cutoff of the telescopes. Due to the 200 MeV cutoff the probability to detect a proton from the target evaporation is two orders of magnitude smaller than that from the projectile evaporation (Fig. 3). At the cutoff energy where both the target and the projectile evaporations can be detected by the telescopes equally, the collective character of the coincidence function vanishes because the collective azimuthal correlation can not be exploited. By changing the lower energy cutoff of the telescopes and their θ angle the bounce-off process could be mapped at different deflection angles. The position of the projectile evaporation peak could be estimated and thus the inelasticity could be measured, as shown in Fig. 4. On the other hand the deflection angle and inelasticity and their dependence on the equation of state and viscous coefficients can be tested in hydrodynamical models[19,20] So this experiment

provides an alternative tool for the investigation of the collective processes.

Another important point is to approach the reaction mechanism by this type of studies. As we have seen two types of correlations show up in the discussed experiment. These are representing two different stages on the way towards the equilibration. The way to local thermo- and fluid- dynamical equilibrium leads through the build up of small interacting clusters first and then later these clusters may grow. The initially unimportant weaker interactions between the clusters later become more important and at later stages the signs of this collective type of correlations show up. In very small systems the reaction cannot reach this stage[23] A major part of nucleons leave the system before larger clusters and collective processes may develop. Otherwise in larger systems the amount of nucleons escaping from initially independent clusters becomes negligible and mainly the signs of collective correlations can be observed. When already collective processes started to develop the reaction mechanism may be influenced considerably by especially strong long range correlations[21] caused by phase transitions for example[24]. By a systematic study of the microscopic and macroscipic correlations the collective processes may be separated from other effects and then their properties and anomalies may indicate us the signs of the extreme states occuring in hot and dense nuclear systems.

The present results are promising and on this basis we hope that the present experimental and theoretical investigations to test the triple differential nucleon correlation cross sections will provide us accurate quantitative information about the properties of nuclear matter and about the reaction mechanism.

The authors thank *Miklós Gyulassy* for suggesting the present theoretical analysis.

VI. Appendix

Here we present shortly the evaporational model and the calculation of the correlation function based on it.

At the break up moment in each point $\boldsymbol{r}$ the fluid is moving with the local collective velocity $\boldsymbol{v}(\boldsymbol{r})$, ($\beta_r = \boldsymbol{v}(\boldsymbol{r})/c$, in the followings the $c \equiv 1$ convention will be used). The thermally equilibrated nucleon distributions $f(\boldsymbol{p},\boldsymbol{r})$ (normalized to the particle densities as: $n(\boldsymbol{r}) = \int d^3p\, f(\boldsymbol{p},\boldsymbol{r})$) should be transformed to the lab system by a *Lorentz* transformation from each fluid cell:

$$ {}^1F_H(\boldsymbol{P},\boldsymbol{r}) = {}^1F_H^{lab}(\boldsymbol{P},\boldsymbol{r}) = [w_r(\boldsymbol{P},W)/W]\; f^{cell}(\boldsymbol{p}_r(\boldsymbol{P},W),\boldsymbol{r}) \;, \tag{8} $$

where $\boldsymbol{p}_r, w_r$ $(\boldsymbol{P},W)$ are rest frame (lab) four momenta respectively. (The experimental observables are $\boldsymbol{P}$, and W, the corresponding cell four momenta are depending not only on $\boldsymbol{P}$, and W but also on $\boldsymbol{r}$.) They are connected by the relations:

$$ w_r(\boldsymbol{P},W) = \gamma_r(W - \beta_r \boldsymbol{P}),\; \boldsymbol{p}_r(\boldsymbol{P},W) = \boldsymbol{P} - \gamma_r\beta_r(w_r + W)/(1+\gamma_r),\; \gamma_r = 1/\sqrt{1-\beta_r^2}. \tag{9} $$

The local momentum distributions $f^{cell}(\boldsymbol{p},\boldsymbol{r})$ in the rest frame of the matter were approximated in the following way: As in refs.[4,20] the free nucleons were taken into account only. For these a relativistic *Fermi - Dirac* momentum distribution $f^{cell}(\boldsymbol{p},\boldsymbol{r})$ was applied. This was then shifted down in energy by the local binding (obtained at the break up from the long range potentials and the equation of state used in the fluid dynamical model) and only those nucleons were allowed to evaporate which had positive energy in this distribution (15-40%). The differential cross section

$$ d\sigma/d\boldsymbol{P} \equiv {}^1\sigma(\boldsymbol{P}) = \int d^2b\, d^3r\, {}^1F_H(\boldsymbol{P},\boldsymbol{r}) \tag{10} $$

is obtained by adding up the contributions of all fluid cells i in the lab system[19] and then summing up the results of the different impact parameter

calculations weighted by the corresponding geometrical surfaces. Changing the variables of the cross section from the momentum to energy and angles we write the triple- differential cross section at a fixed impact parameter as:

$$d^3N/dEd\Phi d\cos\theta \equiv {}^1\omega(\theta,\Phi,E,b) = \Sigma_i \, Vol_i \, w_i(P,W)\sqrt{W^2-m^2} \, f_i^{cell}(p_i(P,W)),$$

$$\text{where} \quad {}^1\omega = {}^1\sigma(P) \, [d^3P/dEd\Phi d\cos\theta] = {}^1\sigma(P(E,\theta,\Phi)) \, W/\sqrt{W^2-m^2}, \quad E = W-m, \tag{11}$$

the spatial integration in eq. (10) is replaced by the sum over the fluid cells i having the volume Vol_i, and the *Lorentz* transformation is applied (eq. (8-9)). The triple differential cross section obtained with normal equation of state[4] (i.e. without phase transition) provides a peak in the impact parameter sensitivity of th telescopes R,U,D at b = 4 ± 1.4 fm (Fig. 5),

$$R \; (= U = D) = \int R'(b) \, d^2b = \int {}^1\omega(\theta=40^0,\Phi,\varepsilon\geq 200\text{MeV},b) \, d\Phi \, d\varepsilon \, d^2b \tag{12}$$

and this peak is about two times as sharp as it would be expected in the fireball model[25]. At this impact parameter the deflection angle is $\theta \simeq 48^0$ in the c.m. system and ~25% of the collective projectile and target momenta are lost. According to eq.(5-6) and considering the experimental restrictions we can evaluate the coincidence rate between the telescope R (U,D) and spectrometer S, $\delta=180^0$ (in the case of U and D telescopes $\delta=90^0,270^0$ respectively):

$$[S(y_\parallel,y_T)\bullet R] = \int {}^1\omega(\theta^2=40^0,\Phi^2,\varepsilon^2\geq 200\text{MeV},b) \; {}^1\omega(y_\parallel,y_T,\Phi^2+\delta,b) \, d\Phi^2 d\varepsilon^2 d^2b. \tag{13}$$

Using the quantities (12-13) the correlation function C can be evaluated by eq.(1).

References

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1.) S. Nagamiya, L.A. Anderson, W. Bruckner, O. Chamberlain, M.C. Lemaire, S. Schnetzer, G. Shapiro, H. Steiner, I. Tanihata, Phys. Lett. 81B (1979) 147; I. Tanihata, M.-C. Lemaire, S. Nagamiya, S. Schnetzer; Phys. Lett. 97B (1980) 363.

2.) J. Knoll, J. Randrup, Phys. Lett. 103B (1981) 264.

3.) L.P. Csernai, W. Greiner, Phys. Lett. 99B (1981) 85

4.) H. Stöcker, J.Maruhn, W. Greiner, Phys.Rev. Lett. 44 (1980) 725 and Z. Phys. A293 (1979) 173; H. Stöcker, L.P. Csernai, G. Graebner, G. Buchwald, H. Kruse, R.Y. Cusson, J.A. Maruhn, W. Greiner, Lawrence Berkeley Laboratory Report No. LBL-11774 (1981) Submitted to Phys. Rev. C

5.) H.G. Baumgardt, J.U. Schott, Y. Sakamoto, E. Schopper, H. Stöcker, J. Hofmann, W. Scheid, W. Greiner, Z. Phys. A273 (1975) 359 and J. Hofmann, H. Stöcker, U. Heinz, W.Scheid, W. Greiner; Phys. Rev. Lett. 36 (1976) 88.

6.) H.G. Baumgardt, E. Schopper, J. Phys. Lett. G5 (1979) L231.

7.) R. Stock, H.H. Gutbrod, W.G. Meyer, A.M. Poskanzer, A. Sandoval, J. Gosset, C.H. King, G. King, Ch. Lukner, Nguyen Van Sen, G.D. Westfall, K.L. Wolf, Phys. Rev. Lett. 44 (1980) 1243.

8.) H.H. Gutbrod, Lawrence Berkeley Laboratory Rep. LBL-11123(1980) Proc. of Symp. on High Energy Nuclear Int. Hakone, Japan ed.: K.Nakai July, 1980 p. 93

9.) A.A. Amsden, G.F.Bertsch, F.H. Harlow, J.R. Nix, Phys. Rev. Lett. 35 (1975) 905 and A.A. Amsden, F.H. Harlow, J.R. Nix, Phys.Rev. C15(1977)2059 and A.A. Amsden, A.S.Goldhaber, F.H. Harlow, J.R. Nix, Phys. Rev. C17 (1978) 2080.

10.) Spherical[11] and axial symmetric[12] models are not able to predict this phenomenon.

11.) J.P. Bondorf, S.Garpmann, J.Zim'anyi, Nucl.Phys. A296 (1978) 320 and L.P. Csernai, B.Luk'acs,J.Zim'anyi, Nuovo Cim.Lett. 27(1980) 111

12.) P. Danielewicz, Nucl. Phys. A314 (1979) 465 and H.H. Tang, C.Y. Wong, Phys.Rev. C21 (1980) 1846.

13.) W.G. Meyer, H.H. Gutbrod, Ch. Lukner, A. Sandoval, Phys. Rev. C22 (1980) 179.

14.) I. Tanihata, S. Nagamiya, S. Schnetzer, H. Steiner, Phys. Lett. 100B (1981) 121.; J.D. Stevenson, J. Martins, P.B. Price, Phys. Rev. Lett. 47 (1981) 990.

15.) I. Tanihata, Lawrence Berkeley Laboratory Report No. LBL- 11320 (1980)

16.) J. Knoll, Phys. Rev. C20 (1979) 773 and Nucl. Phys. A343 (1980) 511; J. Knoll, J. Randrup, Nucl.Phys. A324 (1979) 445.

17.) J.Cugnon, T.Mizutani, J.Vermeulen, Nucl.Phys. A352 (1981) 505; J.Cugnon, S.E. Koonin, Nucl.Phys. A355 (1981) 477; J.Cugnon, J. Knoll,J. Randrup, Nucl.Phys. A360 (1981) 444.

18.) A.R. Bodmer, C.N. Panos, A.D. MacKellar, Phys. Rev. C22 (1980) 1025.

19.) L.P. Csernai, H.W. Barz, Z. Phys. A296 (1980) 173.

20.) G. Buchwald, L.P. Csernai, J.Maruhn, W. Greiner, H. Stöcker, Phys. Rev. C24 (1981) 135.

21.) M. Gyulassy, Lawrence Berkeley Laboratory Rep. No. LBL- 12389 (1981) submitted to Phys. Rev. Letters

22.) Without the thermal evaporation the flow velocity distribution[4] alone would yield a too strong correlation.

23.) H.W. Barz, L.P. Csernai, W. Greiner, University of Frankfurt Report No. UFTP - 62 / 1981, submitted to Phys. Rev. C

24.) M. Gyulassy, W. Greiner, Ann. Phys. 109 (1977) 485

25.) J. Gosset, H.H. Gutbrod, W.G. Meyer, A.M. Poskanzer, A. Sandoval, R. Stock, G. Westfall, Phys. Rev. C16 (1977) 629

Figure Captions

Figure 1) Contour plot of correlation function (eq.(1)) C for Ar + Pb at 800 MeV/A projectile energy. P and T indicate projectile and target momenta per nucleon, respectively, in the nucleon nucleon (n-n) c.m. frame. The dashed circle indicates the free proton elastic scattering kinematics, the cross hatched area shows the kinematical region of protons detected by the R telescope, and the point A the expected position of the quasi elastic n-n knock-out peak. The dashed-dotted circles indicate the collective nucleus nucleus (N-N) scattering kinematics. The maximum is obtained experimentally where it is expected in the collective N-N kinematics (B)

Figure 2) (a) Contour plot of the correlation function C measured in the reaction Ar (800 MeV/A) + Pb and shown on the rapidity plane. The relatively high maximum ($C \geq 1.4$) in the vicinity of the target rapidity means that strong inplane correlation is found, but not at the point where it is expected on the basis of nucleon-nucleon quasi elastic scattering.

(b) Contour plot of the correlation function C for the same reaction calculated in the joint hydrodynamical and linear cascade model. The difference in the normalization might be due to the normalization error $\Delta C \approx 0.1$-0.3 of the experiment (see Sect. II).

(c) Contour plot of the correlation function C for the same reaction calculated in the linear cascade model. Statistical fluctuations are eliminated by Gaussian smooting. At the high rapidity values (hatched area) The statistical error is $\Delta C \geq 0.2$.

(d) Contour plot of the correlation function C for the same reaction calculated in the hydrodynamical model with a simple parabolic equation of state[4,20] (K=200 MeV)

Figure 3) Contour plot of the triple differential invariant cross section $(1/p)d^3N/dEd\Phi d\cos\theta$ for the reaction Ar(800 MeV/A) + Pb at impact parameter b = 4 fm in the reaction plane ($\Phi = 0^0/180^0$) calculated in the hydrodynamical model. The contour lines labelled by parameter q are corresponding to a value of $10^q/(\text{sr MeV}^2)$ The dashed lines indicate the kinematical region where protons are detected by the counter telescopes R,U, and D in the experiment described above (see ref.[1] and chapter II). The points T and P show the target and projectile evaporation peaks, the telescopes are predomonantly sensitive for projectile evaporation according to the model

Figure 4) The dependence of the c.m. bounce off deflection angle and inelasticity on the impact parameter b. At impact parameter of b = 4 fm, the bounce off angle is $\theta \approx 48^0$ and 25% of the c.m. collective momentum is lost. At impact parameters lower than 3 fm the second local maximum of the spectrum vanishes and the inelasticity can-not be uniquely determined, but the bounce off angle is measurable

Figure 5) The impact parameter dependence of the sensitivity of telescopes R(b), (U(b), D(b)) in the hydrodynamical model (as given in eq.(12)).

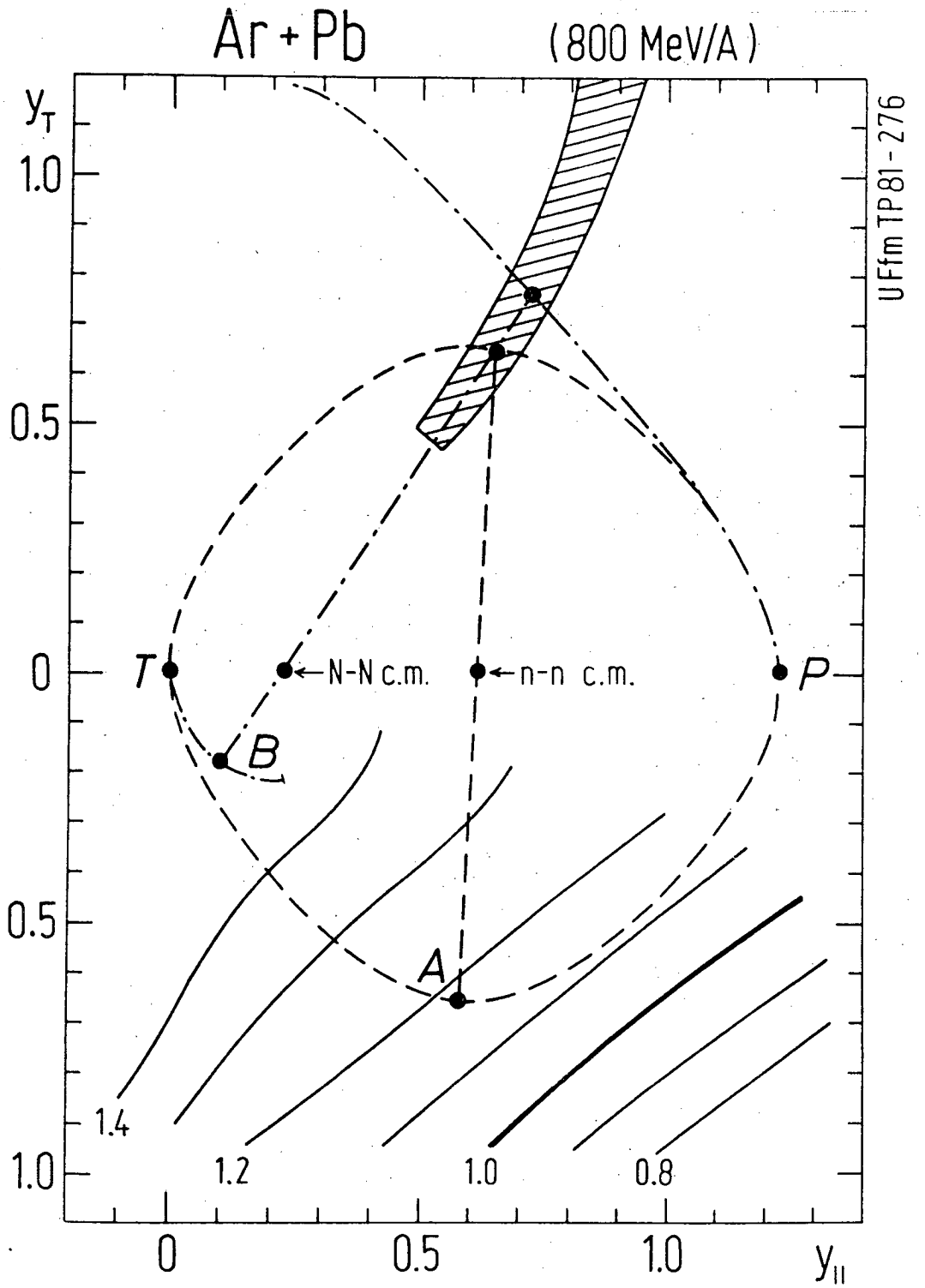

Ar + Pb
(800 MeV/A)
UFfm TP 81 - 276
y_T
1.0
0.5
0
0.5
1.0
T
N-N c.m.
n-n c.m.
P
B
A
1.4
1.2
1.0
0.8
0
0.5
1.0
$y_{\parallel}$

Figure 1

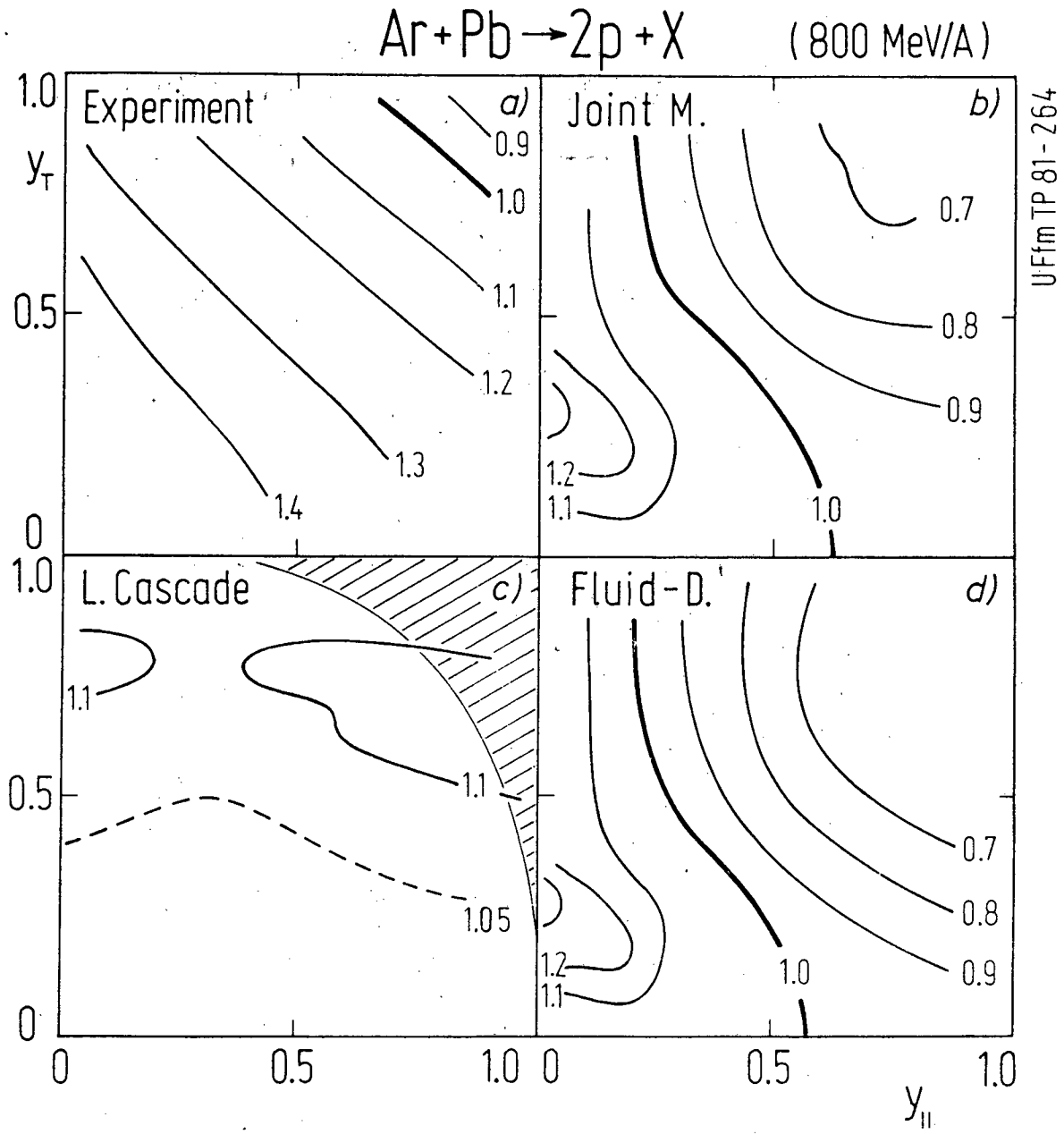

Ar+Pb→2p+X
(800 MeV/A)
Experiment
a)
0.9
1.0
1.1
1.2
1.3
1.4
Joint M.
b)
0.7
0.8
0.9
1.2
1.1
1.0
L. Cascade
c)
1.1
1.1
1.05
Fluid-D.
d)
0.7
0.8
0.9
1.2
1.1
1.0
y_T
$y_{\parallel}$
0
0.5
1.0
UFfm TP 81-264

Figure 2

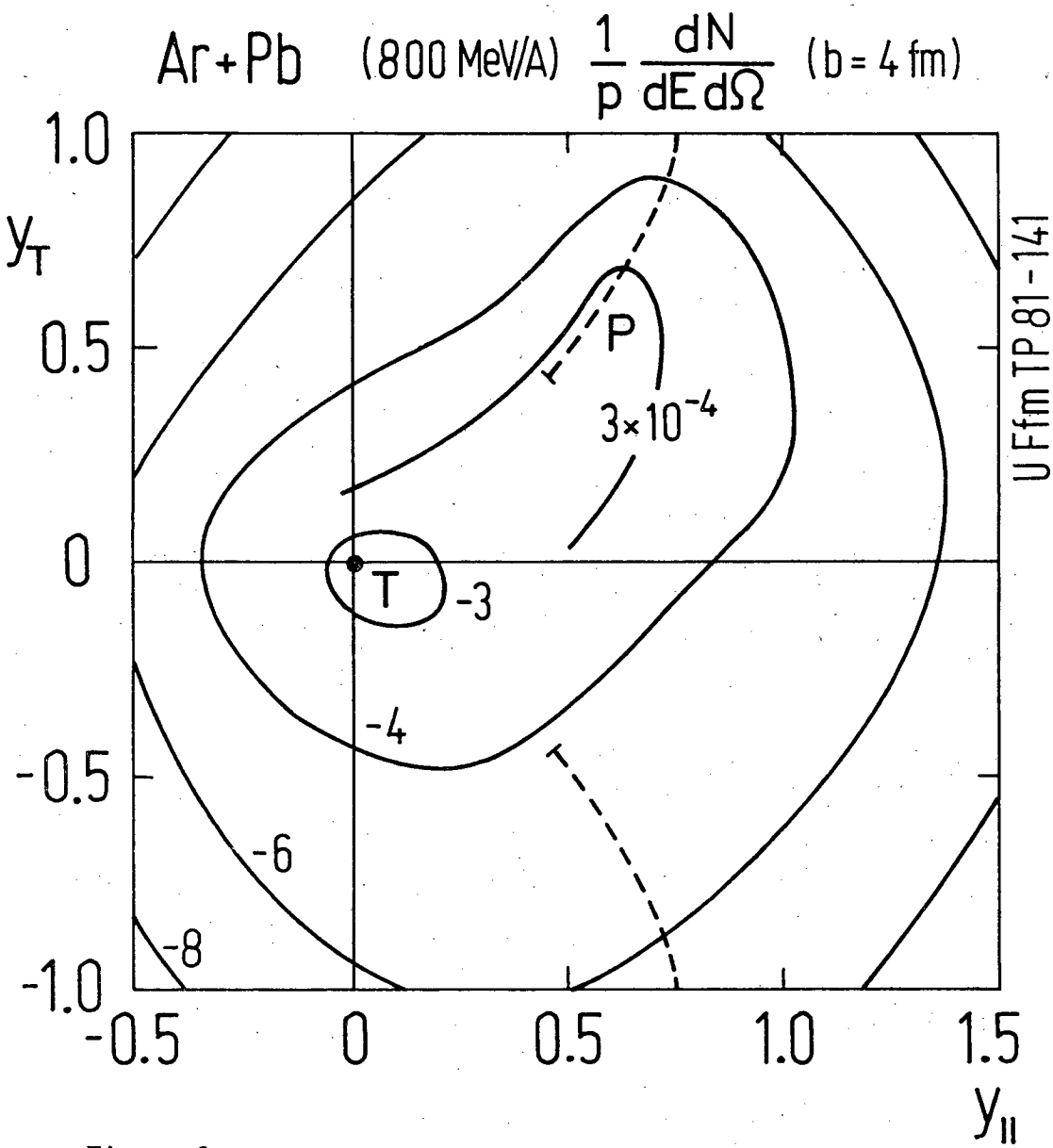

Ar+Pb (800 MeV/A) $\frac{1}{p}\frac{dN}{dE\,d\Omega}$ (b = 4 fm)
1.0
0.5
0
-0.5
-1.0
y_T
-0.5
0
0.5
1.0
1.5
$y_{\parallel}$
P
T
3×10^{-4}
-3
-4
-6
-8
UFfm TP 81-141

Figure 3

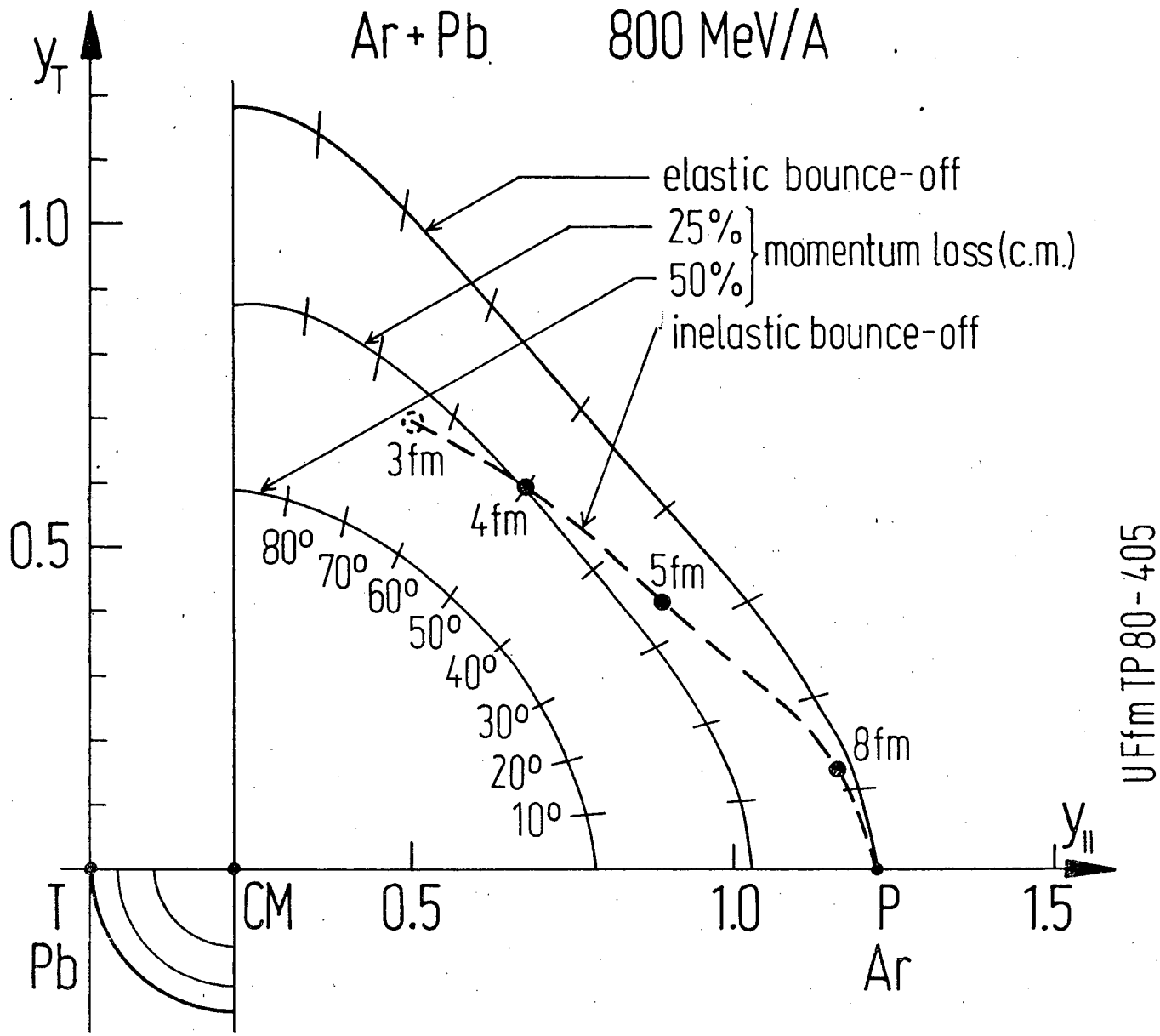
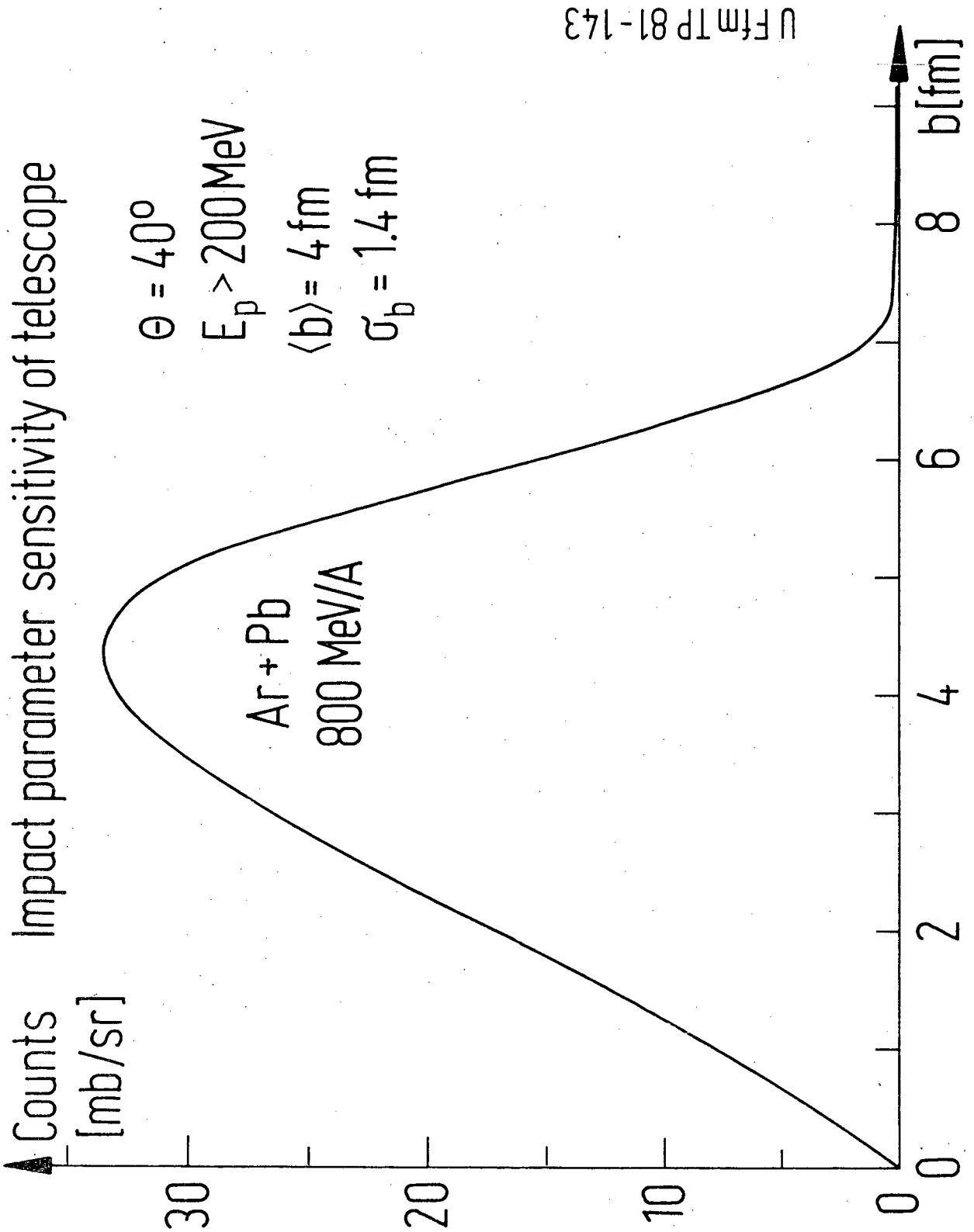

Ar + Pb
800 MeV/A
y_T
1.0
0.5
elastic bounce-off
25%
50%
momentum loss (c.m.)
inelastic bounce-off
3fm
4fm
5fm
8fm
80°
70°
60°
50°
40°
30°
20°
10°
$y_{\parallel}$
T
Pb
CM
0.5
1.0
P
Ar
1.5
UFfm TP 80-405

Figure 4



UFfmTP 81-143

Figure 5

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