LIGHT PARTICLE CORRELATIONS with HEAVY ION COLLISIONS : Space- Time ambiguities .

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Abstract : We emphasize the importance of disentangling time and spatial effects for the quantitative interpretation of particle correlations in the domain of heavy ion collisions at intermediate energies . Several methods dealing with directional selections and complementary measurements of sizes using high granularity 4 detectors are presented . Unlike particle correlations are also shown to give access to the time ordering of emission between different particles . Thus particle correlations are providing detailed and invaluable information for a theoretical understanding of nucleus collision processes .

1. The H-B.T. effect and Nuclear Physics

The discovery of a two-particle interferometry effect in astronomy by Hanbury-Brown and Twiss[1]("HBT effect") took place in 1954. The corresponding quantum effect was discovered in 1959 by Goldhaber[2]et al through the observation of an enhanced probability for identical pions emitted at small relative momenta. This was later interpreted as a result of Bose-Einstein statistics leading to a preference of bosons for a same quantum-state occupation. The real story of interferometry in nuclear physics only started later on with the theoretical papers of Kopylov and Podgoretsky[3]and Koonin[4] where formulations of correlation- functions were discussed in the frame of nuclear collisions

together with the influence of final state interactions . Interferometry is interesting in nuclear physics provided it can help determining spatial and time extents of the emitting source(s) . However , although significant results , regarding the dynamics of heavy- ion collisions , have been brought using this technique , still , many open questions remain , related to the ambiguities and difficulties to disentangle between space and time characteristics of emission .Distinctive features with the genuine HBT method can help to characterize these specific difficulties. In HBT , a space-time correlation is measured in the detector space which can be related after an averaging over time to the energy-momentum picture of the stellar source and then , using its dependence with the angular size to its transverse size. This can be understood by noticing that the two detected photons belong to overlapping energy wave-packets resulting from a superposition field. In other words, the intensity fluctuations are correlated as long as they correspond to two quanta belonging to the same quantum cell and representing the degree of coherence of the light. In nuclear physics correlations, the squared amplitude of the symmetrized two-particle wave function is averaged over the energy-momentum difference of the two detected particles. Through the resulting Fourier transform , the correlation contains a direct dependence on the (conjugate variable) spatial-size extension of the source.

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Another distinctive feature of the nuclear physics domain is the dynamical evolution of the source resulting from the collision process : a large variety of successive emitting scenarios will take place while the source evolves . Then , additional space-velocity correlations are likely to appear which have to be taken out by appropriate detection and/or analysis selections. In addition , their interpretation will have to rely on some model descriptions: transport theories[5] using the time evolution of the one- body phase space Wigner density are presently able to simulate the global features of heavy ion collisions but still suffer from the lack of a correct description of the whole quantum nature of hadron systems based on two - body correlations .

For energetic reasons , most of the available measurements in heavy- ion collisions at intermediate energy have been made with baryons (mainly protons) ; thus , the original quantum effect is affected with additional final state interactions which can play a major role if space- time relative separations are small enough . Only photon- photon and low energy neutron- neutron correlations can avoid this situation and will be presented separately.

1.1. Photon - Photon correlations :

More than 40 years after the discovery of the H.B.T. effect (see ref 1), very few investigations have been made in nuclear physics using the photon probe. Photons don't suffer the final state interactions or re-absorption and appear as an ideal probe .In the heavy-ion intermediate energy domain, it has been well established from different experimental features and B.U.U. calculations that the photon spectrum above the Giant Resonances mainly originates from the incoherent superposition of bremsstrahlung radiation emitted in first-chance individual n-p collisions. Only recently the difficulty to identify photons, among the hadronic and meson-decay background, could be overcome with the unique performances of new electromagnetic calorimeters like TAPS[6] or MEDEA[7]. Two experiments were performed at GANIL. In the TAPS collaboration[8] , two systems were studied : the 86Kr + Ni collision at 60 AMeV and Ta + Au at 40 AMeV. In a Qinv representation and after a simulation of the 0 decay ,a rise observed below 50 MeV for the lighter system has been attributed to the expected interference (with R rms-equiv.= 15 fm). Thus for the first time, the true HBT effect is revealed in nuclear physics. A new interesting interpretation of the oscillatory structure observed for the heavier system has been proposed by Schutz and Marques where they consider density oscillations of the di-nuclear system where bremsstrahlung photons originate from two successive compression phases. Another experiment[9] was carried out at GANIL using the MEDEA detector. The systems 36Ar + Al , Sn ,Au were studied at 95 A.MeV. In order to extract the spatial and lifetime information, both relative momentum qrel and qo correlations have been studied leading to size and time determinations : Rrms = 1.4 fm ;t = 2.0 fm/c for the Al target ; Rrms = 3.0 fm ;t = 6.3 fm/c for the Sn target ; Rrms = 3.8 fm ;t = 9.9 fm/c for the Au target. These low values are found by the authors compatible with the first-chance collision picture for photon production , as indicated for instance by the

comparison of the Rrms with the two- nuclei overlap zone as calculated from the geometrical estimation of the number of the participant nucleons .

1.2 1. Neutron Correlations:

The neutron-neutron correlations measurement is a very difficult experiment but a very attractive tool to exploit quantum-statistical interference effects. Indeed, the absence of Coulomb interaction plus the lowering of interactions between neutrons widely separately in an evaporative nuclear process were for instance exploited in the work of Dunnweber[10] . In the case of neutron correlations observed in the O + Mg collisions at low energy, the average distance between two successive neutrons is estimated around 100 fm, much larger than the singlet S-wave scattering length ($\sim$ 16 fm). The authors observed a dip in the correlation function at a time (or energy) difference corresponding to ECM=0 in the source rest-frame which they proposed to correspond to a quantum effect . From the observed width, and comparison with the quantum description of Kopylov an average lifetime has been deduced : t = 6 x 10-21 s.

The study of the O + Ni nn + X collision at 96 MeV by Gentner[11] allowed to observe a similar anti-correlation from which a lifetime was determined : t = 1.2 x 10-20 s in agreement with an evaporative simulation of the excited compound-nucleus. Conversely, positive correlations have been observed at higher energies[12],[13] which reflect the increasing effects of final state interactions negligible at low energy as compared to Coulomb effects. These results are not reproducible by usual transport theories. Cross-talk rejection methods are of crucial importance for such correlation measurements . New ways of analysis have been more recently presented by A. Galonsky et al[14] for the Ar + Ho system at 25 A.MeV , and J. Pluta et al[15] for the Ar+ Au system at 60 A.MeV , using a new rejection method based on time-of-flight and energy kinematical conditions between two successive neutron layers . Kinetic energy selections as well as comparisons with statistical evaporation model allowed to observe the contribution of a pre- equilibrium (short lifetime) component and measure evaporative lifetimes. Thus the richness of neutron- neutron correlations to investigate space-time characteristics of heavy-ion collisions appears now very promising. One should also notice that they can provide unique investigation of the actual HBT effect with fermionic systems where coherent effects are absent.

The neutron-proton system appears as another interesting case for correlation studies[16][17][18] since there are no more antisymmetrization nor Coulomb effects. This also allows the study of the production of the d* singlet n-p state

2.Proton - Proton correlations

2.1 2. Dynamical features of baryon correlations

Most of the available measurements in the intermediate energy domain have been made with baryons for energy consideration reasons ; thus , the original quantum effect may be affected by additional final state interactions which can play a major role if space- time separations are small enough . Among determinant factors are the excitation energy which can drive the emission time , the observation C.M. angle which can trigger different origins among successive

emission sequences . For energies of tens MeV per nucleon, i.e. around the Fermi energy, the energy relaxation is characterized by a competition between one and two-body potential effects. Two-body effects will result in fast pre-equilibrium emission of particles resulting in short timescales (t < 50 fm/c) characteristics ; whereas for one-body dominated regimes, the complete or locally relaxed degrees of freedom will produce thermalized or pre-thermalized emission. For thermal excitation at temperatures T<5 MeV of, the emission times are estimated larger than a few hundreds fm/c. Here, the Coulomb interaction and Pauli principles should dominate again like in the previous low energy domain. An interesting challenge for two-particle correlations is then to follow subsequent evolution of the correlation patterns between these two extreme regimes in order to provide information on collision dynamics and characterize prevailing dissipative regimes. A crucial point to interpret the results is our ability to describe theoretically the time evolution of the source : the time dependence of the phase-space Wigner density has been studied, for heavy-ion collisions, in the frame of various one-body or N-body transport theories(see ref. 5) .

In the first experimental studies[19] ,a peak was indeed observed at q $\sim$ 20 Mev, attributed to the interplay between the short range attractive S-wave interaction, the long range Coulomb repulsion and the Pauli principle. Its height was related to the source dimension . But because of time averaging effects, one should be extremely careful in drawing quantitative conclusions. Non-equilibrium emission will, for instance, result in short time scales for particle emission causing the nuclear interaction to dominate the correlation pattern and reflect the spatial dimension of the source. Conversely, in the case of compound nuclei formation and equilibrium emission, the average distance between two successive emissions is larger : the Coulomb interaction and Pauli principle will dominate with a sensitivity to the emission rate and thus to the thermal energy of the emitting nucleus. This feature is very clearly observed in low energy experiments (see for ex.[20]). In those cases , 3-body Coulomb trajectories can account for most of the correlation patterns and demonstrate the feasibility and the limitations of compound-nucleus lifetimes determinations using light particule correlations.

For energies of tens MeV per nucleon, several cuts in particule momentum , impact parameter, geometry or relative directions of emission have been usually proposed in order to provide information on collision dynamics and characterize prevailing dissipative regimes.. We refer the reader to the existing literature (see for instance ref [21]) between 30 and 200 A.MeV for detailed description . The results can be summarized by saying that , up to a very recent time, and in spite of clear qualitative distinctions , many ambiguities remain in evaluating quantitatively the average time durations (often set to fixed or negligible values) and their real influence in the observed correlation patterns . Most of these uncertainties originate from the failure of transport theories to describe all dynamical aspects associated with particle production : sequential decays (produced by unstable fragments) , reliable description of two - body processes in

nuclear matter (and their relation with the production preequilibrium emission) . These observations stress the necessity of model - independent and reliable emission time measurements in this energy domain .

2.2 Emission - Time determinations : directional selections and 4 detector methods

It has been proposed by Pratt et al[22] that an elongated phase-space distribution, as predicted for long-lived emission sources can lead through phase space constraints to the emission time dependence of the correlation-function on the direction of the relative momentum. When constructing such correlations in the frame of the emitting source , a clear dependence has been observed for pp[23] and nn[24]measurements . From a contour-plot-of $\chi 2$ as a function of R and τ quantities for longitudinal and transverse correlations, a set of (R, t) values has extracted for the source characteristics. Although containing some model dependent ingredients , the use of these directional dependences opens promising possibilities of probing the space-time characteristics of heavy-ion collisions .

The availability of a new generation of 4 high granularity detectors, like INDRA at GANIL, offers very attractive alternative possibilities . Indeed , from an event - by - event reconstruction of the momentum ellipsoid , it is possible to determine directly the source characteristics . For instance , a separation of particles emitted by the forward (projectile- like) source can be made and related to the size of the emitting source after some density assumption . This has been performed for the Xe + Sn reaction at 50 A. MeV[25](Collaboration with D. Gourio and the INDRA collaboration) . The measured correlations have been fitted using a quantum final state interaction model [26] with source characterizations (size , temperature) deduced from the above approach and the observed energy spectra . As a consequence and for the first time , only the time duration of the source remains as a parameter which can determined by fitting the correlations . Figures 1 and 2 show the results obtained for protons and deuterons with three ranges of impact parameters resulting of a transverse energy selection . The calculations (with normal density assumptions) indicate two interesting features : first , a very little evolution with impact parameter in the case of protons ; secondly very short times for all the cases . Values like 80 fm/c are smaller (or of the order) of the estimated separation time of the two interacting nuclei . Even smaller values would be obtained with lower density assumptions associated with the creation of a more diluted system . Complementary observations of the proton correlations originating from a mid rapidity selected zone (instead of projectile region) have also indicated an angular anisotropy (with a minimum sitting at 90° cm) for peripheral collisions if high energy protons are selected (fig 3) . This is reminiscent of the angular distributions known for free nucleon scattering . From this new type of exclusive measurements , it can thus be postulated that an important contribution of pre-equilibrium particles , likely resulting from N-N scattering , is found over a large rapidity domain . This is supported by recent transport calculations by Eudes et al[27] where an important mid rapidity emission , taking place at the early

phase of interacting nuclei , is found for central collisions . This is also to be related to an (anti-) correlated observation of high energetic protons and energetic photons in the same domain of energy by Sapienza et al [28].

2.3 Time ordering of emission using unlike-particle correlations

It has been shown by Lednicky et al [29] that the occurrence of an anisotropy in the spatial - time distribution is reflected in the directional dependence of unlike-particle correlations and can be for instance used to measure the average delays (and their sign) between emissions of particles of different types. This sign can be determined by comparing correlation-functions R+ and R- where the sign of the scalar product $\vec{k}.\vec{v}$ is fixed > 0 or < 0 (using their relative angle) respectively. Classically, it means that the interaction of the two particles in the case where the faster particle is emitted earlier will be different as compared to the case of its later emission. It has been shown that the Coulomb field of the residual nucleus slightly affects this result.

Such predictions have been compared to experimental (p, d) correlations measured at GANIL for various collisions and energies (see ref 25 for ex.). As an example, in the case of Xe + Sn at E/A = 50 MeV, Fig. (4) shows that the ratio R+/R- is lower than unity : this evolution is attributed to an averaged deuteron emission earlier than the proton emission. The time difference is estimated to be $\sim$ 250 fm/c according to the comparison with Lednicky's calculations. This has to be understood as the result of averaging over a long time sequence between pre-equilibrium and thermal emission for protons whereas deuterons emission resulting mainly from hard nucleon-nucleon collisions is concentrated at a few tens of fm/c. This method can be also used for higher energy problems like the possible observation of strangelets in the frame of the distillation process following the creation of a quark gluon plasma as predicted by C. Greiner et al [30] : in this case , strange and anti - strange particles may not be produced at the same time in a baryon rich system under low bag constant scenarios . Such a prediction has been tested using K+ K- correlations[31] as demonstrated in fig (5) (collaboration with S. Soff, H Stoecker ,Inst Theo. Phys. Frankfurt) .

Thus for the first time, it has been demonstrated that correlation studies, combined with geometrical selections, provide unique tools to measure the time-ordering for particle emission.

3. Conclusions:

Two particle correlations in heavy-ion collisions, have allowed in a unique way to investigate detailed aspects of the collisions process over a large variety of emission processes between equilibrated/ thermalized mechanisms. Different kinematical and directionnal constraints have documented dynamical features of interest for the modelisation of the collisions . However , independent and complementary measurements of lifetimes using either directional selections or a new generation of dedicated high granularity detectors appear very useful to determine and disentangle quantitatively between spatial and time effects . Unlike particle correlations are also able to determine the emission time ordering of different particles .Pioneering works have been also made in neutron and pho-

ton interferometry where the actual HBT effect gives a direct and undistorted measurement of spatial and time properties of the source .

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Figures captions

Fig. 1 Proton-proton correlation as a function of relative momentum for the Xe + Sn reaction . The curves indicate calculations with indicated emission times . (taken from ref. 25).

Fig. 2d-d correlations (same as fig. 1)

Fig. 3p-p correlation as a function of CM relative angle for high energetic protons in Xe+ Sn reaction. (cf ref 25)

Fig. 4(p, d) predicted correlations for R+ ($\vec{k}.\vec{v} > 0$) and R- ($\vec{k}.\vec{v} < 0$) and their ratio indicating which particle is emitted earlier.(taken from ref. 31)

Fig. 5(K+ K-) correlation ratios calculated for R+ ($\vec{k}.\vec{v} > 0$) and R- ($\vec{k}.\vec{v} < 0$)

for different bag constants scenarios indicating a way to search for the strangeness distillation process.(taken from ref 31)

Xe+Sn 50 AMeV Proton-Proton (Forward Source)

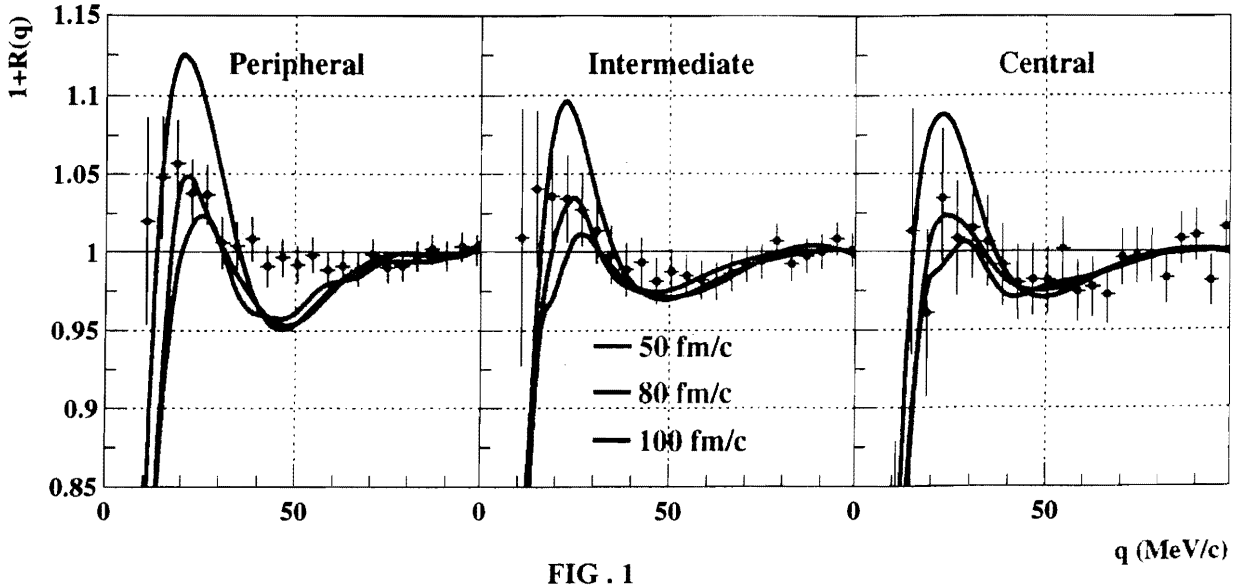


FIG . 1

Xe+Sn 50 AMeV Deuteron-Deuteron (Forward Source)

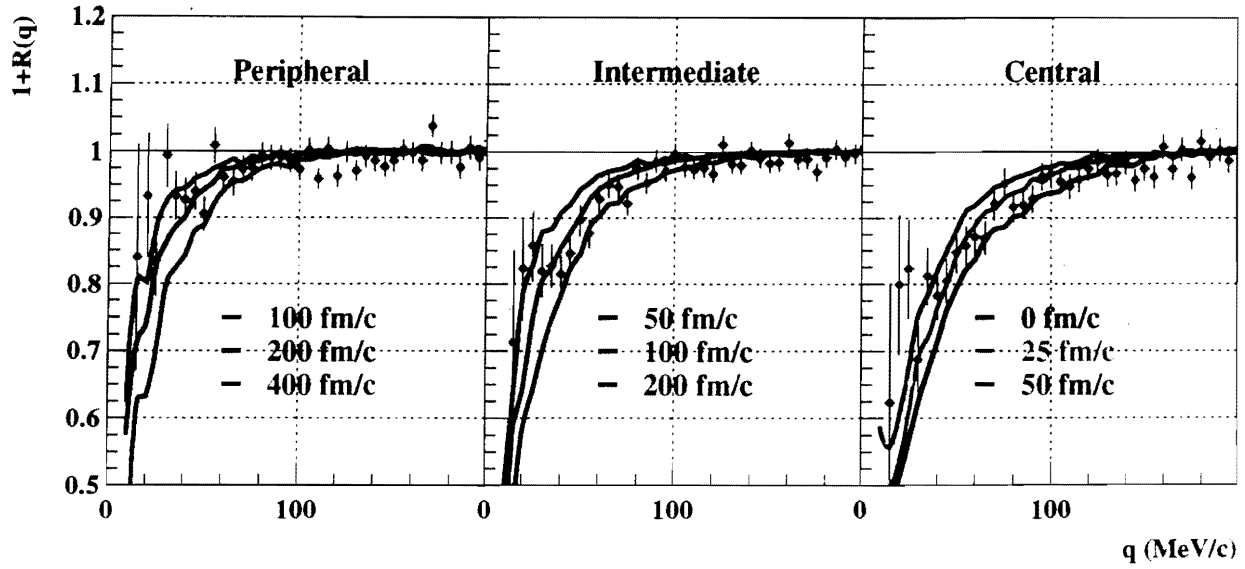
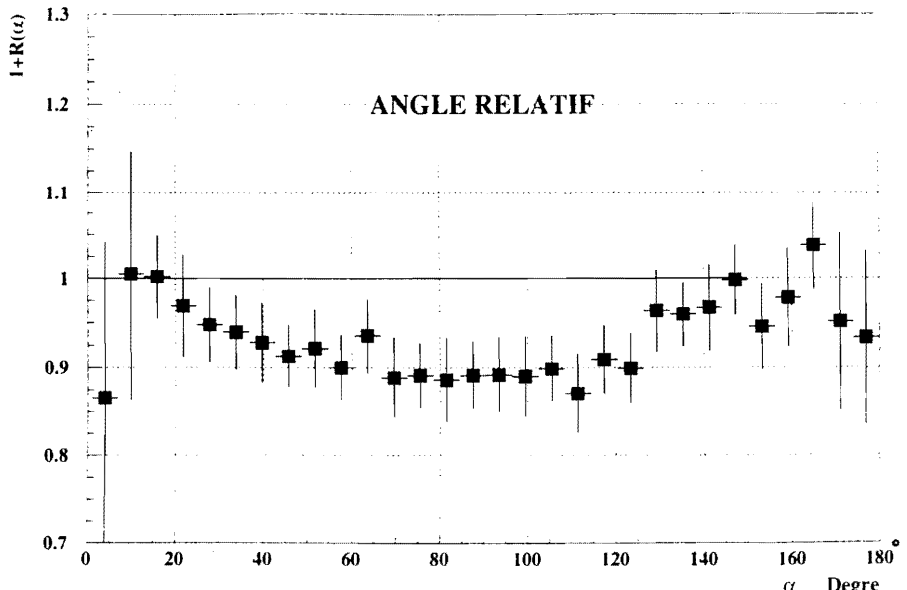


FIG.2

PP ZI : $60^o < \theta < 120^o$ (Ellips.) $E_{prot(cm)} > 20$ MeV

FIG.3



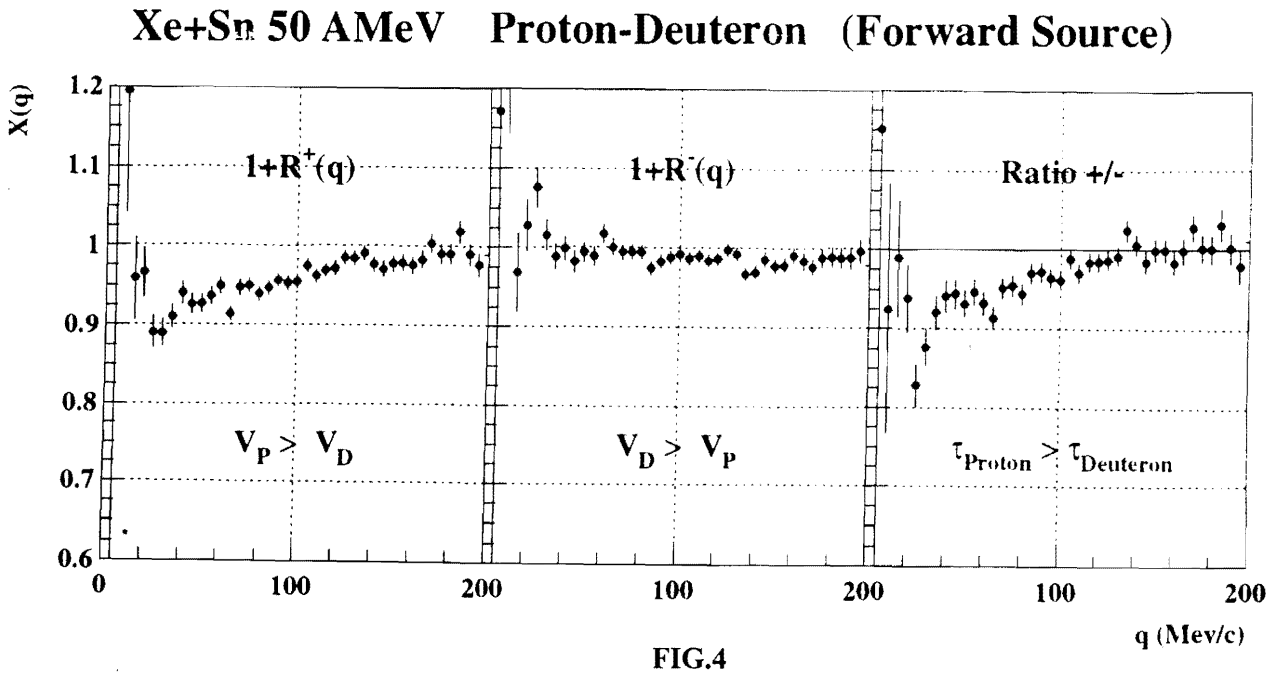

Xe+Sn 50 AMeV Proton-Deuteron (Forward Source)
X(q)
1+R+(q)
1+R-(q)
Ratio +/-
VP > VD
VD > VP
τProton > τDeuteron
q (Mev/c)

FIG.4

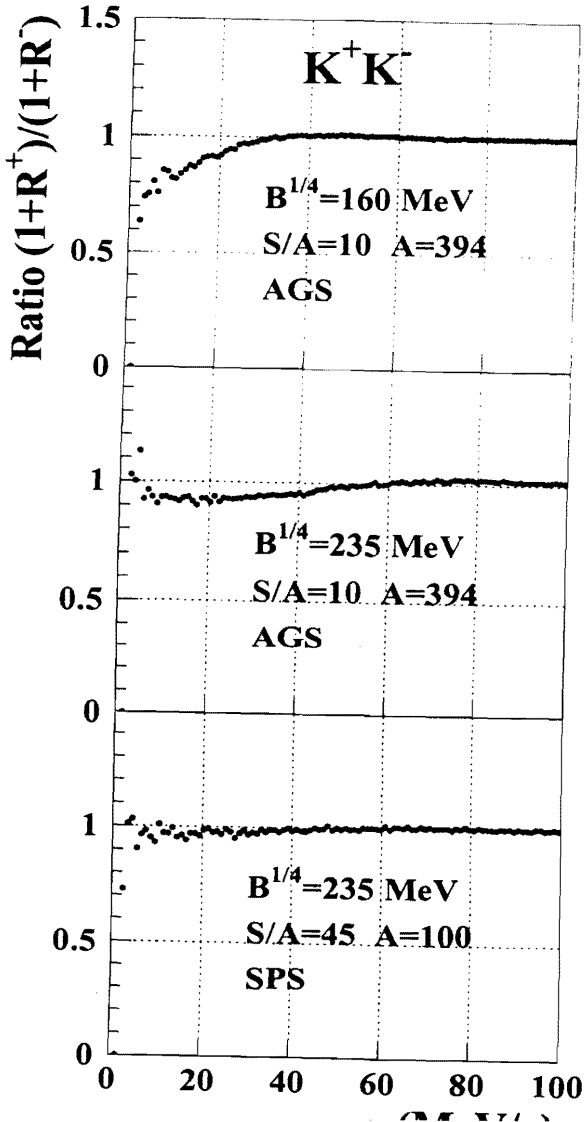

K+K-
Ratio (1+R+)/(1+R-)
B1/4=160 MeV
S/A=10 A=394
AGS
B1/4=235 MeV
S/A=10 A=394
AGS
B1/4=235 MeV
S/A=45 A=100
SPS

FIG.5