PION INTERFEROMETRY STUDIES OF RELATIVISTIC HEAVY-ION COLLISIONS USING THE INTRANUCLEAR CASCADE MODEL

Humanic, T.J.

1984-11-01

LBL-18679
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Submitted to Physical Review Letters

PION INTERFEROMETRY STUDIES OF RELATIVISTIC HEAVY-ION COLLISIONS USING THE INTRANUCLEAR CASCADE MODEL

T.J. Humanic

November 1984

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

Submitted to Physical Review Letters
PACS#'s: 24.60.-k, 13.85.Hd, 25.70.Np

LBL-18679

Pion Interferometry Studies of Relativistic Heavy-Ion Collisions Using the Intranuclear Cascade Model

T. J. Humanic

Nuclear Science Division, Lawrence Berkeley Laboratory
University of California, Berkeley, CA 94720

Abstract

A method is presented by which an intranuclear cascade (INC) model may be used to obtain pion source parameter predictions which can be directly compared with pion interferometry experiments. This method is applied with Cugnon's INC model to extract predictions for recent pion interferometry measurements, and generally good agreement is found.

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics at the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

Intranuclear cascade (INC) models have been widely used to understand various features of relativistic heavy-ion collisions. For example, they have had some success in predicting proton, pion, and kaon inclusive cross sections for laboratory bombarding energies in the range 0.4-2.1 A GeV, and for a variety of projectile-target combinations.[1-3] The basic assumption of INC models is that a relativistic heavy-ion collision can be approximated as a superposition of nuclear-nucleon interactions whose trajectories between interactions are described classically, while the interactions themselves are determined by experimental elastic and inelastic nucleon-nucleon cross sections. Because they are classical models, and the positions and momenta of all particles taking part in the cascade are known as a function of time, they also lend themselves well to understanding the geometric aspects of the collision, such as the size of the interaction region and the duration of particle production. In fact, this is just the kind of information obtained from pion interferometry measurements, where the radius, lifetime, and coherence of the pion source are extracted. Although some theoretical work has been carried out to study the geometry of the pion source with an INC model,[4,5] no study has yet been made which is directed towards understanding existing pion interferometry measurements with this model. Additional incentive is gained to perform such a study as a result of recent measurements which have become available for the systems ^{20}Ne + NaF[6] and ^{40}Ar + KCℓ[6-8]. Thus,the goal of the present work is to extract radius, lifetime, and coherence parameters from an INC model which can be directly compared with the results of these recent measurements.

The procedure for obtaining these INC model predictions consists of three steps: (a) run the INC code for the system of interest to produce a set of "final" pions (pions which suvive to the end of the calculation), recording their momenta and the space-time location where they were created; (b) impose Bose-Einstein symmetry on the pions produced in (a); and (c) form the two-pion correlation function from the symmetrized and unsymmetrized pions, and fit a Gaussian space-time pion distribution to the correlation function to extract R, τ, and λ, the radius, lifetime, and coherence parameters for the distribution.

Cugnon's CASCADE code [5,9] was used to make the INC model calculations. In this model, the Δ-isobars, which represent the mechanism for producing and absorbing pions, are given a Lorentzian mass distribution and an exponential lifetime distribution. Therefore, pions are produced and reabsorbed throughout the time of the collision. Note that CASCADE does not take isospin into account, resulting in only one kind of nucleon, pion, and Δ-isobar in the calculation. At the end of the calculation, the momentum vector of each final pion is tagged with the position and time at which its "parent" Δ-isobar decayed and then is stored for later use. Calculations were made with fixed impact parameter so that the dependence of the pion source upon this variable could be studied.

The next step is to weight the pions produced by CASCADE so that they reflect the fact that they are bosons. This is done by using the expression of Yano and Koonin[10] for the symmetrized two-pion inclusive cross section:

$$\frac{d^6\sigma}{d^3k_1 d^3k_2} = \int d^4X_1 d^4X_2 D(X_1,k_1) D(X_2,k_2) |\Psi^s_{k_1k_2}(X_1,X_2)|^2 \qquad (1)$$

where D(X,k) is the pion source distribution function which describes the production of a pion of 4-momentum k at space-time point X, and Ψ^s is the symmetrized two-pion wavefunction which, for plane waves, becomes

$$\Psi^s_{k_1k_2}(X_1,X_2) = e^{ik_1X_1} e^{ik_2X_2} + e^{ik_1X_2} e^{ik_2X_1} .$$

Gyulassy et.al.[11] have shown that in the limit appropriate for relativistic heavy ion collisions and if no dynamical correlations exist between X and k, Eq.1 follows from an exactly soluable field theoretic model, and that it is valid for collisions with $M_\pi \geq 2$, where M_π is the like-pion multiplicity. To apply Eq. 1, we identify the pion distribution produced by CASCADE in the first step with D(X,k) and, thus, randomly choose pairs of pions which are then weighted by $|\Psi^s|^2$, resulting in a list of symmetrized pion pairs.

The final step in the procedure is to form the two-pion correlation function from the symmetrized and unsymmetrized pions and to extract the R, τ, and λ predictions. The two-pion correlation function, $C(\bar{k}_1, \bar{k}_2)$, can be expressed as [12]

$$C(\bar{k}_1,\bar{k}_2) = A\,\frac{N_2(\bar{k}_1,\bar{k}_2)}{N(\bar{k}_1)N(\bar{k}_2)} \quad , \qquad (2)$$

where $\bar{k}_1$ and $\bar{k}_2$ are the pion momenta, $N_2(\bar{k}_1,\bar{k}_2)$ is the two-pion count rate, $N(\bar{k})$ is the single pion count rate, and A is a normalization constant. $N_2(\bar{k}_1,\bar{k}_2)$ and $N(\bar{k})$ are obtained directly from the lists of symmetrized pion pairs and unsymmetrized single pions, respectively, described above. The pion source parameters R, τ, and λ are extracted by fitting the correlation function (Eq.2) with a Gaussian source distribution,[10]

$$C(q,q_o) = 1 + \lambda\,\exp(-q^2R^2/2 - q_o^2\tau^2/2),$$

using the principle of maximum likelihood where $q = |\bar{k}_1\bar{k}_2|$, $q_o = |E_1 - E_2|$, and $E = \sqrt{k^2+m_\pi^2}$. It is important to note that the computer codes used to form the correlation function and to carry out the fitting are identical to the ones used by Zajc et. al.[6] and similar to those of Beavis et. al.[8] in analyzing their two-pion correlation data. This should minimize programming biases and allow the CASCADE predictions for R, τ, and λ to be directly comparable with the experimental results.

A typical CASCADE generated correlation function and its Gaussian fit, both projected onto the q-axis, are shown in Fig. 1 for the system 1.5 A GeV ^{40}Ar + ^{40}Ar. This case was run with a 4π geometry (as is the case of the streamer chamber in Ref. 8), impact parameter, b, of 2 fm, minimum center-of-mass pion momentum, k_{MIN}, of 50 MeV/c ($k_{MIN} \leq k_1, k_2$), and about 270,000 two pion pairs. Error bars reflect statistical uncertainties only. Note the prominent Bose-Einstein enhancement at small q, which is a consequence of the pion wavefunction symmetrization carried out with Eq. 1. For this example, the extracted pion source parameters are $R = 3.6 \pm 0.1$ fm, $\tau = 3.2 \pm 0.5$ fm/c, and $\lambda = 0.94 \pm 0.05$.

Comparisons between the CASCADE predictions of the present work and recent pion interferometry measurements are presented in Fig. 2. The measurements of Zajc et.al.[6] were performed with a narrow acceptance magnetic spectrometer which was set to accept pions centered about 90° in the center-of-mass with respect to the beam direction, whereas the measurements of Beavis et. al.[7,8] were performed with a streamer chamber having an almost 4π solid angle acceptance. In order to simulate, to some extent, the acceptances found in the two types of experiments, the CASCADE calculations were run with two different sets of center-of-mass windows: a) for the spectrometer experiments, $80^\circ \leq \theta \leq 100^\circ$, $0^\circ \leq \phi \leq 360^\circ$, and k_{MIN} = 150 MeV/c, and b) for the streamer chamber experiments, $0^\circ \leq \theta \leq 180^\circ$, $0^\circ \leq \phi \leq 360^\circ$, and k_{MIN} = 50 or 150 MeV/c (θ is the radial angle with respect to the beam direction, and ϕ is the azymuthal angle). In addition, all CASCADE predictions shown in Fig. 2 were run with b=2 fm. It was found that taking a weighted average over impact parameter for the system 1.5 A

GeV ^{40}Ar + ^{40}Ar resulted in a 1σ or less difference in the pion source parameters from the b=2 fm case. This was judged to give acceptable accuracy for the CASCADE predictions, given the accuracy of the experimental results.

Generally speaking, the CASCADE predictions agree rather well with the experimental results. For the Zajc et. al.[6] measurements, agreement occurs within 1σ for R and τ for both 1.8 A GeV ^{20}Ne + NaF and ^{40}Ar + KCℓ, although CASCADE cannot account for the small measured values of λ, predicting λ to be close to unity for both systems. The measurements of Beavis et. al.[7] for 1.5 A GeV ^{40}Ar + KCℓ are seen to agree with the CASCADE predictions for τ and λ, while the measured R values tend to be somewhat larger than CASCADE, both measurement and CASCADE showing a weak dependence of R on k_{MIN}. Finally, Fig. 2 shows that the Beavis et. al. measurements [8] for 1.2 A Gev ^{40}Ar + KCℓ agree with CASCADE to within 1σ for all three source parameters.

Two other predictions extracted from CASCADE for the 1.5 A Gev ^{40}Ar + ^{40}Ar system are: a) R is not significantly different for the momentum cuts $150 > k_1, k_2 > 0$ MeV/c and $k_1, k_2 > 50$ MeV/c, and b) if the pion source is fit with longitudinal and transverse (with respect to the beam axis) radius parameters, $R_{||}$ and $R_{\perp}$, in a 4π geometry, it is found that the source is nearly spherical ($R_{||} \approx R_{\perp}$). These predictions are consistant with the experimental results in Ref. 7.

Recently, Pratt[13] has derived a more general expression for the two-pion cross section than Eq. 1. This expression more correctly takes into account dynamical correlations which may occur between X and k in the pion source distribution. Equation 1 can be shown to follow from Pratt's expresion in the limit where the source distribution fucntion is uncorrelated in x and k and is sufficiently wide in momentum. Since the results from CASCADE presented above suggest that only weak x-k correlations exist for the systems under study, Eq. 1 should be a reasonable approximation for the present work.

The author wishes to thank Professor J.O. Rasmussen and Professor K.M. Crowe for their support during this work. I also wish to thank Dr. M. Gyulassy and Dr. W. Zajc for enlightening discussions, and Dr. J. Harris for providing the version of Cugnon's CASCADE code used for the calculations. This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics at the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

REFERENCES

1. Y. Yariv and Z. Fraenkel, Phys. Rev. C 20 (1979) 2227.
2. J. Cugnon and R.M. Lombard, Phys. Lett. 134B (1984) 392.
3. Y. Kitazoe et. al., Phys. Rev. C 29 (1984) 828.
4. J. Cugnon and S.E. Koonin, Nucl. Phys. A355 (1981) 477.
5. J. Cugnon et. al., Nucl. Phys,. A379 (1982) 553.
6. W.A. Zajc et.al., Phys. Rev. C 29 (1984) 2173.
7. D. Beavis et. al., Phys. Rev. C 27 (1983) 910.
8. D. Beavis et.al., Phys. Rev. C 28 (1983) 2561.
9. J. Cugnon, Phys. Rev. C 22 (1980) 1885.
10. F.B. Yano and S.E. Koonin, Phys., Lett. 78B (1978) 556.
11. M. Gyulassy et.al., Phys. Rev. C 20 (1979) 2267.
12. G.I. Kopylov, Phys. Lett.50B (1974) 472.
13. S. Pratt, Phys. Rev. Lett. 53 (1984) 1219.

FIGURE CAPTIONS

Fig. 1 Projected two-pion correlation function from CASCADE for the reaction 1.5 A GeV ^{40}Ar + ^{40}Ar, b=2 fm, k_{MIN} = 50 MeV/c

Fig. 2. Comparison between pion source parameters from CASCADE predictions and pion interferometry measurements: a) 1.8 A GeV ^{40}Ar + KCℓ and ^{20}Ne + NaF (Ref. 6); b) 1.5 A GeV ^{40}Ar + KCℓ (Ref. 7,8); and c) 1.2 A GeV ^{40}Ar + KCℓ (Ref. 8).

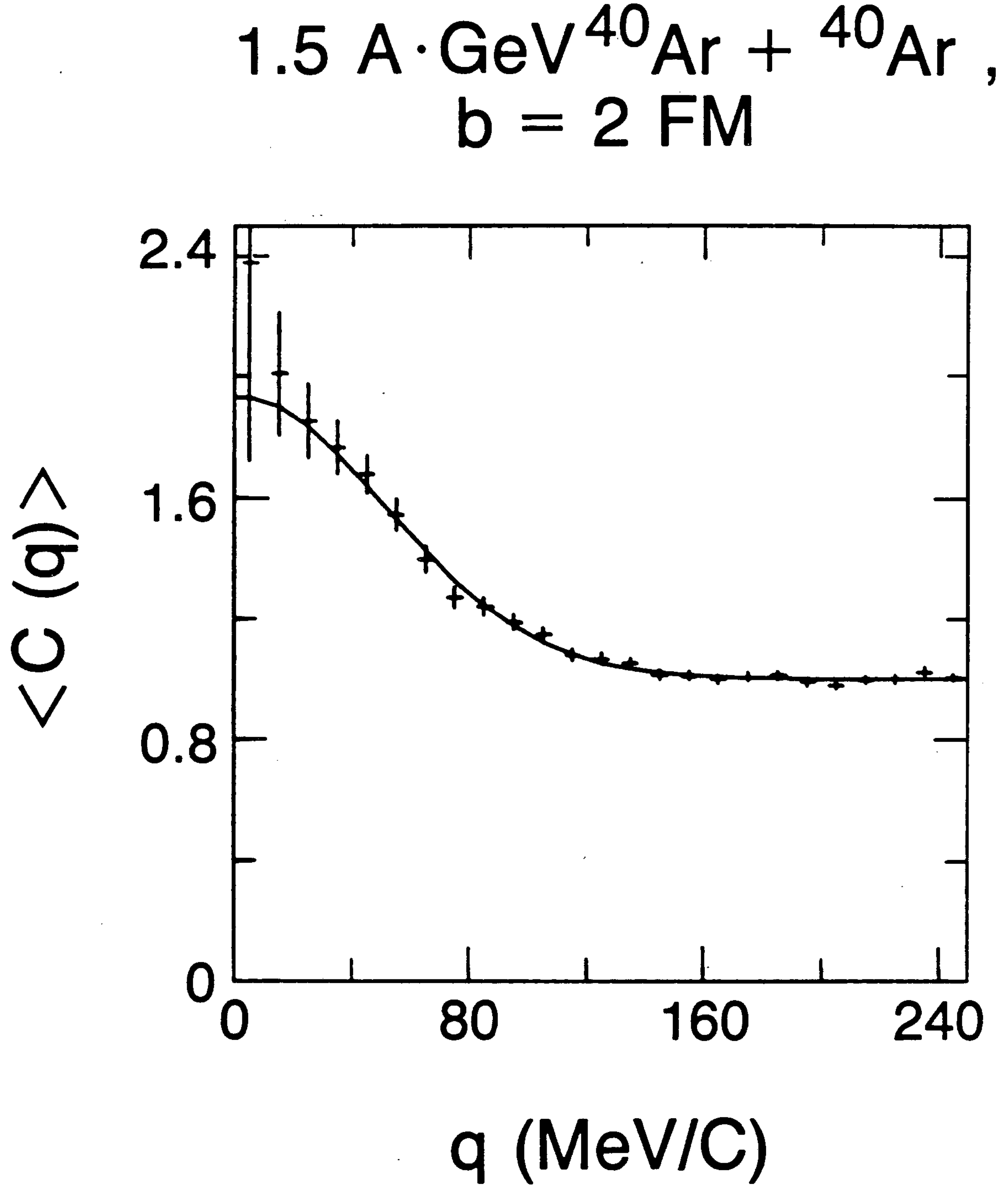

Figure 1

XBL 849-10799

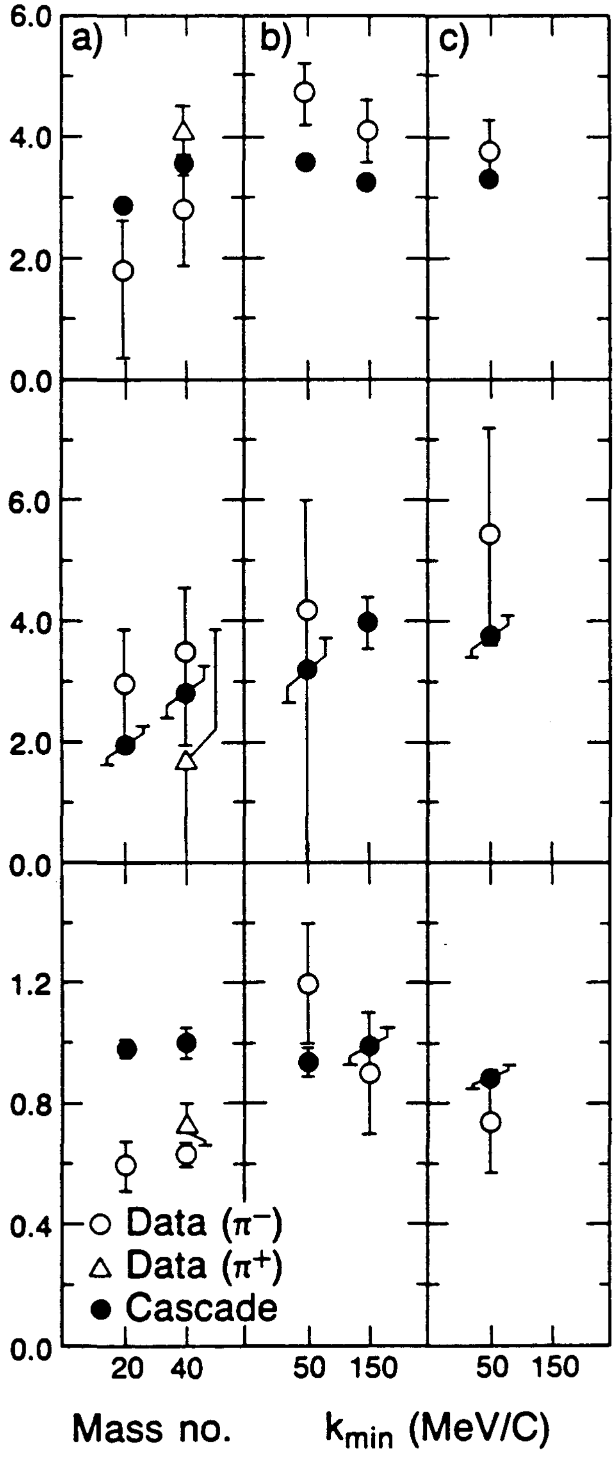

Figure 2 XBL 8410-10909

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720