It is interesting to compare this result with predictions for the ^{18}C mass in the literature. These are summarized in Table II. It may be seen that all predictions based on the transverse Garvey-Kelson formula give a mass excess which is too large by about 500–600 keV. This trend is similar to that observed in recent measurements of masses of neighboring nuclei, ^{17}C and ^{19}N. This suggests that one should recalculate the prediction of the Garvey-Kelson formula using the latest experimental values for the masses of ^{17}C [21.023(35 MeV][12] and of ^{19}N [15.810(90) MeV].[13] This gives the ^{18}C mass excess as 25.037(98) MeV, which is in excellent agreement with our new experimental result.

In summary we have successfully measured the mass of ^{18}C. ^{18}C is found to be more strongly bound than was hitherto believed, a trend similar to that found for other neutron-rich nuclei in this region. The pion double-charge-exchange reaction (π^-,π^+) has been demonstrated to be a powerful tool in the study of neutron-rich nuclei far from the valley of stability. We propose to use it for the study of other light neutron-rich nuclei in the near future.

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[1] A. A. Artukh *et al.*, Nucl. Phys. A137, 348 (1969), and A283, 350 (1977).

[2] J. D. Bowman, A. M. Poskanzer, R. G. Korteling, and G. W. Butler, Phys. Rev. C 9, 836 (1974).

[3] J. A. Nolen, private communication.

[4] T. Marks *et al.*, Phys. Rev. Lett. 38, 149 (1977); R. J. Holt *et al.*, Phys. Lett. 69B, 55 (1977).

[5] R. L. Burman *et al.*, Phys. Rev. C 17, 1774 (1978).

[6] J. Spencer, in *Proceedings of the Seventh International Conference on High Energy Physics and Nuclear Structure, Zurich, 1977,* edited by M. P. Locher (Birkhaüser-Verlag, Basel, 1977), p. 153.

[7] H. A. Thiessen *et al.*, to be published.

[8] D. E. Alburger *et al.*, private communication.

[9] At. Data Nucl. Data Tables 17, 411–608 (1976); A. H. Wapstra, private communication.

[10] N. A.Jelly, J. Cerny, D. P. Stahel, and K. H. Wilcox, Phys. Rev. C 11, 2049 (1975).

[11] C. Thibault and R. Klapisch, Phys. Rev. C 9, 793 (1974).

[12] J. A. Nolen *et al.*, Phys. Lett. 71B, 314 (1977).

[13] C. Detraz *et al.*, Phys. Rev. C 15, 1738 (1977).

Observation of Pion Interferometry in Relativistic Nuclear Collisions

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We present evidence of an intensity interferometric effect of identical pions in relativistic nuclear collisions. From the observed correlation, we determine the space-time structure of the pion-emitting source.

The principle of intensity interferometry was first developed in radio astronomy, now known as the celebrated Hanbury-Brown–Twiss effect. The idea of utilizing this second-order interferometric correlation effect of identical particles as a probe of the space-time structure of the emitting sources in particle physics has been discussed by Cocconi,[1] by Shuryak,[2] and, in much more detail, by Kopylov and Podgoretsky.[3] Fowler and Weiner[4] further emphasized that such study can also shed light on the equally interesting question of the degree of coherence of the emitting system. Experimental study has been reported recently for pp,[5] πp,[6] and πp, Kp, and $\bar{p}p$[7] systems, while an indirect manifestation of this type of effect was observed by Goldhaber *et al.*[8] as early as 1959.

The possibility of using pion interferometry for the study of relativistic nuclear collisions is particularly appealing, as emphasized recently, for example, by Gyulassy[9] and Yano and Koonin,[10] since the ideas of a pion production mechanism and pion coherence as an effective signature of the occurrence of exotic phenomena[9,11] are topics of primary interest.

We report here the first evidence of a pion interferometry effect in relativistic nuclear collisions. Our data come from a triggered-streamer-chamber experiment performed at the Lawrence Berkeley Laboratory Bevalac. The streamer chamber[12] has proven to be an effective tool in the study of relativistic nuclear collisions because of its 4π detection, capacity to be triggered, and accurate angular and momentum information content. For the pion interferometry studies, a particularly salient feature in the design of the present experiment is the thin targets ($\sim\frac{1}{8}$ in.) employed, which allow the detection of very low-energy ($\gtrsim 10$ MeV) pions, with unambiguous identification of negative pions ($<1\%$ electron background contamination), and a minimum of multiple-collision events within the target.

In Fig. 1, we present results from three sets of independent data. We have used a 1.8-GeV/nucleon ^{40}Ar beam and the events in this sample contain two to six negative pions. Figures 1(a) and 1(b) show data from $\mathrm{BaI_2}$ and $\mathrm{Pb_3O_4}$ targets, respectively, in an "inelastic" triggering mode which allows us to detect all but 10–15% of the most peripheral inelastic interactions. Figure 1(c) shows the $\mathrm{Pb_3O_4}$ target data taken in a more restricted triggering mode which selects the most central collisions, amounting to 15% of the total interactions. To search for a signature of pion interferometry, we evaluate, as suggested by Kopylov, the normalized ratio of the number of pairs of negative pions from the same event to the number of pairs of negative pions from different events, $R_{\mathrm{D}--}^{\mathrm{S}--}$, as a function of their relative momentum $q=|\vec{p}_i-\vec{p}_k|$ and energy difference $q_0=|E_i-E_k|$ with a cut $|q_0|\leqslant 300$ MeV. Statistically large samples of uncorrelated pion pairs are generated from pairs of different events, but care is taken to match only events of the same pion multiplicity to further insure the absence of any effect imposed by energy-momentum conservation. It is seen from Fig. 1 that the Kopylov ratio $R_{\mathrm{D}--}^{\mathrm{S}--}$ in all three sets of data exhibits a clear peak at low relative pion momentum (effective mass) of the di-pion system.

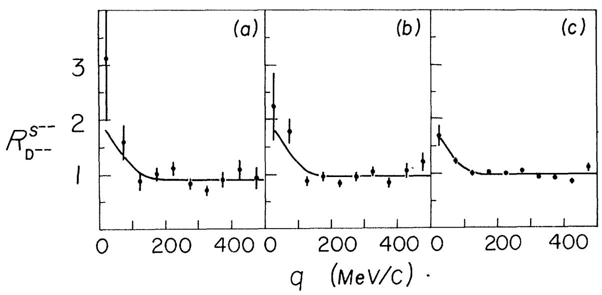

FIG. 1. Kopylov ratio $R_{\mathrm{D}--}^{\mathrm{S}--}$ vs relative pion momentum q. 1.8-GeV/nucleon ^{40}Ar beam incident on (a) $\mathrm{BaI_2}$ and (b) $\mathrm{Pb_3O_4}$ in an "inelastic" triggering mode, and on (c) $\mathrm{Pb_3O_4}$ triggering on the most central collisions. The curves are fits by Eq. (1).

Next we seek to extract relevant parameters from these interference patterns. There exist several analytic expressions for the Kopylov ratio R, based on different physical assumptions on the distribution of radiating matter. For a Gaussian space-time distribution, Yano and Koonin[10] have derived the correlation ratio $R_{\mathrm{D}--}^{\mathrm{S}--}$ with the following functional form:

$$R_{\mathrm{D}--}^{\mathrm{S}--}(q,q_0)=K\left\{1+\exp\left[-\left(\frac{\tau^2 q_0^{\,2}}{2}\right)-\left(\frac{r_0^{\,2}q^2}{2}\right)\right]\right\}, \tag{1}$$

where r_0 and τ are its characteristic space-time parameters, and K is an arbitrary normalization constant.

We have also considered, for a uniform distribution, the correlation ratio analogous to that given by Kopylov:

$$R_{\mathrm{D}--}^{\mathrm{S}--}(q,q_0)=K\left[1+\frac{I^2(r_0 q/\sqrt{2})}{1+(\tau q_0)^2}\right], \tag{2}$$

with $I(x)=2J_1(x)/x$, where J_1 is the Bessel function of the first kind.

Using a maximum-likelihood method, we have fitted our data with Eqs. (1) and (2). The lifetime parameter τ, as expected, turns out to be relatively insensitive and its fitted values range from 2×10^{-24} sec to 5×10^{-24} sec. In Table I we present the fitted values of the pion-emitting source radius r_0 and the associated χ^2 values, together with the corresponding χ^2 values for a straight line fit. In the first two cases, (a) and (b), the lifetime parameter τ is fixed at a nominal value of 5×10^{-24} sec.

For pp collisions the observed radius r_0 is of the order of 1 fm,[5] whereas our r_0 values are 3 to 4 times larger, suggesting more extended sources in nuclear collisions. As our data show in Fig. 1, the widths of the corresponding peaks in R are narrower by the same factor. To see

TABLE I. Fit parameters for data from Fig. 1.

			Eq. (1) fit			Eq. (2) fit		Linear fit
	Target	r_0 (fm)	τ (10^{-24} sec)	χ^2/NDF[a]	r_0 (fm)	τ (10^{-24} sec)	χ^2/NDF[a]	χ^2/NDF[a]
(a)	BaI_2	3.05 ± 1.10	5	9.49/8	3.09 ± 1.17	5	9.57/8	15.45/9
(b)	Pb_3O_4	3.30 ± 0.93	5	11.29/8	2.98 ± 0.76	5	11.60/8	22.13/9
(c)	Pb_3O_4	3.98 ± 0.78	$2.0^{+4.0}_{-1.8}$	14.69/7	3.88 ± 0.64	$3.2^{+4.6}_{-2.0}$	14.29/7	34.01/9

[a] "NDF" stands for "number of degrees of freedom."

more detail in spectra from nuclear collisions thus requires better energy-momentum resolution in the data. Only further experiment can show whether the hint of an oscillatory behavior of the ratio R seen in Fig. 1 is real.

Our observation of the pion interferometric effect should give impetus to further experiments to study in detail the space-time structure, as well as the coherence, of the radiating sources in relativistic nuclear collisions. The detailed experimental program must be augmented by parallel theoretical refinements such as the inclusion of effects of the Coulomb repulsion of like particles and the correction of the Coulomb effect due to target nucleons.[13]

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[1] G. Cocconi, Phys. Lett. 49B, 459 (1974).

[2] E. V. Shuryak, Phys. Lett. 44B, 387 (1973).

[3] G. I. Kopylov, Phys. Lett. 50B, 472 (1974); G. I. Kopylov and M. J. Podgoretsky, Yad. Fiz. 18, 656 (1973) [Sov. J. Nucl. Phys. 18, 336 (1974)], and references quoted there.

[4] G. N. Fowler and R. M. Weiner, Phys. Lett. 70B, 201 (1977).

[5] C. Ezell, L. J. Gutay, A. T. Laasanen, F. T. Dao, P. Schübelin, and F. Turkot, Phys. Rev. Lett. 38, 873 (1977).

[6] M. Deutschmann *et al.*, Nucl. Phys. B103, 198 (1976).

[7] M. Deutschmann *et al.*, CERN Report No. CERN/EP/PHYS 78-1 (to be published).

[8] G. Goldhaber, W. B. Fowler, S. Goldhaber, T. F. Hoang, T. Kalogeropoulos, and W. M. Powell, Phys. Rev. Lett. 3, 181 (1959); G. Goldhaber, S. Goldhaber, W. Lee, and A. Pais, Phys. Rev. 120, 300 (1960).

[9] M. Gyulassy, in Proceedings of the Symposium on Relativistic Heavy Ion Collisions, GSI Darmstadt, Germany, March 1978 (to be published), and Lawrence Berkeley Laboratory Report No. LBL-7704, April 1978 (unpublished).

[10] F. B. Yano and S. E. Koonin, California Institute of Technology, Theoretical Nuclear Physics Report No. MAP-1, June 1978 (to be published).

[11] G. Chapline, private communication.

[12] S. Y. Fung, W. Gorn, G. P. Kiernan, F. F. Liu, J. J. Lu, Y. T. Oh, J. Ozawa, R. T. Poe, L. Schroeder, and H. Steiner, Phys. Rev. Lett. 40, 292 (1978).

[13] L. Lawrence, M. Gyulassy, and S. Koonin, private communication.