OBSERVATION OF DIRECT HADRONIC PAIRS IN NUCLEUS-NUCLEUS COLLISIONS IN JACEE EMULSION CHAMBERS

The JACEE Collaboration+

T.H. Burnett(h), S. Dake(b), M. Fuki(c), J.C. Gregory(g), T. Hayashi(g), T. Hayashi(b), R. Holynski(i), J. Iwai((h), W. V. Jones(e), A. Jurak(i), J.J. Lord(h), O. Miyamura(d), H. Oda(b), T. Ogata(a), T.A. Parnell(f), T. Saito(a), T. Tabuki(a), Y. Takahashi(f), T. Tominaga(d), B. Wilczynska(i), R.J. Wilkes(h), W. Wolter(i), and B. Wosiek(i)

+ Japanese-American-Cooperative-Emulsion-Experiment
(a) Institue for Cosmic Ray Research, University of Tokyo, Tokyo, Japan
(b) Department of Physics, Kobe University, Kobe, Japan
(c) Department of Physics, Okayama University of Science, Okayama, Japan
(d) Department of Applied Mathematics, Osaka University, Osaka, Japan
(e) Department of Physics & Astronomy, Louisiana State University, USA
(f) ES62, Space Science Laboratory, NASA Marshall Space Flight Center, Huntsville, Alabama 35812, USA
(g) Department of Chemistry & Res. Inst. Univ. of Alabama, Huntsville, USA
(h) Department of Physics, University of Washington, Seattle, USA
(i) Institute of Nuclear Physics, Krakow, Poland

ABSTRACT

In a number of high energy ($\geq$ 1 TeV/amu) nucleus-nucleus collisions observed in JACEE emulsion chambers, non-random spatial association of produced charged particles, mostly hadronic pairs, are observed. Similar narrow pairs are observed in about 100 events at much low energy (20 - 60 GeV/amu). Analysis shows that 30 - 50 % of Pair abundances are understood by the Hambury-Brown-Twiss effect, and the remainder seems to require other explanations.

1. Introduction. Frequent association of produced particles in pairs have been noticed in measurements of charged particle angular distributions in nucleus-nucleus collisions. Several high energy events manifested significant abundances in JACEE emulsion chambers. Statistical analyses of larger samples(106 events) at lower energy (20 - 60 GeV/amu) also indicate non-trivial pair abundances.

From the viewpoint of independent superposition models it is not unnatural to expect weaker particle correlations in nucleus-nucleus collisions than those in proton-proton collisions, as long as no space-time structures and no coherent mechanism are considered. Observed pair data does not seem to support an idea of statistical obscuration of correlations.

Recent development in QCD lattice calculations[1] and experimental studies of high multiplicity/high energy density phenomena[2] encourage searches for signatures of Quark-Gluon-Plasma, a new state of matter. Central or quasi-central collisions are most promising to realize the required high density for QGP transitions, while peripheral collisions are least likely to contain possible QGP signals. Inclusive studies of collisions are generally governed by a large fluctuation of impact parameter which only enhances peripheral phenomena, and are very insensitive to the interaction models.[3] Unlike these insensitive parameters (<N> and <N>/D), an exclusive character of pair abundances may not be much obscured even in an inclusive analysis. We examine in this paper whether there are any non-trivial abundances of narrow hadronic pairs in both individual and inclusive nucleus-nucleus interactions.

2. Methods. The charged tracks emanating from the first collision vertices are measured for individual events. The psuedo-rapidity (η) and azimuth angle (ϕ) of a track are given by spatial coordinates measured at many emulsion layers downstream the vertex. Secondary interaction tracks and early $\gamma \to e^+e^-$ conversions are removed from the track data as much as possible. (Fine triangulation of tracks allows this elimination of contaminations whose origins are located at more than 50 - 150 μm downstream the first vertex, depending on η and vertex depth.) Obvious nuclear fragments (including spectator protons) are also excluded from the data.

All charged tracks thus defined are used for obtaining the following three different measures of pair correlation.

[Measure I] $$P(\leq \alpha, \beta) \equiv \frac{\text{No. of pairs } (\Delta\eta \leq \alpha,\ \Delta\phi \leq \beta)}{\text{No. of all charged tracks (Nch)}} \quad (1)$$

[Measure II] $$W(\alpha_1 \leq \Delta\eta \leq \alpha_2) \equiv \int_{\alpha_1}^{\alpha_2} \frac{dN}{d(\Delta\eta)d(\Delta\phi)}\, d(\Delta\eta) \quad (2)$$

[Measure III] $$S(\text{all}) \equiv \frac{dN}{dR^2}, \text{ with } R^2 \equiv \begin{cases} \cosh(\Delta\eta)^2 - \cos(\Delta\phi)^2, \text{ or} \\ (\Delta\eta)^2 + (\Delta\phi) \end{cases} \quad (3)$$

Measure I is useful in the analysis of individual events, and Measure II enhances narrow pairs. Measure III convolves the correlation of the rapidity with that of azimuth angle over the entire available η - ϕ space.

Event Name: Z_P(TeV/n) + Z_T → Nch + (Nf)		Number of Pairs ϕ < 5°	10°	15°
A-5: Mg (3) + C → 86 ch.	DATA	9	14	22
	BG.I	5	9	13
	BG.II	8	12	16
A-52: Fe (1) + C → 71 ch.	DATA	4	12	16
	BG.I	3	6	8
	BG.II	5	8	10
B-4: C (6) + C → 100 ch.	DATA	16	23	28
	BG.I	5	10	14
	BG.II	8	13	18
B-20: He (9) + C → 95 ch.	DATA	13	22	32
	BG.I	6	11	15
	BG.II	9	14	19
B-22: He (12) + C → 117 ch.	DATA	31	49	65
	BG.I	7	13	20
	BG.II	12	18	24
B-146: Fe (.5) + C → 72 ch.	DATA	11	15	20
	BG.I	3	5	8
	BG.II	5	7	9
C-255: C (3) + C → 76 ch.	DATA	8	12	15
	BG.I	4	8	12
	BG.II	7	11	15
D-2: C (10) + C →159(110)ch	DATA	34	63	89
	BG.I	12	28	41
	BG.II	25	37	50
F-250: C (20) + AgBr → 240 ch.	DATA	60	113	158
	BG.I	27	52	78
	BG.II	46	72	97
G-1: C (40) + C → 101 ch.	DATA	14	27	38
	BG.I	8	14	21
	BG.II	13	19	26
G-12: V (1) + C → 150 ch +(S)	DATA	28	47	56
	BG.I	24	39	55
	BG.II	27	43	58
G-20: S (2) + C → > 96 ch.	DATA	17	37	60
	BG.I	8	15	22
	BG.II	13	20	27
G-44: O (2) + C → 76(38) ch.	DATA	7	9	10
	BG.I	2	3	5
	BG.II	3	4	6
G-54: He (20) + C → 80 ch.	DATA	14	19	23
	BG.I	5	9	14
	BG.II	8	13	17
G-102: Ne (7) + C →176(100)+(2He)	DATA	13	24	32
	BG.I	10	19	28
	BG.II	13	22	31

TABLE. I Number of Pairs in events with high energy (> TeV/n) and medium multiplicity (70 < Nch < 250). Background estimates (BG.I and BG.II) are without and with the HBT effect. (Preliminary) Blackets for Nch refer to the number of tracks used in the analysis.

3. Results. An example, event (G12), shows abundant pairs in its forward rapidity region: Figs. 1a and 1b show its linear target diagram and pseudo-rapidity distribution, respectively. It is interesting to note that these pairs in this event seem to form a "ring" structure in rapidities as well as a "jet" structure in the azimuth plane. (This event also contains two "direct e^+e^- pairs" [$m_{e^+e^-}$ being ∿ 100 and 300 MeV] in the same forward rapidity region.) Measure I is used for individual event analy-

Fig. 1a

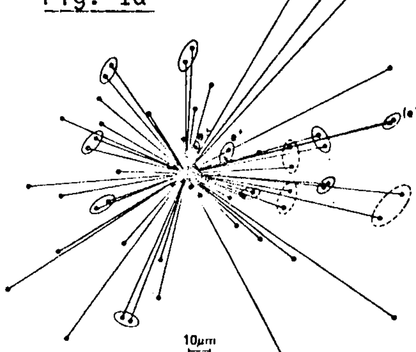
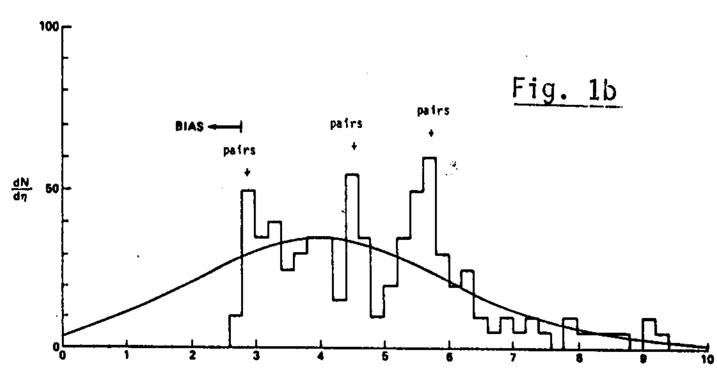


Fig. 1b



ses at high energy (≥ 1 TeV/amu). Table. I gives $P(\lesssim 0.2, 15^o) \times N_{ch}$ for 15 events (1532 tracks) with background expected from random coincidence of two particles(BG I) and that includes the HBT effect(BG II). The data show significant excess above background levels for several events. (Four events(B22, D2, F250, G20) show anomalous pair excess, while the other 11 events give $P(\leq 0.2, 15^o, - \text{BG II}) = 6.9\ \%$.

For low energy events the statistics (106 events for $N_\pi \geq 2$; 3,695 tracks from 20 - 60 GeV/amu Fe + C, AgBr and Pb reactions) is sufficient that both Measure II and III are taken for all samples. $W(0 \leq \Delta\eta \leq 0.1)$ and $W(0.1 \leq \Delta\eta \leq 0.2)$ distributions as a function of $\Delta\phi$ are given in Figs. 2a and 2b, respectively. Since $W = dN/d(\Delta\phi)$ is constant for a random background (shown in Fig. 2 by dotted lines), a signal of pair correlation is apparent in the region $\Delta\phi < 30^o$.

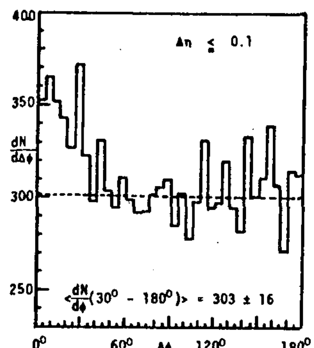


FIG. 2 a.

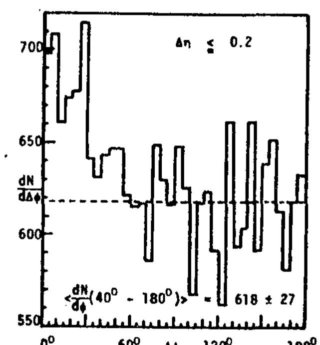


FIG. 2 b.

The same signals can be seen in the inclusive Measure III as well, though the S/N ratio is obviously reduced in dN/dR^2 as a result of inclusion of large population at $\Delta\phi > 0.2$. In Figs. 3a and 3b, the purely random (η, ϕ) background is a flat distribution (dotted lines), while a random distribution in ϕ only is evaluated by a Monte Carlo method; using real η and randomly reassigned ϕ values: (dashed-dot lines). The remainder in Figs. 3a and 3b indicates that there are non-trivial rapidity- and azimuth-correlations.

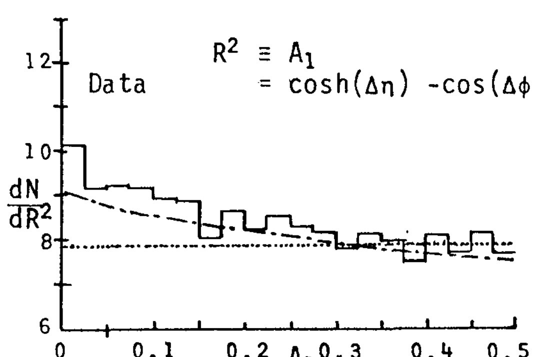


Fig. 3 a. dN/dR^2 ($R^2 \equiv A_1$)

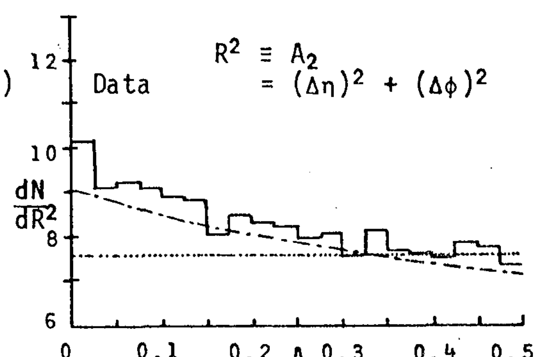


Fig. 3b. dN/dR^2 ($R^2 \equiv A_2$)

4. Discussions. Results presented above indicate a significant non-trivial correlation of short range nature. To evaluate the magnitude of signals we introduce a trial source of a hypothetical parent meson (X) decaying in two pions (or Kaons) with very small Q-values ($\lesssim$ 100 MeV). Non-random signals (P(Data)-P(BG I)) are estimated for eleven high energy events ($\Delta\eta \leq 0.2$, $\Delta\phi \leq 15^o$), and low energy events for ($\Delta\eta \leq 0.1$, $\Delta\phi \leq 30^o$) and ($\Delta\eta \leq 0.2$, $\Delta\phi \leq 30^o$) in terms of $x/\pi \simeq 10.2\ \%$, $8.2\ \%$ and $13.9\ \%$, respectively.

Let's discuss non-random backgrounds. First, Dalitz pairs in $\pi^0 \to \gamma e^+ e^-$ decay(branching ratio: 1.2 %) can be contained in above x/π ratios.

However, this accounts for only $1.2 \times (\pi^0/(\pi^+ + \pi^-)) \simeq 0.6$ %. Next, some early conversions of γ-rays can contaminate the data. As mentioned earlier, our track identification is not efficient for eliminating them within 150μm from the vertex, we expect this contamination upto (150/344,000) = 0.04 %. Even when we fully include proposed internal bremsstrahlung sources[4] in addition to $\pi^0 \to \gamma\gamma$ photons, they are not able to contribute more than 0.2 %. Thus, electron backgrounds from both internal and external conversions do not account for more than 0.8 %. Other experimental errors possibly inherent in measurements are not critically examined at present.

The Hambury-Brown and Twiss effect,[5] the fourth order quantum interference of Bose-Einstein particles, may possibly explain some of the observation, since this effect is of very short range nature for nucleus-nucleus collisions:

$$C \equiv \sigma_0 \frac{d^2\sigma}{d\vec{p}_1 d\vec{p}_2} \Big/ \left(\frac{d\sigma}{d\vec{p}_1} \frac{d\sigma}{d\vec{p}_2} \right) \simeq 1 + \exp\left(- \frac{q^2 R^2}{2} \right). \qquad (4)$$

The hadron source in nucleus-nucleus collisions is considered to be expanded to the size larger than the colliding nuclear volume, and its known[6] radius 3 - 4 fm gives the effective momentum difference $|q| < 100$ MeV. This is sufficiently small that $\pi^+\pi^+$ and $\pi^-\pi^-$ form narrow pairs (mostly in $\Delta\eta < 0.1$ region). The HBT estimate by eq.(4) and flat η distributions gives $P(HBT) \simeq 2 \times 0.5 \times {}_{n/2}C_2 \times \alpha\beta/(2\pi\{\ln s - y_0\})/(n/2) \simeq 3 \sim 7$ % at $\Delta\phi < 30^0$. (Note that this approximation depends on the event multiplicity and effective rapidity range.) An enhanced measure $W(0 \leq \Delta\eta \leq .1)$ would contain $0.5 \times \int W_{b.g.} d(\Delta\phi)$ HBT pairs, where the range of the integral must cover $\Delta\phi$ upto $.5 \times \tan^{-1}(100 \text{ MeV}/\langle P_T \rangle) \simeq 30^0$. It is noticed that the observed pair correlation increased for $\Delta\eta \leq 0.2$ (see Fig. 2b), while the HBT particles should not. This, with the analysis in Fig. 3, favors consideration of some hypothetical parent particles (X).

Freier and Waddington[7] showed similar pair abundances in 2900 tracks obtained from much lower energy ($\geq$ 7.5 GeV/amu) collisions. We estimated $P(0 \leq \Delta\eta \leq .1) = 255/2900 = 8.8$ %. For this result similar to our low energy data (20 - 60 GeV/amu), an HBT estimate explains about 67 pairs, which, with 20 Dalitz pairs, accounts for 35 % of all extracted abundances.

In conclusion, about 30 ~ 50 % of non-random signals can be attributed to the HBT effect from a large nuclear volume (3 ~ 4 fm). Nevertheless, there seem to remain some "unexplained signals" of narrow hadronic pairs. The net signals for "X" (not attributable to known backgrounds) in the present analysis become $X/\pi \to \sim 7$ %; 3.5 % and 6.3 %, for three groups defined previously. A particular group of events at high energies that had the enormous X/π ratio(~30 %) are by no means reconciled in the present analysis. All these results might require further examinations of systematic errors and background estimates before seriously considering (X) sources.

Further experimental and theoretical analyses of hadronic pairs seem to be interesting, not only because unexplained abundances still exist, but also because some exclusive characteristics of QGP, and particularly Chiral phase transitions, can be considered in the narrow pair phenomena.[8]

References: 1. J.Polonyi et al., Phys. Rev. Lett. 53, 644(1984). 2. T.H. Burnett et al.(JACEE), Phys. Rev. Lett. 50, 2062(1983). 3. T.H.Burnett et al.(JACEE), AIP 123, 723(1984). 4. J.D.Bjorken and L.McLerran, Phys. Rev. D31, 63(1985). 5. R.Hambury Brown and R.O.Twiss, Nature, 177, 27(1956). 6. W.A.Zajc et al., LBL-12652, 350(1981); D. Beavis et al., Phys. Rev. C27, 910(1983). 7. P.S.Freier and C.J.Waddington, AIP 49, 87(1979). 8. Y. Takahashi and P.B.Eby, this conference HE 1.3-13.