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Authors

Bossy, H.
Bistirlich, J.A.
Bossingham, R.R.
et al.

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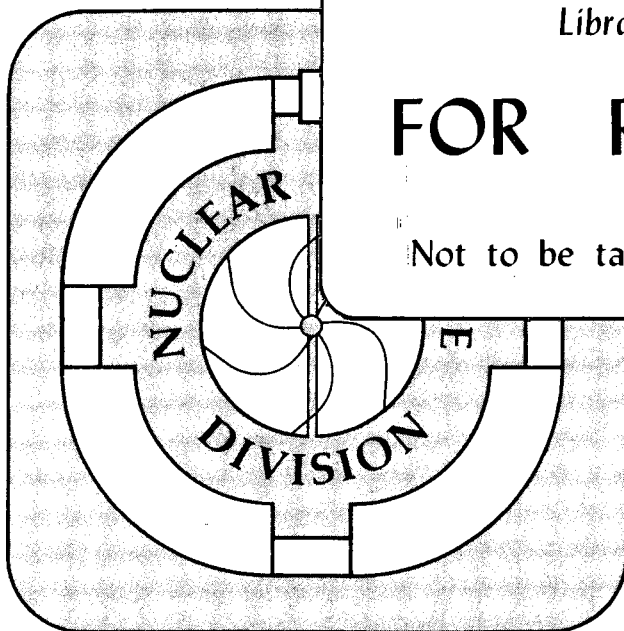
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Two-Pion Correlations and Multiplicity Effects in La on La Collisions

H. Bossy, J. A. Bistirlich, R. R. Bossingham,
A. D. Chacon,^{*} K. M. Crowe, M. Justice,
J. O. Rasmussen, A. A. Shihab-Eldin, M. A. Stoyer,[†]
and K. D. Wyatt

Lawrence Berkeley Laboratory
University of California, Berkeley
Berkeley, California 94720

J. P. Sullivan,[‡] and K. L. Wolf

Cyclotron Institute
Texas A & M University
College Station, Texas 77843

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Abstract

Bose-Einstein correlations of negative pions in heavy ion collisions have been investigated for the reaction $^{139}\text{La} + \text{nat}\text{La} \rightarrow 2\pi^- + X$ at 1.26 GeV/nucleon at two acceptances, centered at laboratory observation angles of approximately 0° and 45° with respect to the beam axis. A scintillation counter array downstream of the target was used to sample the charged particle multiplicity of each event and hence distinguish between peripheral and central collisions. Including results from previous experiments, space-time dimensions of the pion source are now available for mass-symmetric collisions in the mass range of $A = 40$ to 139. An oblateness of the source region generally persists for all systems, although La + La central collisions viewed near 45° in the lab. (90° in the center of mass) are spherical. The perpendicular radius R_\perp is never less than 4 fm, regardless of the centrality of the La + La collision. Furthermore, R_\perp seems independent of the mass of the collision system. In general, the source parameters of the 0° data do not depend in a statistically significant way on the multiplicity requirement, whereas, for the 45° observation angle, an unexplained dependence is observed.

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I. INTRODUCTION

Since the discovery by Goldhaber *et al.*[1, 2] that proton-antiproton annihilations produce more like-charged than oppositely charged pion pairs with small momentum difference, many theoretical[3–18] and experimental[19–34] studies have been done to investigate the “Goldhaber-Goldhaber-Lee-Pais” (GGLP) effect. The intensity correlation of two like particles is a consequence of the quantum mechanical symmetry requirement imposed on the wave functions of bosons. Bose-Einstein correlations were first employed in radio astronomy by Hanbury-Brown *et al.*[35] to measure the size of stellar objects; similarly, intensity correlations of pions, kaons and other particles can be used to determine the space-time dimensions and chaoticity of particle sources (non-chaotic or coherent sources do not show any correlation effects[7]). The determination of the dimensions of hadronic sources in heavy ion collisions provides experimental data for the test of transport calculations that try to describe the complex collision process of a large number of nucleons. By grouping the data according to the charged particle multiplicity it should be possible to measure the space-time dimensions of the particle source as a function of the centrality of the collision. Furthermore, there have been predictions[9, 14] of phase transitions from ordinary nuclear matter to quark-gluon plasma occurring in collisions of highly relativistic nuclei which could be studied by two-pion correlation measurements.

II. EXPERIMENT

In this work we continue the systematic investigation of two-pion correlations in symmetric projectile-target systems at the Lawrence Berkeley Laboratory Bevalac with an experiment using a 1.26 GeV/nucleon ^{139}La beam on a $^{\text{nat}}\text{La}$ target

of 0.5 g/cm^2 thickness. Negative pion pairs were measured with the magnetic spectrometer Janus at angles of 0° and 45° (lab.) with respect to the beam axis, the latter angle corresponding to approximately 90° in the center-of-mass (c.m.) system. The experimental set-up, described in detail by Zajc *et al.*[24] and Chacon *et al.*[34], is shown in Fig. 1. As an addition to the previous set-ups, an array of 28 scintillation counters (see Fig. 1, insert) was mounted 363 cm downstream of the 45° target position to record the charged particle multiplicity of each event. The downstream scintillator array was shifted to compensate for beam steering by the C-magnet, such that the beam was always centered on the array. The gain of the photomultiplier tubes was adjusted to measure protons and light charged fragments. The attempt to detect beam particles and heavy residues with the innermost counters was not successful due to high counting rates and excessive radiation damage to the scintillators. Therefore, these counters were excluded from the analysis. This gives an average angular detection range from 0.80° to 3.61° for area “C” and 3.61° to 5.41° for area “A” (see Fig. 1, insert). The electronic event trigger was the same as in previous experiments[28, 34]. That is, the coincidence condition requires (1) a coincidence signal from the two scintillation counters before the Janus magnet, (2) two separated hits in the two-plane scintillator array after the magnet and (3) the prompt signals signal from the tracking wire chambers[34]. This trigger effectively selected those events where two negative particles had passed through the spectrometer. Time and pulse-height signals of each multiplicity counter were recorded for each event.

III. ANALYSIS

Assuming a Gaussian space-time source distribution with a radius perpendic-

ular to the beam direction R_{\perp} , radii parallel to the beam direction R_{\parallel} , a lifetime τ , and a chaoticity parameter λ , the following correlation function was fit to the data:

$$C(q_{\perp}, q_{\parallel}, q_0) = B[1 + \lambda \exp\{(-q_{\perp}^2 R_{\perp}^2 - q_{\parallel}^2 R_{\parallel}^2 - q_0^2 \tau^2)/2\}] \quad (1)$$

where q_{\perp} , q_{\parallel} are projections of the relative two-pion momentum $\mathbf{q} = (\mathbf{p}_1 - \mathbf{p}_2)$ perpendicular and parallel to the beam axis, q_0 is the energy difference $|E_1 - E_2|$, and B is a normalization factor. The experimental correlation function is the ratio of a two-pion probability $N_2(\mathbf{p}_1, \mathbf{p}_2)$ to the product of single-pion probabilities $N(\mathbf{p})$:

$$C(\mathbf{p}_1, \mathbf{p}_2) = \frac{N_2(\mathbf{p}_1, \mathbf{p}_2)}{N(\mathbf{p}_1)N(\mathbf{p}_2)} \quad (2)$$

The Coulomb interactions between pions and nuclear matter and between the pions themselves were taken into account[34]. Final-state pion-pion strong interactions are expected to be small[15], and therefore are not considered in the analysis. Details of the track finding and data reduction procedures are given by Chacon[29]. The laboratory momenta of the pion pairs analyzed were in the range of 300 to 900 MeV/c in the 0° acceptance, and 150 to 1000 MeV/c in the 45° acceptance. As a standard requirement for all events, the projectile frame momentum of each pion had to be greater than 50 MeV/c to keep the (projectile fragment) Coulomb correction small. The final data sample consisted of roughly 28,000 (38,500) pion pairs for the $0^\circ(45^\circ)$ measurement.

The reference sample, i.e., the single-pion momentum distribution of Eq. 2 with no Bose-Einstein correlations, was generated using the event-mixing method[24, 29]. To remove the residual correlation in the “mixed-event” sample, correlation function parameters (in Eq. 1) from a previous fit were taken,

and used to generate (by event weighting) a reference sample with the residual correlation effect removed[24, 29]. This reference sample was used to generate a new set of parameters by fitting the correlation function to experimental data. These steps were repeated until the fit results were stable, which was usually the case after 3 to 5 iterations. In Fig. 2 different projections of experimental data and correlation function fits are shown for the 45° measurement. The differences in shape between the correlation function used in the fit (Eq. 1) and the projections are due to the acceptance weighting of the projections[34]. No significant deviations from the simple Gaussian source model are evident, such as higher-energy pp studies[33] have observed and attributed to heavier mesons beyond the production energy of the Bevalac.

IV. RESULTS AND DISCUSSION

The dependence of the source parameters on the projectile mass number A for the 0° and 45° configurations is given in Tables I and II, respectively, and is shown in Fig. 3a and 3b. Previous results for Ar, Fe, and Nb have been taken from Chacon *et al.*[28, 34]. The χ^2 given here is restricted so that more than five counts in a bin were required for the bin to be included in the calculation. The χ_{FML}^2 is a χ^2 based on the log-likelihood function used in the principle of maximum likelihood fit, and reduces to the usual χ^2 for sufficient statistics[24, 29]. NDF is the number of degrees of freedom. For both observation angles the source exhibits an oblate shape ($R_{\perp} > R_{\parallel}$) except in the case of Nb for which the source is nearly spherical, The parameter R_{\perp} is fairly constant over the whole mass range at about 5.0 fm (0°) and 4.5 fm (45°).

The lifetime τ strongly increases with the mass number, whereas the chaoticity

λ seems to be increasing only in the 0° data. Note that in the 0° configuration measurements λ approaches the value of 1, corresponding to a completely chaotic source. The general trend in the 45° data seems to indicate a chaoticity parameter of around 0.7. This is in disagreement with nuclear cascade calculations[13] and the “final-state shadowing” effect[8] which both predict λ -values around or greater than unity. Fowler *et al.*[11] attribute the lower chaoticity to an increase in stimulated emission through Δ decay along the longer R_\perp -axis.

The distribution of the charged particle multiplicity from the multiplicity array is shown in Fig. 4 for the 45° data. The average number of hits in the array for both viewing angles is about three. For the 0° data, the selection of two-pion events according to multiplicity does not have a statistically significant effect on the source parameters, as demonstrated in Fig. 5a and Table III. The various cuts on the multiplicity in the array (M) are indicated, along with the unbiased data (“unbd”). In contrast to the 0° data, the requirement of low multiplicities in the 45° data causes the source shape to become more oblate, and the selection of high multiplicities leads to almost spherical source shapes (see Fig. 5b and Table IV). To enlarge the data set of “very peripheral” collisions, the zero hit condition was relaxed to also include events that had pulse-height overflows, the idea being that heavy beam residues either passed (undetected) through the center of the multiplicity array or caused an overflow in the innermost ring of counters (This condition is denoted “ $M=0OF$ ” in Fig. 5, and in Tables III and IV). The one-standard-deviation error bars in Fig. 5 take into account the correlation of the components of R and the lifetime τ . Thus, the finite value reported for τ is significant, and with the large small-acceptance data set it is not necessary to force τ to zero, as in some earlier streamer-chamber studies. The chaoticity parameter

in both measurements is relatively unaffected by the multiplicity cut. It has been verified that the multiplicity dependence in the 45° data is not an artifact of the Coulomb correction. However, demanding that the pions have a projectile frame momentum of greater than 250 MeV/c leads to a nearly spherical source shape, similar to the unbiased one. This case is shown for multiplicity $M \leq 2$ in Fig. 5 and in Table IV (denoted “ $M \leq 2P$ ”).

The multiplicity dependence of source radii determined by two-particle correlation measurements has been investigated earlier. In Refs.[27, 30, 33] no such multiplicity dependence has been found, whereas Refs.[20–23, 25, 31] report an increase of the radius with increasing multiplicity (centrality) of a collision.

It is believed that the data show the important role of pion scattering in the spectator matter, since the value of R_\perp does not decrease for the zero multiplicity cut (“ $M=0OF$ ”) but is at its maximum for both angles of observation (Tables III and IV, and Fig. 5). Further confirmation of the role of pion scattering is the near constancy of R_\perp with mass number A of the colliding system (Tables I and II, and Fig. 3). This “universal” R_\perp value near 5 fm is interestingly close to the intranuclear maximum mean free path for pions well below the $\Delta(1232)$ resonance at around 50 MeV kinetic energy in the spectator frame.

The systematic occurrence of chaoticity parameter λ values below unity could indicate a special role for double pion production in the same nucleon-nucleon collision, hence, with related phases. These two pions need not be formed with the same charge, since charge-changing is a major part of pion scattering in the spectator matter.

V. SUMMARY

The determination of space-time dimensions of pion sources in heavy-ion collisions using Bose-Einstein correlations has been extended to La ($A = 139$). As in previous measurements, the radius perpendicular to the beam axis has been found to be larger than the radius in the beam direction. Our results do not follow an $A^{1/3}$ dependence of the radii on the mass of the projectile[36] but are nearly constant. The chaoticity parameter λ shows only small variations with the projectile mass, whereas the lifetime increases for heavier projectiles. For the 0° observation angle the source shows almost completely chaotic behavior ($\lambda \approx 1$), and at the 45° (90° c.m.) angle the chaoticity is reduced ($\lambda \approx 0.7$). An unexplained multiplicity dependence of the 90° c.m. data has been observed showing small, spherical source sizes at high multiplicities and oblate sources with large R_\perp at low multiplicities. In the 0° configuration the source parameters do not exhibit a multiplicity dependence.

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- * Present address: Cyclotron Institute, Texas A & M University, College Station, TX 77843.
- † Present address: MS L-234, University of California, P. O. Box 808, Lawrence Livermore National Lab., Livermore CA 94550
- ‡ Present address: P2 Division, MS D456, Los Alamos National Lab., Los Alamos, NM 87545.
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TABLES

TABLE I. Fit results of the 0° data for different projectiles with $|\mathbf{p}_{\text{proj}}| > 50 \text{ MeV}/c$.
The results for Ar, Fe, and Nb are taken from Chacon *et al.*[34].

0° Data, $ \mathbf{p}_{\text{proj}} > 50 \text{ MeV}/c$				
Projectile	Ar	Fe	Nb	La
$R_{\perp}(\text{fm})$	4.8 ± 0.3	4.8 ± 0.2	5.1 ± 0.2	5.3 ± 0.3
$R_{\parallel}(\text{fm})$	4.2 ± 0.4	2.7 ± 0.3	4.4 ± 0.3	3.7 ± 0.7
$\tau(\text{fm}/c)$	$1.1^{+1.4}_{-1.1}$	2.7 ± 0.6	3.9 ± 0.4	4.7 ± 0.9
λ	0.81 ± 0.06	0.88 ± 0.03	1.11 ± 0.03	1.08 ± 0.06
χ^2/NDF	581/537	939/729	1144/1087	1224/1113
$\chi^2_{\text{PML}}/\text{NDF}$	2979/2590	2938/2420	3776/3235	4344/4277
Events	12 900	32 000	49 400	28 000

TABLE II. Fit results of the 45° data for different projectiles with $|p_{\text{proj}}| > 50$ MeV/c. The results for Ar, Fe, and Nb are taken from Chacon *et al.*[34].

45° Data, $ p_{\text{proj}} > 50$ MeV/c				
Projectile	Ar	Fe	Nb	La
R_{\perp} (fm)	4.5 ± 1.0	4.0 ± 0.65	4.8 ± 0.55	4.5 ± 0.75
R_{\parallel} (fm)	1.0 ± 1.0	$1.5^{+0.55}_{-0.9}$	3.8 ± 0.2	3.6 ± 0.4
τ (fm/c)	$0.0^{+2.3}_{-0.0}$	1.7 ± 1.7	4.8 ± 1.0	7.6 ± 1.0
λ	0.72 ± 0.10	0.66 ± 0.06	0.89 ± 0.035	0.70 ± 0.04
χ^2/NDF	138/156	381/403	846/795	561/541
$\chi^2_{\text{PML}}/\text{NDF}$	1702/1662	2194/1925	2612/2098	1958/1603
Events	3300	8400	39 100	38 500

TABLE III. Source parameters for the 0° measurement with varying biases imposed through multiplicity cuts. For an explanation of the symbols, see the text.

0° Data				
Class	$M > 4$	$M > 2$	$M \leq 3$	$M \leq 2$
$R_{\perp}(\text{fm})$	5.6 ± 0.5	5.2 ± 0.4	5.5 ± 0.5	5.4 ± 0.4
$R_{\parallel}(\text{fm})$	3.6 ± 1.1	3.8 ± 0.8	3.9 ± 0.9	3.7 ± 0.9
$\tau(\text{fm}/c)$	4.5 ± 1.4	4.3 ± 1.2	5.4 ± 1.0	4.9 ± 1.1
λ	1.12 ± 0.10	1.12 ± 0.08	1.08 ± 0.08	1.06 ± 0.08

0° Data		
Class	$M = \emptyset\text{OF}$	unbd
$R_{\perp}(\text{fm})$	5.6 ± 0.5	5.3 ± 0.3
$R_{\parallel}(\text{fm})$	3.2 ± 1.3	3.7 ± 0.7
$\tau(\text{fm}/c)$	4.9 ± 1.4	4.7 ± 0.9
λ	1.16 ± 0.11	1.08 ± 0.06

TABLE IV. Source parameters for the 45° measurement with varying biases imposed through multiplicity cuts. For an explanation of the symbols, see the text.

45° Data				
Class	$M > 4$	$M > 3$	$M \leq 3$	$M \leq 2$
R_\perp (fm)	3.5 ± 1.4	4.1 ± 1.2	5.9 ± 0.9	6.1 ± 1.0
R_\parallel (fm)	3.8 ± 0.6	3.7 ± 0.5	3.8 ± 0.5	3.4 ± 0.5
τ (fm/c)	8.0 ± 1.6	7.6 ± 1.4	6.7 ± 2.1	6.4 ± 2.3
λ	0.74 ± 0.07	0.76 ± 0.06	0.72 ± 0.06	0.74 ± 0.07

45° Data			
Class	$M = \emptyset OF$	$M \leq 2P$	unbd
R_\perp (fm)	7.4 ± 1.3	4.0 ± 1.6	4.5 ± 0.8
R_\parallel (fm)	1.3 ± 0.8	3.2 ± 0.6	3.6 ± 0.4
τ (fm/c)	$3.0^{+3.6}_{-3.0}$	6.9 ± 1.9	7.6 ± 1.0
λ	0.62 ± 0.08	0.67 ± 0.07	0.70 ± 0.04

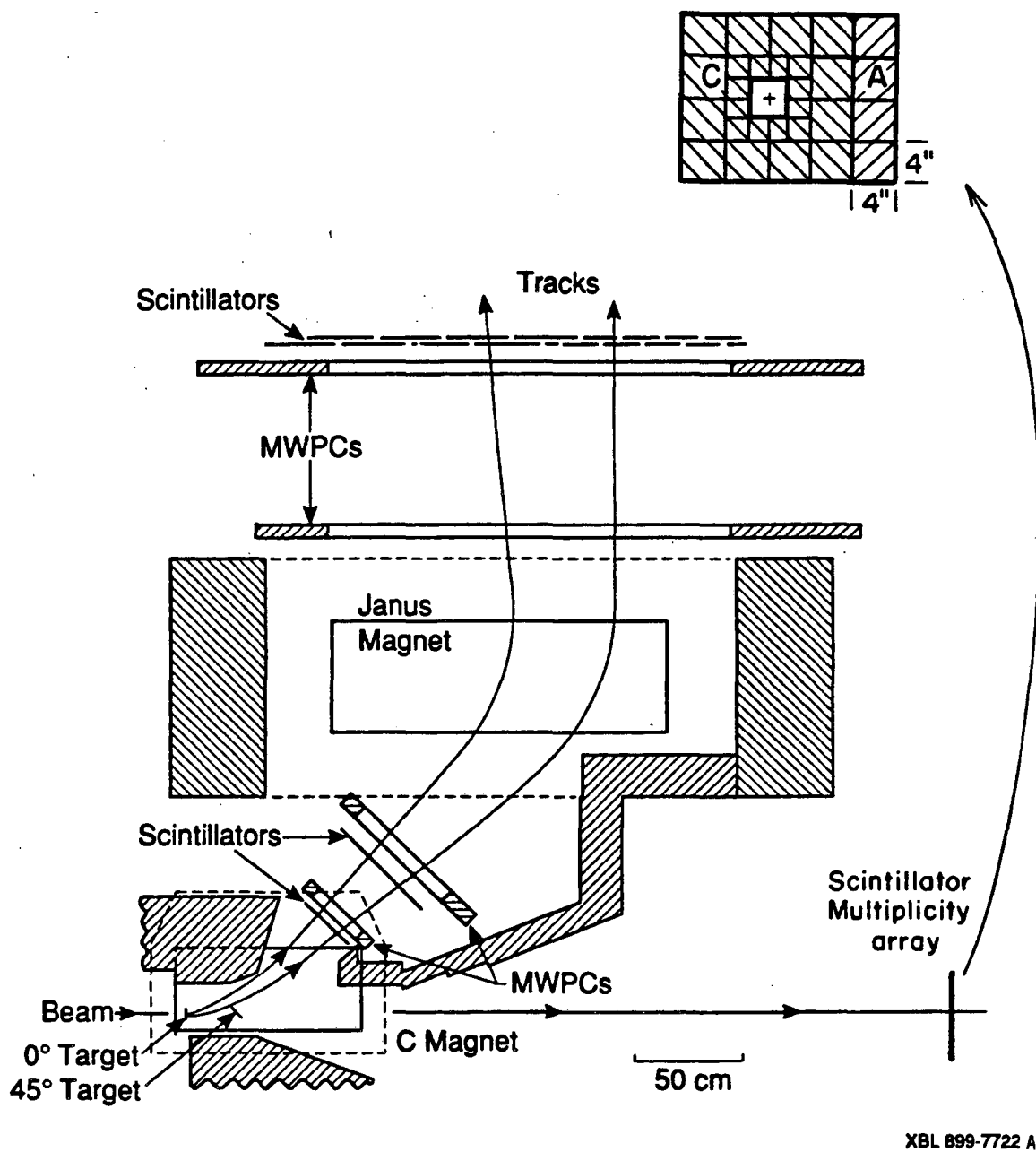
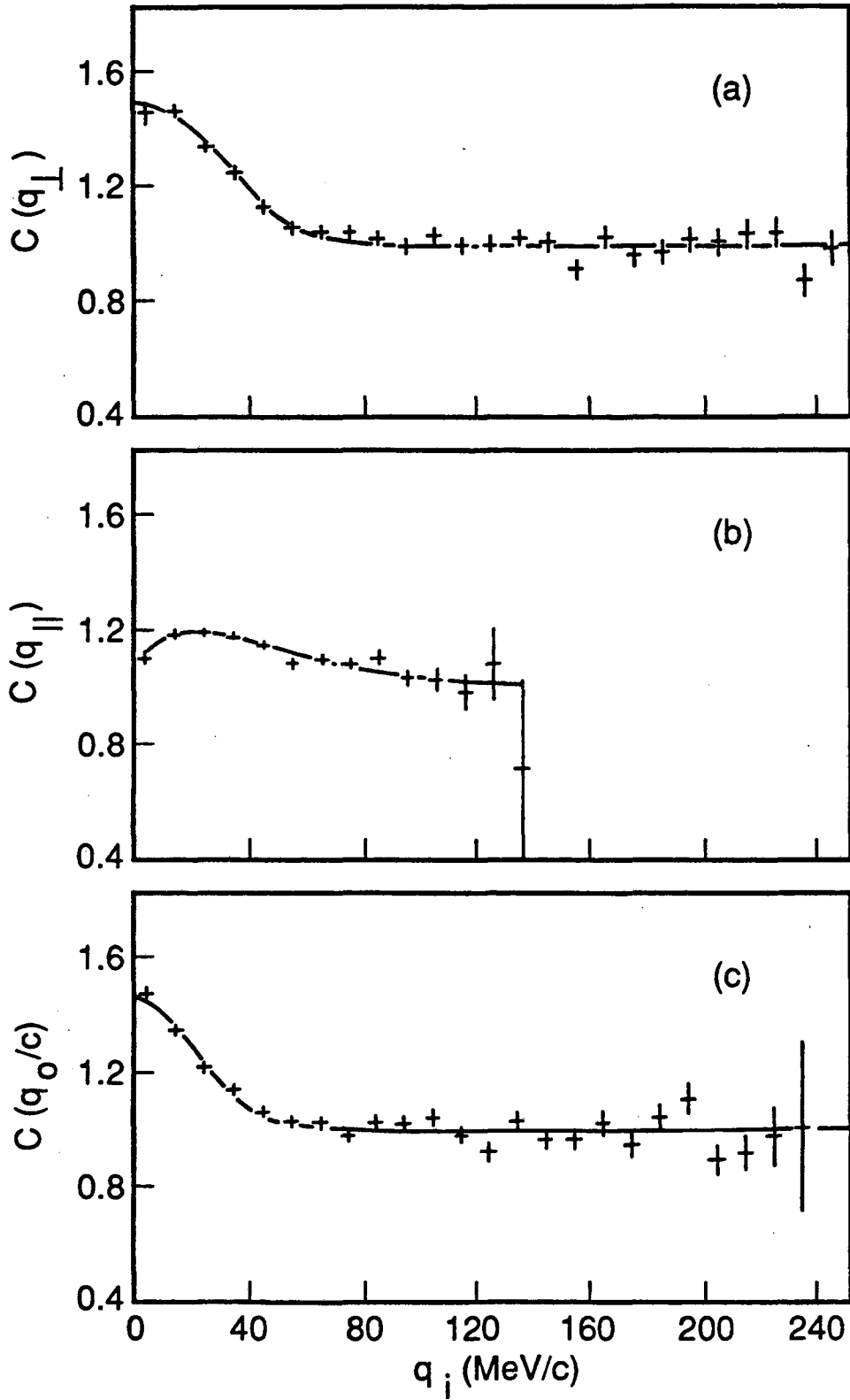
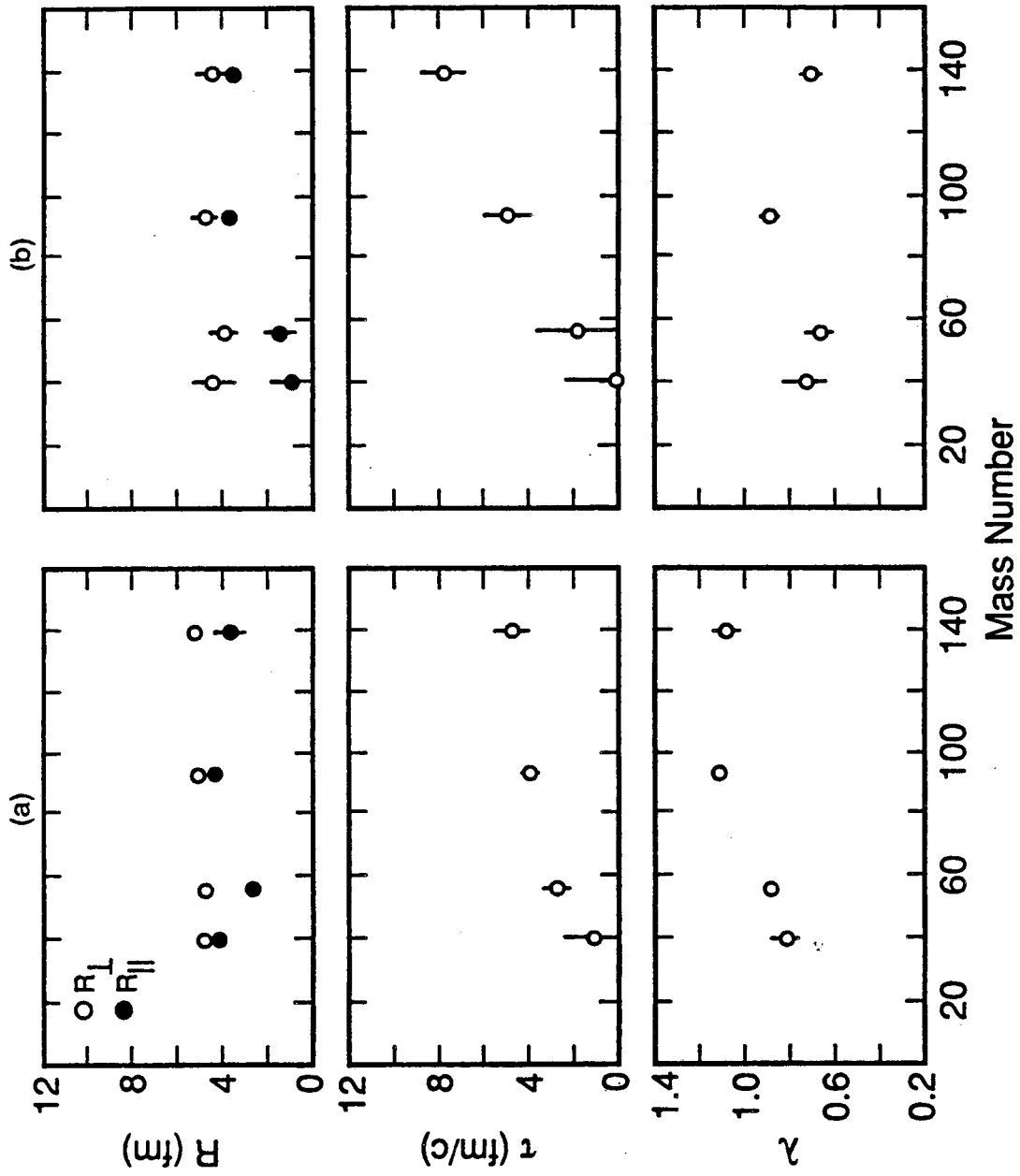


FIG. 1. Top view of the experimental set-up. Insert: front view of the multiplicity counter array with central scintillators (labelled "C") and peripheral scintillators ("A").



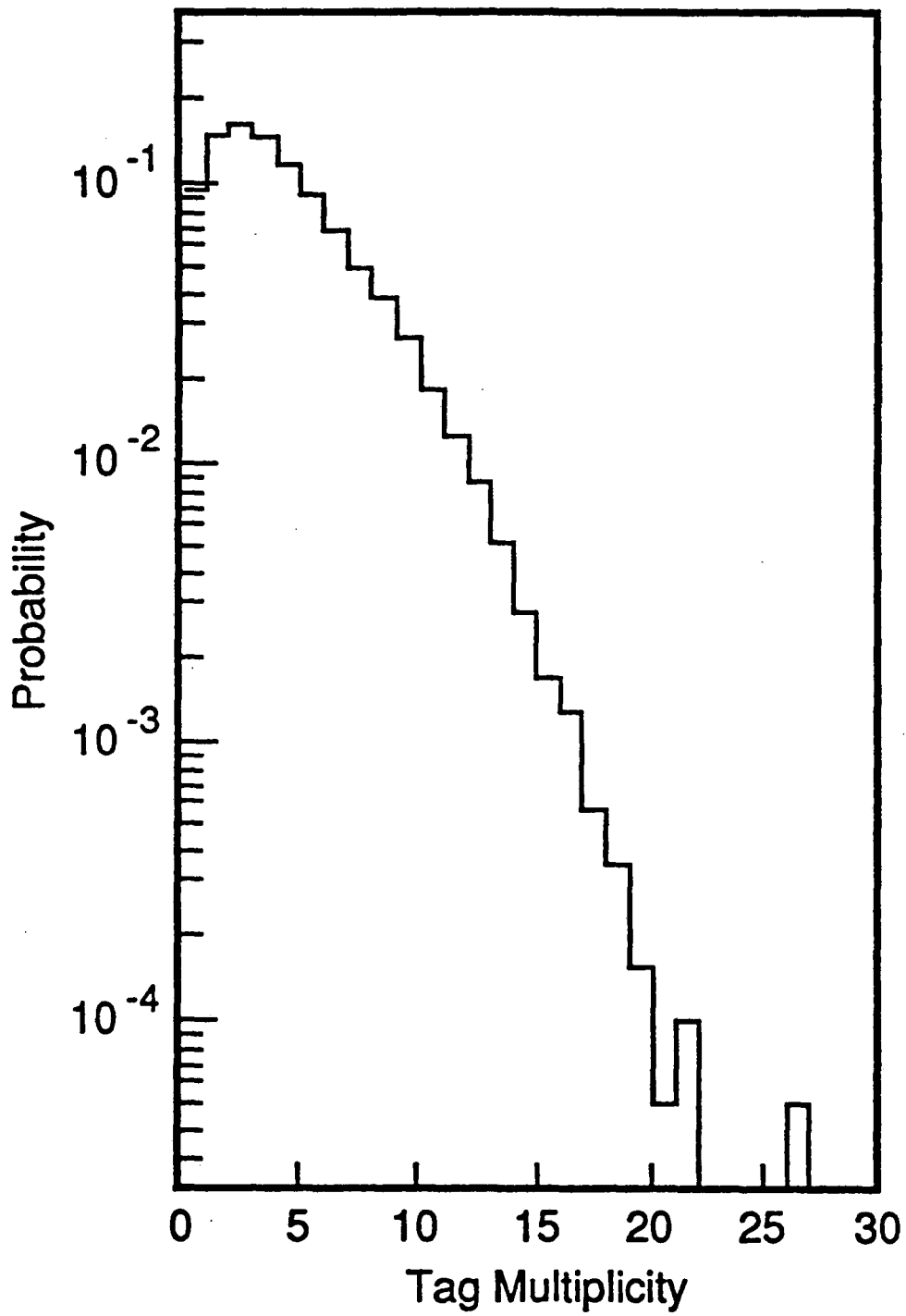
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FIG. 2. Experimental 45° data and correlation function fits for different projections: (a) $C(q_{\perp})$, (b) $C(q_{\parallel})$, and (c) $C(q_0/c)$.



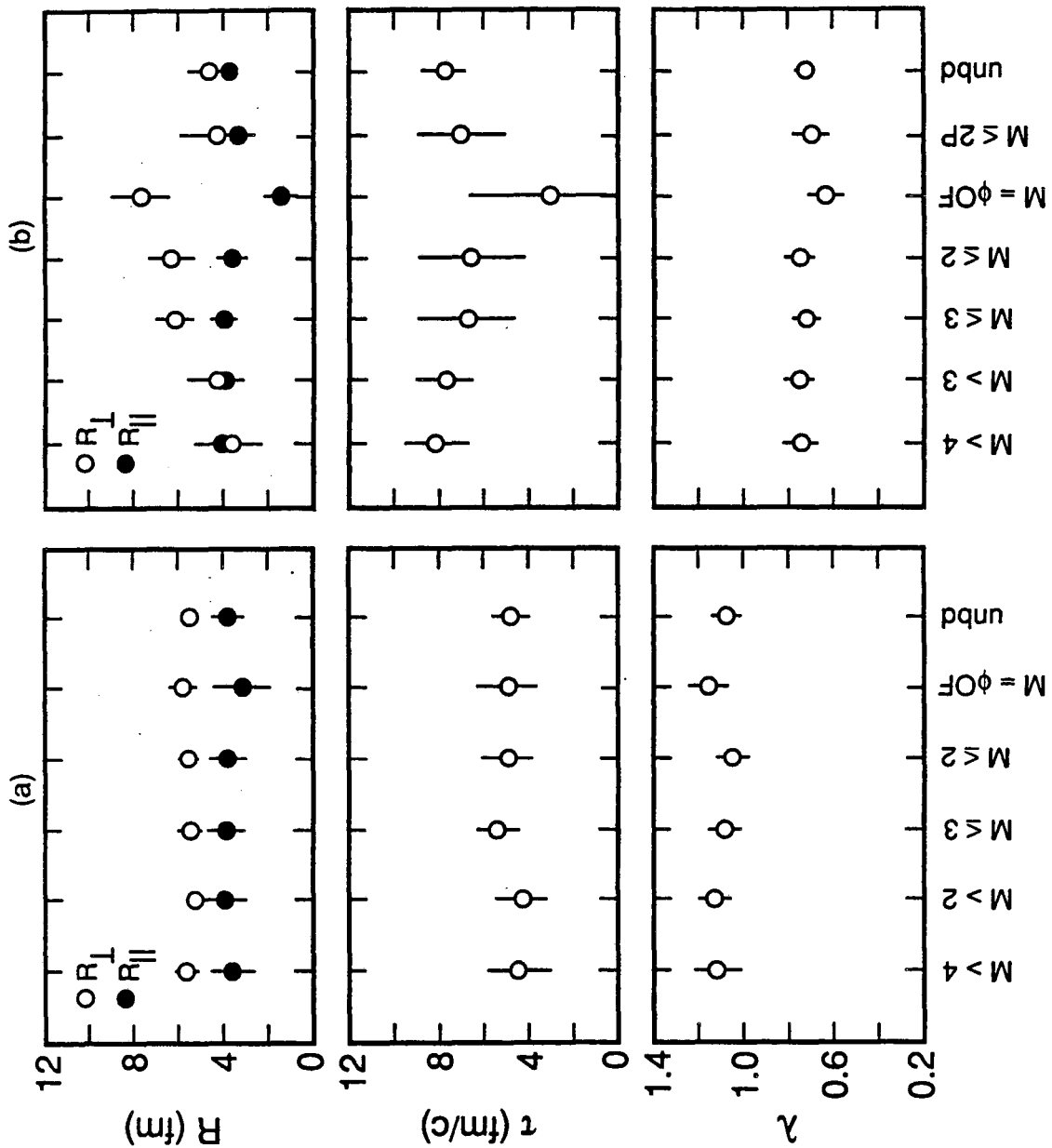
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FIG. 3. Gaussian source shape parameters as a function of the mass number of the projectile (= target) for (a) 0° and (b) 45° measurements.



XBL 914-815

FIG. 4. Distribution of the charged particle multiplicity detected by the multiplicity array for 45° data.



XBL 9111-2372

FIG. 5. Gaussian source shape parameters for different multiplicity requirements on (a) 0° and (b) 45° data. Results with no multiplicity requirements are labelled “unbd” (for unbiased), and the zero multiplicity condition “ $M=\emptyset\text{OF}$ ” is explained in the text. The data set labelled “ $M\leq 2P$ ” shows the effect of a projectile-frame momentum cut ($|\mathbf{p}_{\text{proj}}| > 250$ MeV/c rather than the usual cut of $|\mathbf{p}_{\text{proj}}| > 50$ MeV/c) on a $M\leq 2$ multiplicity data sample.

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