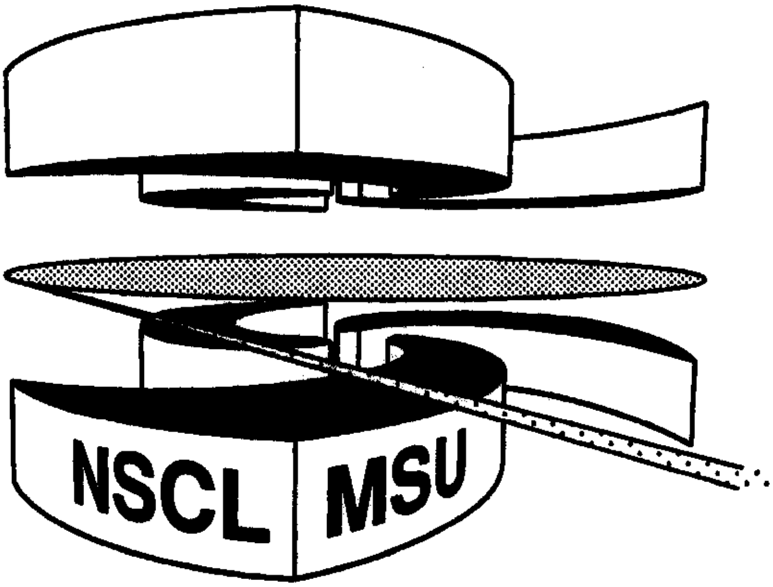
Michigan State University

National Superconducting Cyclotron Laboratory

HIGH-ORDER AZIMUTHAL CORRELATION FUNCTIONS: POWERFUL PROBES FOR COLLECTIVE MOTION IN HEAVY ION REACTIONS

J. LAURET, ROY A. LACEY, A. ELMAANI, A. TSEPETIS,
A. MOORES, G.D. WESTFALL, D. CRAIG, E. GUALTIERI,
S. HANNUSCHKE, T. LI, W.J. LLOPE, R. PAK, N. STONE,
A. VANDER MOLEN, J. YEE, A. NADASEN, R.S. TICKLE,
and E. NORBECK



MSUCL-948

AUGUST 1994

10 November 1994

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 339 (1994) 22–27

High-order azimuthal correlation functions: powerful probes for collective motion in heavy ion reactions

J. Lauret[a], Roy A. Lacey[a], A. Elmaani[a], A. Tsepetis[a], A. Moores[a], G.D. Westfall[b], D. Craig[b], E. Gualtieri[b], S. Hannuschke[b], T. Li[b], W.J. Llope[b], R. Pak[b], N. Stone[b], A. Vander Molen[b], J. Yee[b], A. Nadasen[c], R.S. Tickle[d], E. Norbeck[e]

[a] *Department of Chemistry, State University of New York at Stony Brook, Stony Brook, NY 11794-3400, USA*
[b] *National Superconducting Cyclotron Laboratory and Department of Physics, Michigan State University, East Lansing, MI 48824-1321, USA*
[c] *Department of Physics, University of Michigan at Dearborn, Dearborn, MI 48128, USA*
[d] *Department of Physics, University of Michigan, Ann Arbor, MI 48109-1120, USA*
[e] *Department of Physics, University of Iowa, Iowa City, IA 52242, USA*

Received 16 June 1994; revised manuscript received 7 September 1994
Editor: J.P. Schiffer

Abstract

We have investigated the utility of high-order azimuthal correlation functions as probes of collective motion from both rotation and flow at intermediate energies. Reaction simulations indicate new and distinct signatures for rotational collective motion which are important for its characterization and its distinction from collective flow. For the system Ar + Sc (35–115*A* MeV), experimental high-order correlation functions are used for a clear demonstration of the disappearance of collective flow at 93 ±4*A* MeV. The method is direct and circumvents reaction-plane assignment.

The study of collective motion in intermediate energy heavy ion collisions is predicted to provide important insight into heavy ion reaction dynamics and the nuclear equation of state (EOS) [1–6]. In fact, recent microscopic transport models [7–10] have linked the magnitude of parameters of the EOS to the dominance of repulsive versus attractive collective motions in heavy ion reactions. Such collective motions – termed flow – are currently under active investigation [11–15]. In addition, much effort has been devoted to the study of rotational collective motion which must be distinguished from flow in intermediate energy heavy ion reactions [16–21].

Measured azimuthal angle distributions [with respect to an inferred reaction plane] have been shown to be sensitive to both flow and rotational collective motion [17,18,20]. However, their quantitative utilization is marred by the large corrections that must be applied to experimental results to account for the dispersion of the experimentally inferred reaction plane about the true reaction plane. Various methods have been exploited to improve the accuracy of the assignment of the reaction plane from experimental data and to correct for its dispersion [4,22,23]. Nonetheless, reservations are still expressed in the literature [24] concerning the accuracy of measured collective variables (e.g. flow) which rely on a knowledge of the reaction plane.

SSDI 0370-2693(94)01212-1

Multifragment azimuthal correlation functions have been shown to provide another potentially powerful probe for heavy ion collision dynamics [21,25]. Unlike the more "remote" azimuthal angular distributions, these correlation functions can be directly interpreted and do not require any assignment of the reaction plane. An important consequence of this is that one circumvents the event-by-event estimation of the reaction plane and hence, the corrections for dispersion of the angle of this plane about the true reaction plane. Collateral benefits include a reduction in systematic uncertainties associated with detector acceptance, efficiency, etc. Another virtue of multifragment azimuthal correlation functions is that they allow the direct investigation of higher-order correlations between fragment multiplets (three or more fragments). Such high-order correlation functions have been recently used to study collective flow in the system Ar + Au (0.4A GeV) [26].

In this letter we extend the utility of high-order multifragment azimuthal correlation functions to the study of both rotational collective motion and the disappearance of collective flow at intermediate energies. On the one hand, we show – by way of reaction simulations – that high-order multifragment azimuthal correlation functions yield new and distinct signatures for rotational collective motion. We believe that these signatures are important for the distinction and characterization of both rotational collective motion and flow. On the other hand, we report new experimental high-order correlation functions for the system Ar + Sc (35A MeV to 115A MeV) which show clear evidence for the disappearance of collective flow at 93 ± 4A MeV and its resurgence at higher energies.

The ^{40}Ar beams (35A MeV to 115A MeV) used in the experiments were provided in 10 MeV steps by the K1200 cyclotron at the National Superconducting Cyclotron facility (NSCL). The beam intensity was approximately 100 electrical pA and the thickness of the Sc target was 1.6 mg/cm^2. Charged reaction products were detected with the MSU 4π Array [27].

The MSU 4π Array consists of a main ball of 170 phoswich detectors (arranged in 20 hexagonal and 10 pentagonal subarrays) covering angles from 23° to 157° and a forward array of 45 phoswich detectors covering angles from 7° to 18°. The thirty Bragg curve detectors recently installed in front of the hexagonal and pentagonal sub-arrays were operated in ion chamber mode (for ΔE determination) with a pressure of 500 torr of P5 gas (95% argon, 5% methane). Since the hexagonal anodes of the five most forward Bragg curve detectors are segmented, 55 separate ΔE gas detectors were employed for these measurements.

The gas detectors provided ΔE signals for charged particles ($Z \geq 2$) that stopped in the fast plastic scintillator of the main ball. Consequently, the Array was capable of detecting charged fragments from $Z = 1$ to $Z = 12$. Low energy thresholds for the main ball were 17A MeV, 3A MeV, and 5A MeV for fragments of $Z = 1$, 3, and 12, respectively. The low energy threshold for the forward array was $\approx$17A MeV. Data were taken with a minimum bias trigger (charged particle multiplicity $(m) \geq 2$) and a more central trigger $(m \geq 5)$.

Following the approach exploited in Refs. [21,26], the high-order multifragment azimuthal correlation function is defined as a ratio of two distributions

$$C(\psi_\omega) = \frac{N_{\mathrm{cor}}(\psi_\omega)}{N_{\mathrm{uncor}}(\psi_\omega)}, \tag{1}$$

where $N_{\mathrm{cor}}(\psi_\omega)$ is the observed ψ_ω distribution for fragment multiplets selected from the same event and $N_{\mathrm{uncor}}(\psi_\omega)$ is the ψ_ω distribution for fragment multiplets selected from mixed events. The two distributions are area normalized. For a multiplet of ω fragments, ψ_ω represents the geometric mean of the k pairwise azimuthal separations $(\Delta\phi)$ between the fragments [26]

$$\psi_\omega = \left(\prod_{ij}^{k} (\Delta\phi)_{ij} \right)^{1/k}, \quad k = \tfrac{1}{2}\omega(\omega - 1). \tag{2}$$

There are $M!/(M-\omega)!\omega!$ possible multiplets of size ω for an event in which M fragments are detected. Consequently, each event was appropriately weighted by the factor $(M-\omega)!\omega!/M!$ to ensure equal contribution to ψ_ω by all events. For the results presented here, mixed events were obtained by randomly selecting each member of a fragment pair or multiplet from different events with the same impact parameter. Impact parameters were determined by way of cuts on the total transverse momentum [28,29].

For orientation, we show simulated high-order correlation functions for flow and rotational collective motion in Fig. 1. The simulations, which were made

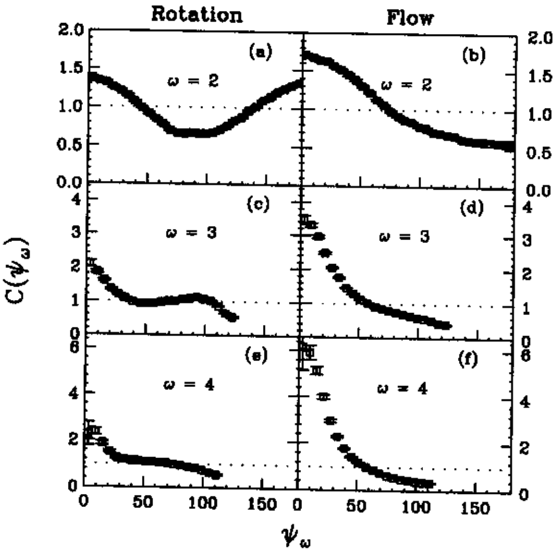


Fig. 1. Reaction simulation for rotational collective motion (left column) and flow (right column) for the system Ar + Sc. Azimuthal correlation functions are shown for fragment pairs (a and b), three-fragment multiplets (c and d), and four-fragment multiplets (e and f). See text for details.

for several characteristic event shapes, employ Gaussian fragment momentum distributions to simulate collective motion for negative rapidity fragments. For rotational collective motion we used an oblate momentum distribution ($\sigma_x = \sigma_z > \sigma_y$) where z is the beam axis, x is in the reaction plane, and y is normal to the reaction plane. For flow we used a prolate momentum distribution rotated (20°) about the y axis. The left column of Fig. 1 shows results for pure rotational collective motion. The right column shows results for pure flow. The two top frames (Figs. 1a and 1b) show correlation functions for fragment pairs. The other frames show high-order correlation functions for three-fragment multiplets (Figs. 1c and 1d) and four-fragment multiplets (Figs. 1e and 1f). A comparison of the correlation functions for flow (right column Fig. 1), indicates that the strength of the correlation function increases appreciably (an approximate four-fold increase at low ψ) as the size ω of the fragment multiplet increases from 2 to 4. However, the basic shape of the correlation functions does not change with ω. The peaks [at low ψ] in these correlation functions are a manifestation of the extent to which collective flow causes fragment multiplets to be closely spaced in azimuthal angle. For pedagogic reasons, we note that an isotropic emission pattern leads to a flat ($C(\psi_\omega) = 1$) high-order correlation function for all fragment multiplets.

For rotational collective motion (left panel Fig. 1), the evolution of the correlation functions [with ω] is significantly different from those shown for flow. They do not show the large change in magnitude [at small ψ] with increasing ω displayed by the correlation functions for flow. Instead, one can clearly see characteristic and distinct shape changes as ω is increased. The apparent shape differences between the correlation function for fragment pairs (Fig. 1a) and those for three-fragment (Fig 1c) and four-fragment (Fig. 1e) multiplets is particularly striking. The general features of these correlation functions are consistent with the fact that rotational collective motion gives rise to preferential fragment emission in a plane perpendicular to the rotational axis. We conclude from Fig. 1 that high-order correlation functions aid the distinction between rotation and flow and may provide important insights on collective motion [in multifragment decay] which are inaccessible via conventional two particle azimuthal correlation functions.

Experimental correlation functions for Ar + Sc [35A MeV] are shown in Figs. 2b, 2d, and 2f for fragment pairs, three-fragment multiplets, and four-fragment multiplets, respectively. In order to enhance possible signatures for flow and collective rotational motion [17,20,21], only fragments with negative cm rapidities ($-0.5 < y < -0.05$) from relatively central collisions ($b/b_{\max} < 0.33$) were used (b is the estimated impact parameter and $b_{\max}$ is the maximum impact parameter [28,29]). In constructing these correlation functions, the fragment yield for each detector was randomized (in azimuth) over its surface. In addition, we required the presence of a He "trigger" fragment in each of the fragment pairs or multiplets used to evaluate ψ. These experimental correlation functions have shapes which are qualitatively different from the correlation functions shown in Fig. 1. On the contrary, there are unmistakable similarities between these experimental correlation functions and the simulated correlation functions shown in Figs. 2a, 2c, and 2e. These latter correlation functions were constructed assuming nearly equal contributions from flow and rotational collective motion. We conclude from these results that, at low bombarding energies, there are significant contributions from both flow and

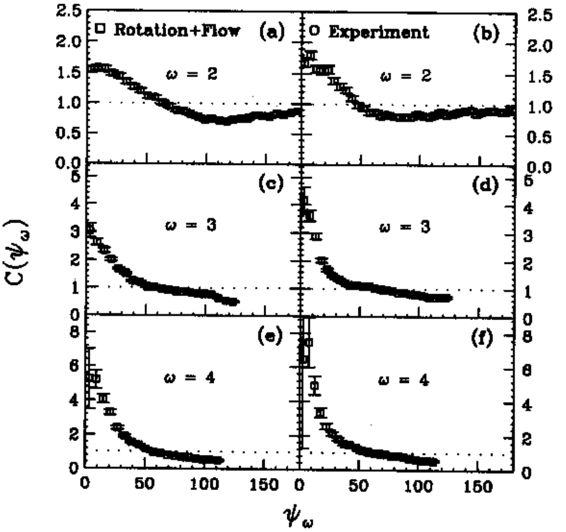


Fig. 2. Experimental (right column) and simulated (left column) azimuthal correlation functions for the system Ar + Sc (35*A* MeV). From top to bottom, correlation functions are shown for fragment pairs, three-fragment multiplets, and four-fragment multiplets, respectively.

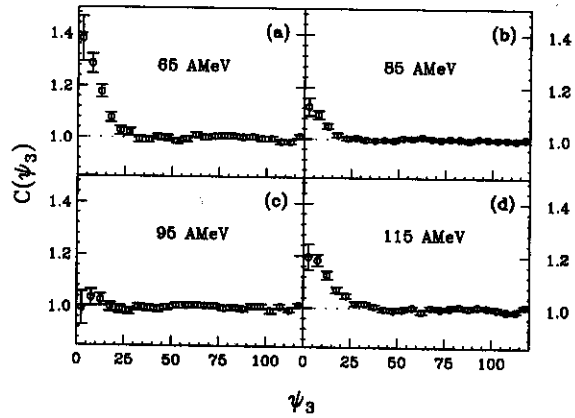


Fig. 3. High-order azimuthal correlation functions for three-fragment multiplets. Correlation functions are shown for the system Ar + Sc for several beam energies as indicated.

rotational collective motion. Of greater significance is the fact that these high-order correlation functions provide new and powerful signatures for their characterization.

Fig. 3 shows experimental high-order azimuthal correlation functions for three-fragment multiplets measured at several different beam energies for Ar + Sc. As discussed above, only fragments with negative cm rapidities ($-0.5 < y < -0.05$) from central collisions ($b/b_{\max} < 0.33$) are used for the evaluation of these correlation functions. Figs. 3a–3d show results for 65, 85, 95, and 115*A* MeV, respectively, subsequent to small corrections for momentum conservation. In contrast to the experimental correlation function shown earlier for the 35*A* MeV beam (cf. Fig. 2d), the overall features of these correlation functions are consistent with a preponderance of collective flow. The validity of this notion is demonstrated in Fig. 4 where the experimental three-fragment correlation function for negative rapidity fragments (Fig. 4e) is compared to that for mid-rapidity fragments (Fig. 4f). For orientation, calculated results for pure collective flow (Figs. 4a, and 4b), and pure rotational collective motion (Figs. 4c, and 4d) are also included in the figure. A comparison of Figs. 4a and 4b clearly shows that the strong flow signature exhibited by negative rapidity fragments is essentially absent when mid-rapidity fragments are selected. On the contrary, the signature for rotational collective motion shown by negative rapidity fragments is unperturbed when midrapidity fragments are selected (cf. Figs. 4c and 4d). This being the case, it is evident from Fig. 4f that rotational contributions to the experimental correlation function shown for negative rapidity fragments (Fig. 4e) are not significant at 65*A* MeV. If present,

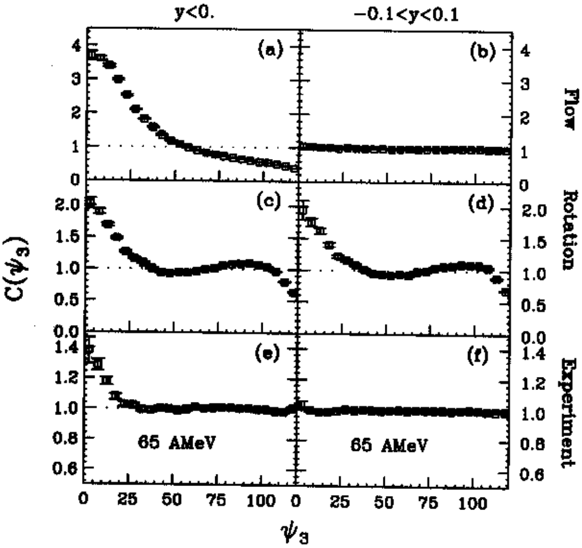


Fig. 4. Correlation functions for negative rapidity fragments (left panel) and mid-rapidity fragments (right panel). Simulated results are shown for flow (a and b) and rotation (c and d). Experimental results are shown for 65*A* MeV Ar + Sc (e and f).

the characteristic features of such contributions would show up in Fig. 4f. A similar analysis leads to the same conclusion for beam energies $\geq 65A$ MeV. This finding is consistent with earlier work [21] which demonstrated that rotational collective motion is negligible [for the Ar + Sc system] for beam energies $\gtrsim 65A$ MeV.

A prominent feature of Fig. 3 is the evolution of collective motion with increasing beam energy. In this figure, one observes that the positive correlations at small ψ angles decrease with increasing beam energy up to $\approx 95A$ MeV. This decrease is consistent with the disappearance of flow. As the beam energy is increased above $95A$ MeV, one sees clear evidence for an increase in the strength of the correlation function at small ψ, indicating the re-appearance of flow. These results constitute the first demonstration of the power of high-order correlation functions for the study of the disappearance of flow. They are particularly important because they circumvent any significant complication associated with reaction plane determinations.

Precise measurements of the beam energy at which collective flow disappears ($E_{\rm bal}$) is of great current interest for constraints on the nuclear EOS. Consequently, we have made a first attempt to extract $E_{\rm bal}$ from our multifragment correlation data. In light of the discussion above, one can assume that the peaks [in the correlation functions] at small ψ angles are dominated by flow for beam energies $\geq 65A$ MeV. Using this assumption, we represent the magnitude of collective flow as an integral of $C(\psi_3) - 1$ over the angular range 0–40 degrees. These integrals are plotted as a function of beam energy in Fig. 5. In the figure, we have assigned negative flow values for beam energies less than $95A$ MeV in accordance with results from BUU calculations [9,10]. The dashed curve in Fig. 5 illustrates the results of a fit to the unsigned values of the integrals with the function Flow = $A \times |E_{\rm beam} - E_{\rm bal}|$. The value of $E_{\rm bal}$ ($93 \pm 4A$ MeV) extracted from such a fit corresponds to the point of intersection of the curve with the dotted line representing zero flow in Fig. 5. When the analysis is repeated for $\omega = 2$, a similar value is obtained for $E_{\rm bal}$ ($94 \pm 8A$ MeV) but the associated error bar is much larger. The reported error bars represent the 90% confidence limits obtained for $E_{\rm bal}$ from the fits. The extracted value of $E_{\rm bal}$ [for $\omega = 3$] compares rather well with the value ($\approx 87 \pm 12A$ MeV) previously obtained for the Ar + Sc system [15,30]; however, the accuracy is much better and the approach provides for considerable improvement.

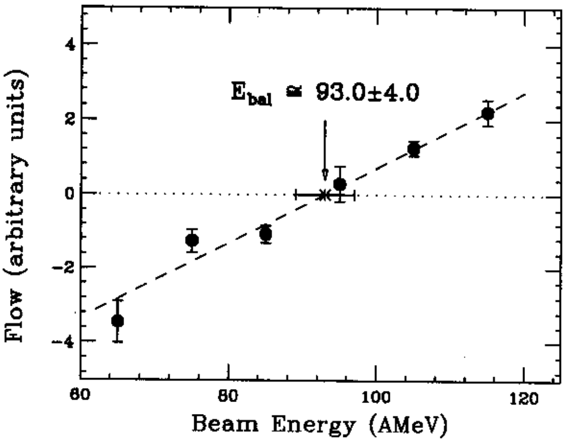


Fig. 5. Flow vs. beam energy for the system Ar + Sc. Negative flow values are assigned for beam energies $<95A$ MeV (see text). The dashed curve represents a fit to the data as discussed in the text.

In summary, we have demonstrated the utility of high-order multifragment azimuthal correlation functions as probes for rotational collective motion and the determination of $E_{\rm bal}$ (i.e. the disappearance of flow) at intermediate energies. We have shown that higher-order correlation functions yield new and distinct signatures for rotational collective motion that allow its distinction from flow. Such signatures may very well prove invaluable for the distinction and characterization of these types of collective motion. We have also shown that high-order correlation functions offer a powerful alternative for the study of the disappearance of flow at intermediate energies. First results for the system Ar + Sc yield a value for $E_{\rm bal} = 93 \pm 4A$ MeV. The directness and precision of high-order multifragment azimuthal correlation functions can be said to provide an alternative/supplement to those analyses of collective motion which rely on knowledge of the reaction plane.

This work is supported in part by the National Science Foundation and the Department of Energy. J.L. acknowledges support from the Conseil Général de la Réunion (France) and the Institut des Sciences Nucléaires de Grenoble (France).

References

[1] G. Bertsch et al., Phys Rep. 160 (1988) 189.
[2] H. Stocker et al., Phys. Rev. C 25 (1982) 1873.
[3] Gutbrod et al., Rep. Prog. Phys. 52 (1989) 1267.
[4] P. Danielewicz et al., Phys. Rev. C 38 (1988) 120.
[5] G.M. Welke et al., Phys. Rev. C 38 (1988) 2101.
[6] G. Peilert et al., Phys. Rev. C 29 (1989) 1402.
[7] G. Bertsch et al., Phys Lett. B 189 (1987) 384.
[8] J.J. Molitoris et al., Nucl. Phys. A 477 (1986) 13c.
[9] W. Bauer et al., Phys. Rev. Lett. 61 (1988) 2534.
[10] V. De La Mota et al., Nantes-GANIL-Grenoble preprint (1992), and references therein.
[11] D. Krofcheck et al., Phys. Rev. Lett. 63 (1989) 2028.
[12] C.A. Ogilvie et al., Phys. Rev. C 42 (1990) R10.
[13] J.P. Sullivan et al., Phys. Lett. B 249 (1990) 8.
[14] W.M. Zhang et al., Phys. Rev. C42 (1990) R491.
[15] G.D. Westfall et al., Phys. Rev. Lett. 71 (1993) 1986.
[16] F. Garcias et al., LPN Nantes Preprint (1991).
[17] W.K. Wilson et al., Phys. Rev C 41 (1990) R1881.
[18] M.B. Tsang et al., Phys. Rev. C 44 (1991) 2065.
[19] T. Ethvignot et al., Phys. Rev. C 43 (1991) R2035.
[20] W.K. Wilson et al., Seventh Winter Workshop on Nuclear Dynamics (W. Bauer and J. Kapusta ed.) World Scientific Pub. (1991) 139-146.
[21] R.A. Lacey et al., Phys. Rev. Lett. 70 (1993) 1224.
[22] W.K. Wilson et al., Phys. Rev. C 45 (1992) 738.
[23] M.B. Tsang et al., Phys. Lett. B 297 (1992) 243.
[24] J.P. Sullivan et al., Nucl. Phys. A 540 (1992) 275.
[25] S. Wang, Phys. Rev. C 44 (1991) 1091.
[26] J. Jiang et al., Phys. Rev. Lett. 68 (1992) 2739.
[27] G.D. Westfall et al., Nucl. Instr. and Meth. A 238 (1985) 347.
[28] T. Li et al., MSU Preprint.
[29] C. Cavata et al., Phys. Rev. C 42 (1990) 1760.
[30] D. Krofcheck et al., Phys. Rev. C 43 (1991) 350.