BRIEF REPORTS

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Deep inelastic collisions in the system $^{40}Ar + ^{232}Th$ at 31 MeV/nucleon

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The charge, velocity, and angular distributions of three coincident fragments measured for the system ^{40}Ar on ^{232}Th at an incident energy of 31 MeV/nucleon evidence a deep inleastic collision process followed by fission. The estimated total kinetic energy loss is about 600–800 MeV which represents roughly 60–80% damping of the initial kinetic energy.

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In heavy-ion reactions with incident energies below 10 MeV/nucleon, deep inelastic collisions (DIC) are a well-known phenomenon. These reactions are interpreted as collisions in which the projectile follows an orbital trajectory around the target nucleus. This trajectory is governed by the balance between attractive nuclear and repulsive Coulomb forces. The long contact time between projectile and target allows for a large mass transfer and a high-energy dissipation. The collision system $^{40}Ar + ^{232}Th$, studied in this article, has previously been investigated at energies close to the Coulomb barrier and the typical behavior of the DIC has been well demonstrated [1,2].

In the medium energy regime (above 20 MeV/nucleon) a new reaction class has been found in which intermediate mass fragments (IMF) are emitted. The reaction mechanism of peripheral collisions is often described in terms of the participant-spectator picture where the nucleons of the overlapping region of the two nuclei form a highly excited subsystem while the remaining parts of the projectile and target continue on their way with almost beam velocity or stay at rest in the laboratory system, respectively [3]. The energy spectra of the IMF's have been analyzed in this framework by decomposition into a targetlike, a projectilelike, and an intermediate component. Only recently has an attempt been made to take DIC into account as a production mechanism for the IMF's at 27 MeV/nucleon [4]. In an experiment where the circular polarization of γ rays emitted in coincidence with IMF was measured [5], negative deflection angles were observed for the fragments. The polarizations measured in coincidence with fragments with $A \geq 4$ were comparable to the polarizations observed for DIC at much lower incident energies. The present paper is focused on the existence of DIC at 31 MeV/nucleon.

The reaction $^{40}Ar + ^{232}Th$ has been previously studied at medium energies and gave evidence for a rapid disappearance of fission in central collisions with increasing incident energy [6]. For a closer inspection of the evolution of central collisions a second experiment had been performed at GANIL, Caen (France). Analyzing these new data we found an interesting event class: triple coincidences with two medium-mass fragments and a third rather light nucleus. The part of the experimental setup which is relevant for discussing these events is shown in Fig. 1. It consisted of three position-sensitive parallel-plate avalanche counters (PPAC's). Two of them (PPAC 1 and PPAC 2), sized 30×30 cm^2 [7], were mounted at a distance of 30 cm from the target and at angles of 55° and 50°, covering angular ranges of 28°–82° and 23°–77°, respectively. PPAC 3, sized 17×15 cm^2, was mounted at an angle of 110° relative to the beam direction on the same side as PPAC 2 and at the same distance and spanned an angular range of 94° to 126°. PPAC's 1 and 2 were operated with n-heptane at a pressure of 3 mbar, while isobutane at a pressure of 7 mbar was utilized for PPAC 3. A metallic 1.2 mg/cm^2 thick ^{232}Th target was used. The energy loss and the velocity of the fragments were measured with the PPAC's, using the time signal of the accelerator. From these two quantities an estimate of the atomic number of the fragments was obtained using an iterative procedure [8] yielding a charge resolution of about 30%. The amplitude of the ΔE signal was calibrated using a ^{252}Cf source. This allowed to calculate the efficiency of the PPAC which was limited by the threshold applied to the ΔE signal. With this method an efficiency of 100% was determined for fragments with $Z > 10$. Since the precise determination of the lower threshold in Z is of big importance for the charge distri-

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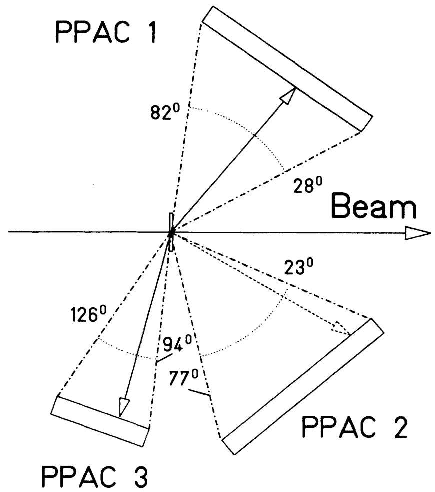

FIG. 1. Experimental setup consisting of three large-area parallel-plate avalanche counters (PPAC).

butions shown in this paper it has been verified by increasing the ΔE threshold offline and controlling its influence on the resulting charge distributions.

The main characteristics of the triple coincidences are summarized in Fig. 2. Figures 2(a)–2(d) show the velocity and charge distributions at 31 MeV/nucleon incident energy for PPAC 1 and PPAC 2. The detection of a third fragment in PPAC 3 introduces a strong asymmetry in the spectra of PPAC 1 and PPAC 2 despite their symmetric position relative to the beam. The fragments detected in counter 1 show a narrow velocity distribution, centered at 1.4 cm/ns, their charge distribution is peaked at $Z \approx 40$. In Fig. 2(e) the relative velocity between the fragments detected in PPAC 1 and PPAC 3 is shown. The narrow distribution, centered at the Viola velocity, together with the charge and velocity distribution of the fragment detected in counters 1 and 3 (not shown) indicate that coincidences between two fission fragments were observed with these counters. In PPAC 2 fast ($v \approx 3$ cm/ns) and light fragments are detected. The dotted line in Fig. 2(d) marks the lower threshold for full detection efficiency of the PPAC. The peaked structure of the measured distribution reflects therefore the efficiency loss of the counter, folded with the resolution of the analysis method used for the charge measurement. A small fraction of events was observed, with two fission fragments detected in PPAC 1 and PPAC 2, together with an IMF in PPAC 3. These events were removed in the analysis by suppressing fission in PPAC 2 by a v_2-ΔE_2 cut.

The velocity and charge distributions observed for the fragments detected in counter 2 show properties characteristic of inelastically scattered projectiles as observed in the low-energy regime. Namely, (i) their charges are close to the projectile charge, (ii) the velocities are well below those of the beam (7.7 cm/ns), (iii) the angular distribution is strongly forward peaked [Fig. 2(f)], and finally (iv)—as shown in Fig. 3—the fragments in counter 2 lie preferentially in the plane spanned by the two fission

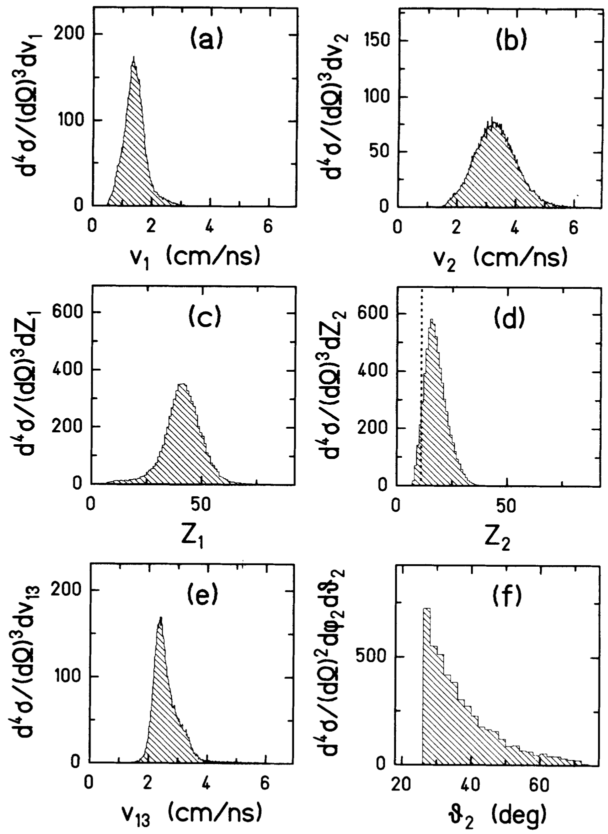

FIG. 2. Properties of triples coincidences in PPAC's 1, 2, and 3. (a) Distribution of fragment velocities measured with PPAC 1. (b) The same quantity measured with PPAC 2. (c) Fragment-charge distribution measured with PPAC 1. (d) The same quantity measured with PPAC 2. The dotted line marks the threshold for full detection efficiency. (e) Distribution of relative velocities between fragments detected in PPAC 1 and PPAC 3. (f) Angular distribution of the fragments detected in PPAC 2.

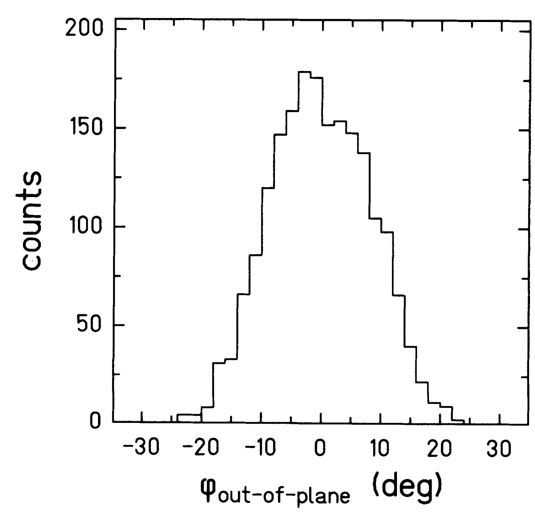

FIG. 3. The distribution of the measured azimuthal angles $\psi_{\text{out-of-}plane}$ between the projectilelike fragment and the fission plane exhibits a strong in-plane correlation.

fragments. In the picture of a deep inelastic collision, this results from the transferred angular momentum in the primary collision. The subsequent fission process of the targetlike fragment occurs preferentially in the plane perpendicular to the spin axis. The width of this out-of-plane distribution is significantly smaller than the geometrical acceptance of the respective PPAC ($\phi=\pm 30°$). All these observations lead us to conclude that the projectilelike partner (or the remaining part) of a DIC is observed.

To calculate the total kinetic energy loss (TKEL) of the reactions leading to the triple coincidences a detailed momentum balance of all fragments was done, including the momentum carried away by preequilibrium particles. The masses of the detected fragments were calculated using the iterative method for kinematical coincidences from Casini *et al.* [9]. This method takes advantage of the overdetermined kinematics for three fragments and yields the primary velocities. Required input for the calculations—besides the angles and velocities of the fragments—are the total mass of the three-body system, which depends on the number of preequilibrium particles assumed for the respective calculation and its center-of-mass velocity. The center-of-mass velocity was determined by comparing the masses deduced from the kinematical coincidence analysis to the charges calculated from the velocity and ΔE information of the PPAC's. The momentum balance finally allowed to determine the velocity and kinetic energy of the preequilibrium particles. Their number has been varied between 20 and 30 such that their velocities fall in the range of 0.5–1 times the beam velocity. With this assumption TKEL values of 600–800 MeV are obtained which corresponds to 60–80 % damping of the available kinetic energy.

It is interesting to compare our results with the 4π neutron detector data for the system $^{40}Ar+^{197}Au$ at 44 MeV/nucleon incident energy [10,11]. High neutron multiplicities are observed in reactions triggered by projectilelike fragments at 20°, yielding similar TKEL values as in our case. Also, Boltzmann-Uehling-Uhlenbeck calculations performed for nearly the same incident energy, evidence typical binary deep-inelastic collisions from the grazing impact parameter up to half its value [12]. For strongly damped collisions the contact times are very similar to those obtained in experiments close to the Coulomb barrier.

The experimental data show no dependence of the deduced TKEL value upon the deflection angle of the projectile fragments, in the angular range between 30° and 70° studied here, i.e., at values larger than the grazing angle (9°). A similar observation has been made for the system $^{40}Ar+^{nat}Ag$, where such a correlation was seen only in the vicinity of the grazing angle [4]. This suggests that the projectilelike fragment is deflected towards negative angles, as observed for the system $^{14}N+^{154}Sm$ at similar incident energies [5].

To get an estimate of the cross section, a Monte Carlo calculation was performed to obtain the efficiency of our setup for triple coincidences. In the angular range of 30° to 60°, a contribution of around 100 mb is estimated for IMF's to originate from DIC (followed by fission).

In summary, the triple coincidences observed in the system $^{40}Ar+^{232}Th$ are interpreted as projectilelike fragments issuing from DIC followed by fission of the targetlike partners. This process has been identified by the charge, energy, and angular distribution of the light fragments and the relative velocity and charges of the two other fragments. TKEL values were estimated to about 600–800 MeV corresponding to a rather strong damping of the initial motion. This high-energy loss, which is independent of the emission angle, indicates negative deflection angles for these collisions.

The presence of DIC shows that, even at Fermi energies, nuclei behave collectively. This process must be taken into account when studying multiplicities and cross sections for IMF production in this regime.

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[1] A. G. Arthuk, G. F. Gridnev, V. L. Mikeev, V. V. Volkov, and J. Wilczynski, Nucl. Phys. **A215**, 91 (1973).

[2] J. C. Jacmart, P. Colombani, H. Doubre, N. Frascaria, N. Poffé, M. Riou, J. C. Roynette, C. Stéphan, and A. Weidinger, Nucl. Phys. **A242**, 175 (1975).

[3] R. Dayras, A. Pagano, J. Barrette, B. Berthier, D. M. De Castro Rizzo, E. Chavez, O. Cisse, R. Legrain, M. C. Mermaz, E. C. Pollacco, H. Delagrange, W. Mittig, B. Heusch, R. Coniglione, G. Lanzano, and A. Palmeri, Nucl. Phys. **A460**, 299 (1986).

[4] B. Borderie, M. Montoya, M. F. Rivet, D. Jouan, C. Cabot, H. Fuchs, D. Gardès, H. Gauvin, D. Jacquet, F. Monnet, and F. Hanappe, Phys. Lett. B **205**, 26 (1988).

[5] M. B. Tsang, W. G. Lynch, R. M. Ronningen, Z. Chen, C. K. Gelbke, T. Nayak, J. Pochodzalla, F. Zhu, M. Tohyama, W. Trautmann, and W. Dünnweber, Phys. Rev. Lett. **60**, 1479 (1988).

[6] M. Conjeaud, S. Harar, M. Mostefai, E. C. Pollacco, C. Volant, Y. Cassagnou, R. Dayras, R. Legrain, H. Oeschler, and F. Saint-Laurent, Phys. Lett. **159B**, 244 (1985).

[7] H. Stelzer, W. H. Daues, and N. Shenhav, GSI Scientific Report 1984, p. 293.

[8] V. Lips, Diploma thesis, Technische Hochschule Darmstadt 1989, GSI Scientific Report, 1987, p. 309.

[9] G. Casini, P. R. Maurenzig, A. Olmi, and A. A. Stefanini, Nucl. Instrum. Methods A **277**, 445 (1989).

[10] J. Galin, J. L. Charvet, B. Cramer, E. Crema, H. Doubre, J. Frehaut, B. Gatty, D. Guerreau, G. Ingold, D. Jacquet, U. Jahnke, D. X. Jiang, B. Lott, C. Magnago, M. Morjean, J. Patin, E. Piasecki, J. Pouthas, F. Saint-Laurent, E. Schwinn, A. Sokolov, and X. D. Wang, in *Proceedings of the Symposium on Nuclear Dynamics and Nuclear Disassembly,* Dallas 1989, edited by J. B. Natowitz (World Scientific, Singapore, 1989), p. 320.

[11] A. Sokolov, D. Guerreau, J. L. Charvet, B. Cramer, H.

Doubre, J. Fréhaut, J. Galin, B. Gatty, G. Ingold, D. Jacquet, U. Jahnke, D. X. Jiang, B. Lott, C. Magnago, M. Morjean, Y. Patin, E. Piasecki, J. Pouthas, and E. Schwinn, Nucl. Phys. **A562**, 273 (1993).

[12] M. F. Rivet, B. Borderie, C. Grégoire, D. Jouan, and B. Remaud, Phys. Lett. B **215**, 55 (1988); D. Jouan, B. Borderie, M. F. Rivet, C. Cabot, H. Fuchs, H. Gauvin, C. Grégoire, F. Hanappe, D. Gardès, M. Montoya, B. Remaud, and F. Sébille, Z. Phys. A **340**, 63 (1991).