Unusual Behavior of Projectile Fragments from the Interaction of Copper with Relativistic Ar Ions

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Projectile fragments formed in the interaction of 0.9*A*- and 1.8*A*-GeV ^{40}Ar ions with a Cu disk interact with a second Cu disk and the relative yields of products in the two disks are measured by radioactivation techniques as a function of the distance between them. The data at 1.8*A* GeV demand either (1) decay in flight ($t_{1/2} \approx 10^{-10}$ s) of some projectile fragments having large cross sections or (2) production of secondaries with unexpectedly large transverse momenta.

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The formation of projectile fragments (PF) with anomalously short mean free paths in relativistic heavy-ion collisions has attracted considerable interest in recent years.[1] The existence of these "anomalons" has not been definitively established.[2–10] Thus, it is important that as many different techniques as possible be used to study the problem. We report here the first results of experiments in which the formation, interaction, and possible decay of PF has been investigated by use of radioactivation techniques.[11]

The principle of the experiment is shown in Fig. 1. An Ar-ion beam is used to irradiate two Cu disks. The primary Ar beam along with any secondary fragments from Ar-Cu interactions can induce target-fragmentation reactions in the Cu disks, which produce the usual observable radioactive products. The ratio, R_d, of the radionuclide activities found in the downstream ("detector") disk to those in the upstream ("target") disk is measured for three separations of the disks, $d = 0.0$ cm (contact), 10 cm, and 20 cm. For radionuclides resulting from the interaction of the primary Ar beam or strongly foward-peaked PF with the disks, we would expect R_d to be independent of the distance between the disks (provided that the beam is not diverging). If R_d decreases with increasing d, then the species inducing the target-fragmentation reactions in the second disk either have a broad angular distribu-

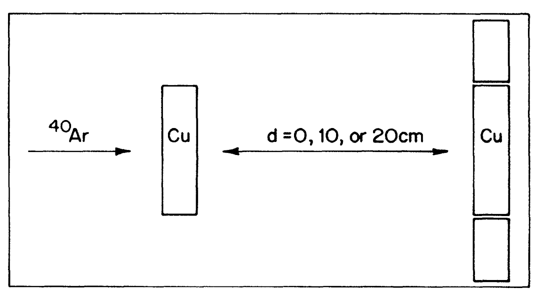

FIG. 1. Schematic diagram of the target arrangement. The two copper disks (diameter = 8 cm, thickness = 1 cm) are separated by a distance d ($d = 0$, 10, or 20 cm). The downstream disk is surrounded by a 1-cm-thick Cu ring, 14 cm in outer diameter.

tion causing them to "miss" the second disk, or decay in flight between the disks. To evaluate the former possiblity, large annular guard rings are installed around the second disk. If broad PF angular distributions cause R_d to decrease with d, significant activities should be observed in the guard rings when the disks are far apart. In the absence of such an effect, a decrease of R_d with d may be a measure of the lifetime of any decaying PF.

The circular Cu disks were 1 cm thick and 8 cm in diameter. The 1-cm-thick guard rings had inside diameters of 8 cm and outside diameters of 14 cm. Thus the rings subtended angles of approximately 83°–86° with respect to the center of the first disk when the disks were in contact, and angles of 11°–20° when the disks were separated by 20 cm. Replicate sets of Cu disks were irradiated with about 10^{12} 0.9A- and 1.8A-GeV ^{40}Ar ions in the irradiation station of the Lawrence Berkeley Laboratory (LBL) Bevalac. Autoradiographs of each irradiated disk showed the beam spot to be less than 1 cm in diameter and to be the same for all disks.

The radionuclides present in the irradiated Cu disks and guard rings were assayed by off-line gamma-ray spectroscopy. The guard rings were cut into sections and reassembled to simulate the disk geometry. Measurements were made with Ge(Li) detectors ($\Delta E = 1.8$ keV). Differences in counting efficiencies due to sample geometry were determined with homogeneous ^{24}Na sources produced by the ^{27}Al(n,α) reaction and found to be less than 2%. The analysis of the energy spectra was based on standard radiochemical procedures.[12] Counting was begun within a few hours after the end of irradiation (at LBL) and was continued for several months (at Philipps Universität, Marburg). Independent determinations of most of the radionuclides present in each disk were made at LBL, Purdue University, and Marburg. All of the results agreed within experimental uncertainties and the values from the different laboratories were averaged to give the final results.

Figure 2 shows the dependence of R_d on product mass number for two different separations of the disks for the two ^{40}Ar energies. The dependence of R_d on A is a reflection of the energy spectrum and angular distribution of the PF inducing secondary reactions in the disks. The results for 0.9A-GeV ^{40}Ar show that when the two disks are in contact (R_0), the PF most likely to strike the detector disk lead to the formation (by target fragmentation) of products with $A \approx 55$ and substantial yields are seen for all products with $A > 40$. The products with $A < 30$ (^{7}Be,^{24}Na,^{28}Mg) are formed only in high-deposition-energy target-fragmentation events.[13] They cannot be projectile fragments because these are much too energetic to stop in the copper disks.[14]

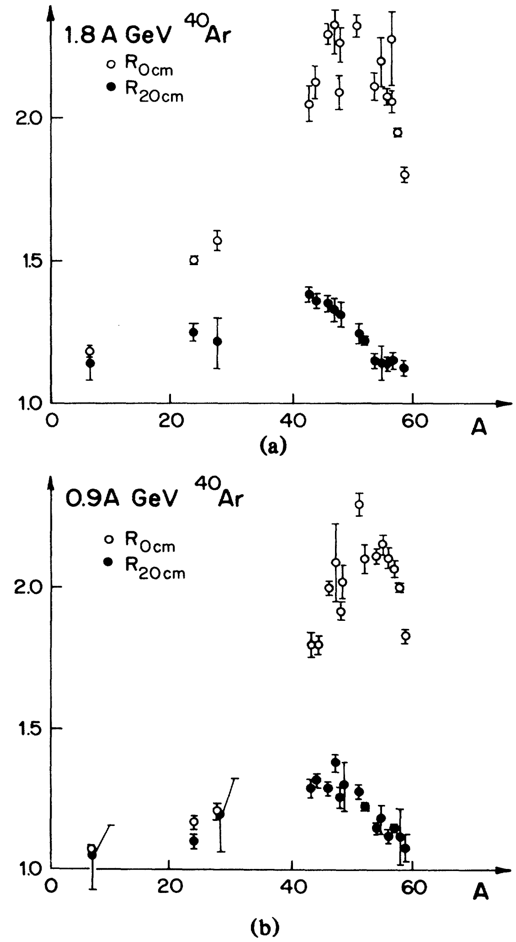

FIG. 2. Product-mass-number dependence of the ratio R_d of the activity in the downstream to that in the upstream Cu disks for nuclides produced in the interaction of copper with relativistic ^{40}Ar ions.

The R_0 values for the light fragments, e.g., 1.17 ± 0.02 for ^{24}Na, can be understood as follows: The interaction of a 0.9A-GeV ^{40}Ar with Cu leads to one heavy projectile fragment plus sixteen energetic nucleons, on average.[14] All of these secondaries can produce ^{24}Na from copper. However, they are more likely to interact in the downstream disk, thereby leading to $R_0 > 1$.

When the disks are moved to 20 cm apart, the detector disk samples a different subset of the PF created in the target disk, i.e., the more strongly foward-focused and thus higher-energy fragments. As a result, the PF most likely to reach the second disk now lead to the formation of products with $A \approx 45$ and the formation of heavier fragments is less likely. The fragments with $A < 30$ are produced with the same yields regardless of disk separation because they are only produced by highly forward-focused, energetic projectile fragments. The activities found in the guard rings support this interpretation. Thus, the guard ring shows essentially no activity of $A < 30$ products ($< 1\%$ of the disk activity for ^{24}Na) when the disks are in contact and very little activity ($\approx 4\%$ of the disk activity for ^{24}Na) when the disks are separated by 20 cm.

For the 1.8A-GeV ^{40}Ar bombardment, the dependence of R_0 on A for $A > 40$ is similar to that obtained with 0.9A-GeV ^{40}Ar except for the shift of the most probable product mass number to a slightly lower value ($A \approx 50$). The values of R_{20} (for $A > 40$) are also similar to those obtained at 0.9A GeV. However, the results for products with $A < 30$ are significantly different from those obtained with 0.9A-GeV ^{40}Ar. The values of R_0 are substantially higher, ranging from 1.2 to 1.6. Furthermore, the ratios decrease with separation between the disks, with the values of R_{20} being 1.1 to 1.2. However, the activities of these products in the guard rings remain low ($< 1\%$ of the disk activity of ^{24}Na at $d = 0$ cm and $\approx 8\%$ at $d = 20$ cm). The variation of R_d with d is shown for ^{24}Na and ^{28}Mg at both bombarding energies in Fig. 3.

The differences between the data for the $A < 30$ products obtained at 0.9A and 1.8A GeV may be examined by means of the quantity

$$X_d = 100(R_d^* - 1)\%,$$

where R_d^* is defined analogously to R_d but with the activity in the guard rings added to that of the detector disks. For ^{24}Na we obtain $X_0 = 17 \pm 2$, $X_{20} = 14 \pm 3$, and $X_{20} - X_0 = -(3 \pm 3)\%$ at 0.9A GeV, and $X_0 = 50 \pm 2$, $X_{20} = 34 \pm 2$, and $X_{20} - X_0 = -(16 \pm 3)\%$ at 1.8A GeV. Thus, at 0.9A GeV, by adding the ^{24}Na activity in the guard ring to that in the detector disk, we are able to account for any apparent loss of activity with increasing disk separation due to the finite width of the PF angular distribution. At 1.8A GeV, however, the same procedure indicates that $(16 \pm 3)\%$ of the activity is "missing." Qualitatively similar results (with larger uncertainties) are obtained for ^{28}Mg.

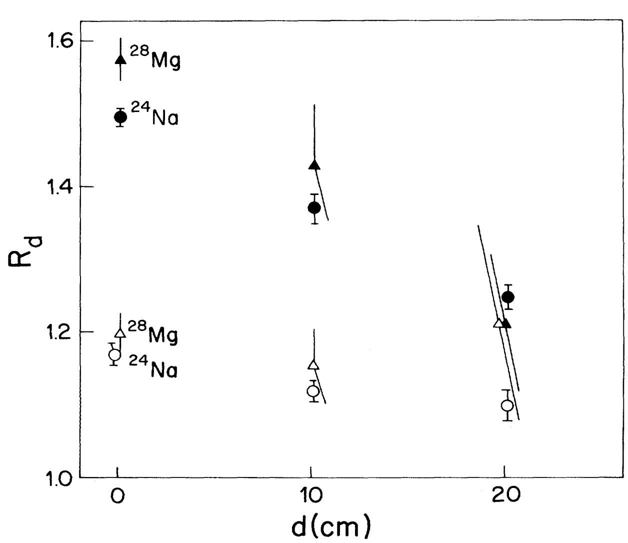

FIG. 3. The ratio R_d for ^{24}Na and ^{28}Mg as a function of the separation distance d between the Cu disks for 0.9A - and 1.8A -GeV ^{40}Ar irradiations. Open points, 0.9A GeV; closed points, 1.8A GeV.

The conventional explanation of the results is that the number of very energetic PF emerging at large angles to the beam increases between 0.9A and 1.8A GeV. The increased yields of these PF would account for the increase in R_0 while their broad angular distribution would cause them to miss the second disk as the disks are moved apart. However, the small fraction of the activities of $A < 30$ products observed in the guard rings as well as the known energy spectra and angular distributions[15] of normal PF and other secondary particles are inconsistent with this interpretation, provided that one takes into account the known high threshold for $A < 30$ production from Cu[13] and the low mean transverse momenta of all secondaries.

To confirm the conclusion, we have performed a "worst case" Monte Carlo calculation of the expected relative ^{24}Na activities in the disks and guard rings (as well as "missed" activity) for a disk separation of 20 cm. In this calculation, we evaluated the ^{24}Na production in the second disk and its guard ring due to three different types of secondaries produced in the first disk: (a) protons evaporated from PF moving with beam velocity, (b) "mid-rapidity" protons "evaporated" from a fireball moving with the p-p center-of-mass velocity and $T = 120$ MeV,[16] and (c) pions which are treated as "evaporating" from the p-p center of mass with $T = 80$ MeV.[17,18] We have further assumed that 80% of the protons evaporated from the PF had $T = 10$ MeV and 20% had $T = 40$ MeV[15] and that the three types of secondaries (a), (b), and (c), are produced in equal abundance. In the computation, each evaporated particle is assigned momentum components p_x^*, p_y^*, and p_z^* drawn randomly from a Gaussian distribution of zero mean and dispersion $\sigma = (mT)^{1/2}$ (where p_i^* refers to the relevant moving frame). The quantities p_z^* and the total energy E^* of the emitted particle are Lorentz transformed into the laboratory-frame quantities $p_{\parallel}$ and E_L. Since the transverse momentum p_T is invariant under Lorentz transformation, each emitted particle emerges at laboratory angle θ, where $\theta = \tan^{-1}(p_t/p_{\parallel})$. The value of θ for each particle emerging from the first disk will determine whether that particle will strike the second disk or its guard ring or miss both, and the probability of inducing a Cu $\rightarrow$ ^{24}Na reaction is calculated by use of the known excitation functions for the reactions $\mathrm{Cu}(p,X)^{24}\mathrm{Na}$ and $\mathrm{Cu}(\pi^-,X)^{24}\mathrm{Na}$.[19,20]

The results of this calculation indicate that the activity of ^{24}Na in the guard ring is about 5% of that in the detector disk at 0.9*A* GeV and decreases to < 1% at 1.8*A* GeV. Similarly, 1.4% of the ^{24}Na activity is expected to be "lost" beyond the guard ring at 0.9*A* GeV but < 1% is expected to be lost at 1.8*A* GeV. Furthermore, the contributions from mid-rapidity protons to the ^{24}Na activities are so low as to exclude also the possibility that even the most energetic protons ($T = 40$ MeV) evaporated from the target nucleus could play any significant role in this problem. Thus, on the basis of conventional nuclear physics, one would not expect any secondary fragments to be produced at 1.8*A* GeV with broader angular distributions than those observed at 0.9*A* GeV. Hence, this explanation of our observations can be ruled out.

Our results can be explained by postulating either one of the following two unconventional effects, or a combination thereof: First, we postulate the formation of a new, unusual, short-lived type of energetic PF as the beam energy increases from 0.9*A* to 1.8*A* GeV. If we assume that the decrease in R_d for 1.8*A*-GeV ^{40}Ar is entirely due to the decay of heavy anomalous PF ($Z > 3$), then a lifetime of $\approx 2\times10^{-10}$ s would be indicated. The production of short-lived particles (Λ, K), which can also form ^{24}Na, is much too low in primary heavy-ion interactions (< 1%) to permit their decay to account for the missing activity.[21] Second, we postulate the emission of highly energetic secondaries with unexpectedly broad angular distributions, i.e., large transverse momenta, a process that is inconsistent with conventional nuclear physics.[14]

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[1]E. Friedlander *et al.*, Phys. Rev. Lett. **45**, 1084 (1980), and Phys. Rev. C **27**, 1489 (1983), and references therein.

[2]M. L. Tincknell *et al.*, Phys. Rev. Lett. **51**, 1948 (1983).

[3]W. Heinrich *et al.*, Phys. Rev. Lett. **52**, 1401 (1984).

[4]A. P. Gasparian *et al.*, Z. Phys. (to be published).

[5]P. L. Jain and G. Das, Phys. Rev. Lett. **48**, 305 (1982).

[6]P. L. Jain *et al.*, Phys. Rev. Lett. **52**, 2213 (1984).

[7]M. M. Aggarwal *et al.*, Phys. Lett. **112B**, 31 (1982).

[8]H. A. Gustafsson *et al.*, Phys. Rev. Lett. **51**, 363 (1983).

[9]J. D. Stevenson *et al.*, Phys. Rev. Lett. **52**, 515 (1984).

[10]T. J. M. Symons *et al.*, Phys. Rev. Lett. **52**, 982 (1984).

[11]The word "decay" in this context should be taken to mean some drastic change as a function of time in the interaction cross section of the projectile fragments.

[12]D. J. Morrissey *et al.*, Nucl. Instrum. Methods **158**, 499 (1978).

[13]J. B. Bumming *et al.*, Phys. Rev. C **17**, 1632 (1978).

[14]Y. Yariv and Z. Fraenkel, Phys. Rev. C **24**, 488 (1981).

[15]H. G. Baumgardt *et al.* J. Phys. G **7**, L175 (1981).

[16]R. Brockmann *et al.*, Lawrence Berkeley Laboratory Report No. LBL-17755, 1984 (unpublished).

[17]S. Nagamiya *et al.*, J. Phys. Soc. Jpn., Suppl. **44**, 378 (1978).

[18]It is easy to show that for a relativistic nucleus evaporating secondary particles of mass m with temperature T, the root mean square angle of emission of the secondary particle in the laboratory frame is given by $\theta_{\rm rms} \simeq (2T/m)^{1/2}/(\gamma^2-1)^{1/2}$, where γ is the Lorentz factor for the emitting system. At any given temperature, the *lightest* evaporation product has the broadest angular distribution. Thus it is sufficient for our purpose to consider only the case of the lightest secondaries.

[19]J. Hudis *et al.*, Phys. Rev. **129**, 434 (1963).

[20]P. E. Haustein, Phys. Rev. C **20**, 1092 (1979).

[21]Gustafsson *et al.*, Ref. 8, investigated the possible decay of anomalons produced in the interaction of copper with 1.7*A*-GeV ^{56}Fe ions. Their experiment was sensitive to the emission at angle 1° to the beam of anomalous fragments with $Z > 5$ and a lifetime of 10^{-11} s. No evidence of decay was observed and it was concluded that the data were consistent both with the nonexistence of anomalons and with the existence of anomalons having a lifetime longer than 5×10^{-11} s. These conclusions are not inconsistent with the results of this work.