PHYSICAL REVIEW C VOLUME 37, NUMBER 3 MARCH 1988

Unusual backward emission of multifragmentation products in ultrarelativistic nucleus-nucleus collisions

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(Received 2 October 1987)

Light fragments such as ^{24}Na resulting from the multifragmentation of Au by 232-GeV ^{16}O are emitted preferentially backwards in the laboratory system ($F/B = 0.81 \pm 0.05$). This effect is not seen for similar products from V, Cu, or Ag targets, or for fission products from Au.

Recent developments in particle accelerator technology have opened a new area of research involving ultrarelativistic nucleus-nucleus collisions at energies above $10A$ GeV. Of special interest to us was the opportunity to study target fragmentation, i.e., the production of large, low velocity, target-related fragments in such collisions. In our work, we looked for any substantial deviations from previously observed behavior for reactions induced by ultrarelativistic protons and relativistic heavy ions ($\lesssim 2A$ GeV). This Brief Report reports evidence for such deviations in the form of an unusual backward emission *in the laboratory system* of multifragmentation products from the interaction of 232-GeV ^{16}O with Au.

Standard thick-target–thick-catcher techniques[1] were used to determine the average kinematic properties of a number of target fragmentation products formed in the reaction of 232-GeV ^{16}O with V, Cu, Ag, and Au targets. Stacks of metal foils with forward and backward catcher foils were irradiated in an external beam of the Brookhaven alternating-gradient synchrotron (AGS) with 232-GeV ^{16}O ions for periods up to 54.5 hours (total particle fluence of 6.3×10^{12} ions). The descriptions of each foil stack are summarized in Table I. Assay of the radioactivity in the central target metal foil and the Mylar catchers was begun within a day after the end of the irradiation. Standard techniques which have been described elsewhere[1] were used to identify the radionuclides present and to determine the activity of each nuclide in the forward and backward catchers and in the target.

These measurements yield the fractions of each target fragmentation radionuclide which recoiled out of a target of thickness W (mg/cm^2) in the forward (F) and backward (B) hemispheres. Table II gives the derived values of the forward-to-backward ratio, F/B, and a quantity, $2W(F+B)$, approximately equal to the mean range of ^{24}Na in the target material. For comparison, data from a similar experiment[2] with 400-GeV protons are also included. Based on trends of results for lower energy heavy ions and protons, it was our initial expectation that the kinematic properties of target fragments from the interactions of 232-GeV ^{16}O ions would be similar to those of 400-GeV protons. The experimental data, however, show significant differences, the most striking being the low F/B ratio for ^{24}Na production from Au by the 232-GeV ^{16}O ions. This effect is not unique to ^{24}Na: the weighted mean F/B value for all observed products with $A < 60$ from Au is 0.85 ± 0.02. These low-mass products are thought to be formed from Au at high bombarding energies exclusively by the high-deposition-energy multifragmentation mechanism.[3] While slightly backward-enhanced, sideward-peaked angular distributions have been observed previously for such products from p-nucleus[4] and nucleus-nucleus collisions,[5] and thick-target–thick-catcher measurements have yielded F/B values near unity, this is the first report in which F/B ratios are so much less than unity.

Large differences between heavy-ion and proton-induced reactions at very high energies appear to be associated with the most violent interactions. The mean F/B value obtained in the present work for typical lower-deposition-energy fission fragments ($A = 70-120$) from 232-GeV ^{16}O interactions with Au was a "normal" 1.35 ± 0.06, in reasonable agreement with that from previous proton-nucleus[6] and nucleus-nucleus[7] studies of Au targets. Examination of Table II also indicates that the F/B ratios for ^{24}Na production from Cu and Ag targets by 232-GeV ^{16}O ions are smaller than those for 400-GeV protons; however, the difference is less pronounced than that for gold. It is interesting to note that values of

TABLE I. Description of target foil stacks.

Central foil material	Central foil thickness (mg/cm^2)	Mylar catcher foil thickness (mg/cm^2)
V	84.5	16.5
Cu	110.6	16.4
Ag	30.0	14.1
Au	49.1	21.8
	223.4	32.0

TABLE II. Comparison of thick-target–thick-catcher recoil properties for ^{24}Na obtained in the present work with those reported for 400-GeV protons. (Reference 2.)

Target	Projectile	F/B	$2W(F+B)$ (mg/cm^2)
V	^{16}O, 232 GeV	2.83±0.09	2.26±0.04
Cu	^{16}O, 232 GeV	1.90±0.07	2.55±0.04
	^{1}H, 400 GeV	2.20±0.06	2.75±0.07
Ag	^{16}O, 232 GeV	1.39±0.05	3.96±0.12
	^{1}H, 400 GeV	1.48±0.04	4.09±0.16
Au	^{16}O, 232 GeV	0.81±0.05	10.7±0.5
	^{1}H, 400 GeV	1.26±0.03	11.8±0.3

$2W(F+B)$ in Table II show at most a small dependence ($<10\%$) on projectile type. Since these "pseudoranges" are determined primarily by some deexcitation step leading to the final product,[1] we conclude that the striking difference in F/B values for the Au target reflects differences in the initial interactions of high-energy heavy ions and protons rather than a change in the breakup mechanism.

In Fig. 1, we compare our measurements of F/B with data from previous investigations[2,6–12] of ^{24}Na production in p-nucleus and nucleus-nucleus collisions involving Cu and Au targets. In the case of Cu, a large body of existing data on ^{24}Na production and for other products as heavy as ^{58}Co is consistent with a simple kinematic model for the interactions.[9,12] This model correctly predicts the limiting fragmentation behavior (independence of bombarding energy) of F/B observed for incident protons above 28 GeV (Fig. 1), but, in its simplest form, suggests the same limit should be reached for heavy ions. The present results show that the limit, if it has indeed been reached for 232-GeV ^{16}O ions, is lower than that for protons, and the model will require modification to include a projectile dependence.

Returning now to ^{24}Na production from Au, data available prior to the present work indicated a rapid convergence of recoil properties with increasing beam energy. As can be seen in Fig. 1, the F/B value for ^{24}Na formation in heavy-ion-induced reactions becomes equal to that for protons at ~25 GeV. The near energy independence of F/B for incident protons above that energy is consistent with limiting fragmentation behavior. While recent measurements[13] suggest that this is also true for production cross sections from heavy ion interactions leading to ^{24}Na, the present experiment indicates a continuing decrease in F/B between 25 and 232 GeV.

The trends of F/B values for ^{24}Na production from Au in Fig. 1 can be correlated qualitatively with changes in fragment angular distributions.[4,5,14,15] For both proton- and heavy-ion-induced multifragmentation reactions, there is a shift at energies between ~3 and ~25 GeV from forward- to sideward-peaked distributions. The distribution for ^{37}Ar produced by 25-GeV ^{12}C ions[5] is virtually identical to those of comparable products from proton interactions.[15] At this energy and above, there is a tendency for peaks in the angular distributions to move to angles somewhat greater than 90°. It has been concluded from a detailed analysis of experiments with 400-GeV protons that this backward enhancement is not the result of a kinematic shift.[16] Velocity spectra of fragments were found to show small "normal" forward shifts. If this is also the case for 232-GeV ^{16}O interactions leading to low-mass products, then the low F/B values observed in the present work imply even more strongly backward-shifted angular distributions than those reported previously.

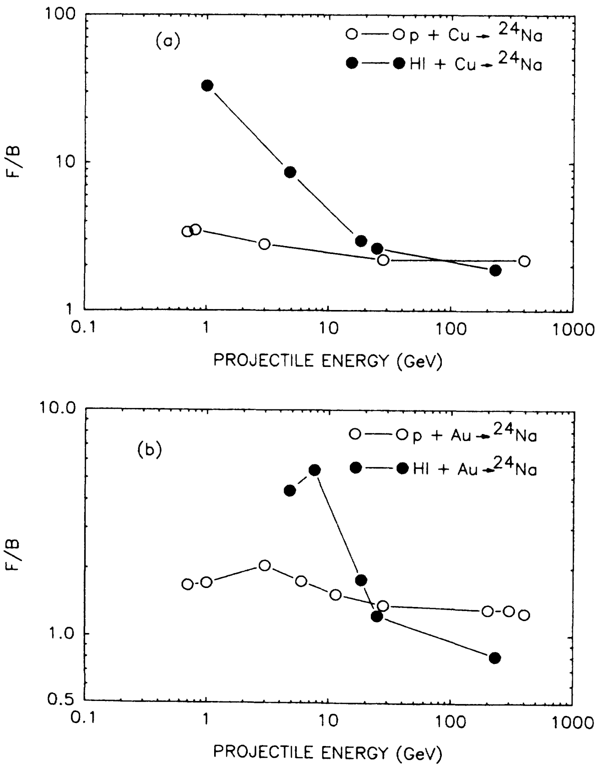

FIG. 1. (a) Energy dependence of the F/B ratio determined by thick-target–thick-catcher measurements for ^{24}Na produced in the reactions of protons and heavy ions (C, O, Ne) with Cu. (b) Same as (a) except the target nucleus is Au.

It would be of obvious interest to measure directly a thin target angular distribution for light products and/or to make more exclusive measurements of multifragmentation events in ultrarelativistic nucleus-nucleus collisions. Such events appear, from our measurements, to have a new character which poses an interesting challenge for theoretical interpretation.

We wish to thank D. Beavis, C. Casey, D. Klingensmith, J. Whitfield, and Z. Xu for their assistance during this experiment. We gratefully acknowledge the support of the U. S. Department of Energy for this work through Contracts DE-AM06-76RL02227, DE-AC02-76CH00016, and DE-AC02-76ER01505, and of the Swedish Natural Sciences Research Council.

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