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Unusual Backward Enhancement in the Angular Distribution of Products from the Interaction of ^{238}U with 400 GeV Protons

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Angular distributions of various Mg, Sc, Cu, Ag, and Ba nuclides produced in the interaction of ^{238}U with 400 GeV protons have been measured. While all the angular distributions peak at ∿ 90°, those obtained for certain products are characterized by greater backward than forward emission in the laboratory system. This category includes both neutron-deficient and neutron-excess Sc fragments as well as neutron-deficient Cu and Ag nuclides.

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The measurement of the angular distributions of light fragments and deep spallation products formed in the interaction of heavy elements with high-energy protons has been of value in the elucidation of the reaction mechanisms. While forward peaking in the laboratory system has been observed up to 3 GeV,[1-4] the results obtained at 11.5 and 29 GeV indicate the occurrence of sideward peaking.[4-6] By contrast, the angular distributions of fission products are sideward-peaked over the entire GeV regime.[2,6] The change from forward- to sideward-peaked angular distributions may be the result of a change in the nature of hadron-nucleus interactions at high energies and has been interpreted as the effect of a nuclear shock wave,[5,7] or the result of a coherent interaction with a part of the nucleus.[8,9] However, a definitive explanation has not as yet been given.

It is of interest to determine whether additional changes in the angular distributions occur at yet higher energies. We report here the first results of angular distribution measurements performed on light fragments, deep spallation products, and fission fragments emitted in the interaction of ^{238}U with 400 GeV protons. While some of these products have distributions that are very similar to those obtained at lower energies, others reveal a novel and highly unusual feature, namely, a larger number of fragments emitted at backward than at forward angles in the lab system.

Thin (200-300 $\mu g/cm^2$) UF_4 targets evaporated onto pure Al backings were irradiated in an evacuated chamber with a 400 GeV proton beam in the Neutrino Hall at Fermilab. The targets, which were inclined at 45° to the beam, faced a cylindrical holder at a radial distance of 9 cm on which were mounted pure Al or Mylar recoil catcher foils. The assembly was irradiated with approximately 3-5 x 10^{13} protons/min for about a one-week period. Autoradiographs and assays of the segmented target indicated that the beam had a full-width of ∿ 3 mm and did not shift during the irradiations. The catcher foils intercepted relatively large solid angles (0.06-0.35 sr) in order to ensure that adequate counting rates would be obtainable. The catchers were therefore cut along laboratory isotheta (θ_L) lines[10] and the solid angles intercepted by each foil were determined with a code which, in addition to the target-catcher geometry,[11] took into account the beam profile at the target location.[12] In a given experiment, the angular distribution was determined between 5° and 105° (or 75°-175°). The foils were cut in 15° wide segments except for the 5°-15° and 165°-175° intervals. The angular distributions obtained at forward and backward angles were normalized at their common intervals. Replicate experiments were performed.

Following the bombardments, magnesium, scandium, copper, silver, and barium were radiochemically separated from the catchers and the samples assayed with γ-ray, X-ray, or β-detectors. Subsidiary experiments indicated that the contribution from impurity activation could be neglected except in the case of ^{28}Mg, where a blank ranging from 2 to 10% was subtracted. Table I lists the nuclides for which results were obtained. Typical angular distributions are shown in Fig. 1 where the laboratory differential cross sections per unit solid angle are normalized to unity at 90°. It was found that good fits to the angular distributions could be obtained with the function

$$F(\theta_L) = 1 + A_1 \cos\theta_L + A_2 \cos^2\theta_L \qquad (1)$$

and the results of these fits are given by the curves in Fig. 1. The least-squares values of A_1 and A_2 are tabulated in Table I. The parameter A_1 is a measure of the forward-backward asymmetry while A_2 reflects the anisotropy. Table I also lists the ratio of the fitted differential cross sections integrated over the forward and backward hemispheres,

$$R(\theta_L) = \int_o^{\pi/2} F(\theta_L)\ \sin\theta_L d\theta_L / \int_{\pi/2}^{\pi} F(\theta_L)\sin\theta_L d\theta_L \qquad (2)$$

It is seen that all the angular distributions peak at ∿ 90°. However, the extent of the anisotropy is not at all uniform. The distributions range from nearly isotropic for ^{111}Ag, a typical symmetric fission product, to highly anisotropic for Sc fragments. The results of similar experiments at 11.5 GeV have been reported for Sc and Ba products.[4,6] The angular distributions of these products were found to peak at sideward angles but the anisotropy was somewhat less pronounced than it is at 400 GeV. Sideward peaking thus appears to be a general feature for fragments, deep spallation products, and fission products at highly relativistic energies.

While some of the products have the usual type of forward-backward asymmetry, i.e. $A_1 > 0$ and $R(\theta_L) > 1$, others display an unusual feature: More fragments are emitted at backward than at forward angles in the lab system ($A_1 < 0$, $R(\theta_L) < 1$). This feature is displayed by both neutron-deficient and neutron-excess Sc fragments and by the neutron-deficient Cu and Ag nuclides. It is not displayed by neutron-excess ^{28}Mg or by any of the Ba nuclides. The backward enhancement lies well outside of experimental error and the fact that it is not displayed by all the products indicates that it cannot be due to some systematic error. While the data are not complete enough to permit a delineation of the (Z,A) region featuring this effect, it is clear that the largest effect occurs for the most neutron-deficient isotopes of those elements for which it is found and appears to be most pronounced in the A=40-50 mass region.

It is of interest to examine the energy dependence of the backward enhancement. The results obtained for Sc fragments at 11.5 GeV[4] show just the slightest hint of this effect ($A_1 \sim -0.02\pm0.01$).[12] Cumming[13] has also found a similar backward enhancement in the angular distributions of some products from the interaction of 29 GeV protons with Au. The observed effect thus appears to occur uniquely at very high energies.

Assuming that emission occurs from a moving system, the backward enhancement can be interpreted in one of the following two limiting ways: Either the emitting nucleus moves backward in the lab system and breaks up symmetrically or, more likely, it travels in the forward direction[14] but the asymmetry in the moving system is even more pronounced than it is in the lab. It is difficult to see how this preferential backward emission arises from the presently known characteristics[8,9,15] of hadron-nucleus interactions at highly relativistic energies. The inclusive nature of the present experiment prevents us from offering a definitive explanation. It would be of interest to perform detailed correlation experiments in order to determine whether these products are formed in some particular type of breakup process. It would also be of interest to determine if the effect is even more pronounced in the TeV energy region, thus providing information on whether the regime of limiting fragmentation has been attained at 400 GeV.

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Table I. Least-squares fit of Eq. (1) to the angular distribution of products from the interaction of ^{238}U with 400 GeV protons.

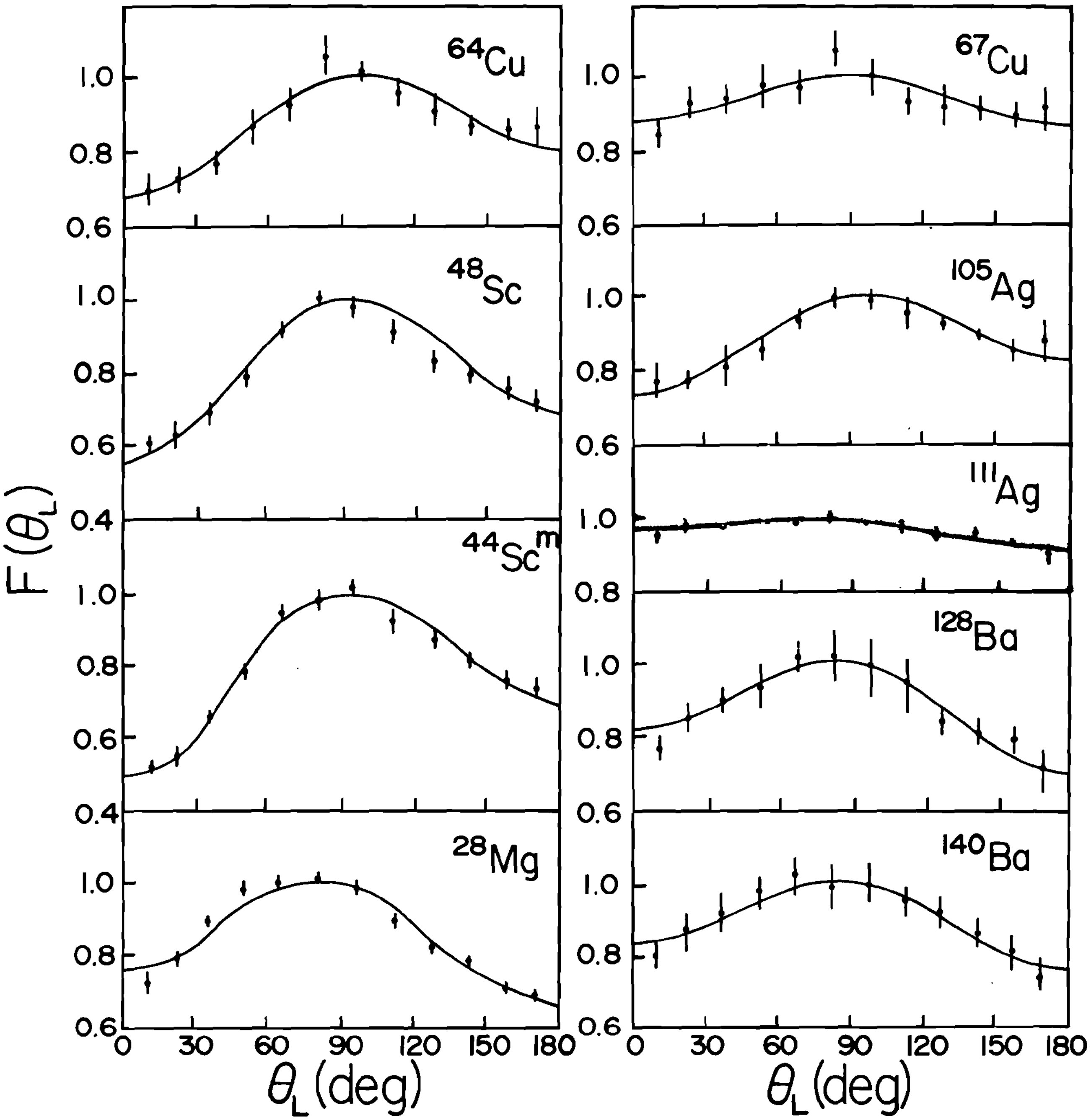
Nuclide	A_1	A_2	$R(\theta_L)$
^{28}Mg	0.054 ± .019	-0.289 ± .020	1.06 ± .02[a]
$^{44}Sc^m$	-0.100 ± .007	-0.411 ± .009	0.89 ± .01[b]
^{46}Sc	-0.056 ± .011	-0.356 ± .012	0.94 ± .01[b]
^{47}Sc	-0.072 ± .008	-0.377 ± .010	0.92 ± .01[b]
^{48}Sc	-0.064 ± .009	-0.374 ± .012	0.93 ± .01[b]
^{64}Cu	-0.067 ± .015	-0.257 ± .016	0.93 ± .01[c]
^{67}Cu	0.008 ± .017	-0.124 ± .019	1.01 ± .02[c]
^{105}Ag	-0.056 ± .017	-0.218 ± .021	0.94 ± .02[a]
$^{106}Ag^m$	-0.042 ± .013	-0.160 ± .021	0.96 ± .01[a]
$^{110}Ag^m$	0.045 ± .015	-0.065 ± .022	1.05 ± .02[a]
^{111}Ag	0.030 ± .003	-0.051 ± .005	1.03 ± .003[a]
^{128}Ba	0.064 ± .037	-0.234 ± .037	1.07 ± .04[b]
^{131}Ba	0.067 ± .020	-0.184 ± .028	1.07 ± .02[b]
^{140}Ba	0.033 ± .012	-0.200 ± .014	1.04 ± .01[b]

a. Data obtained by Chicago group.

b. Data obtained by Purdue group.

c. Data obtained by Argonne group.

Fig. 1. Angular distribution of products from the interaction of ^{238}U with 400 GeV protons. The points are averages of replicate experiments and the curves represent a least-squares fit of Eq. (1).



^{64}Cu
^{48}Sc
^{44}Sc^{m}
^{28}Mg
^{67}Cu
^{105}Ag
^{111}Ag
^{128}Ba
^{140}Ba
F(θL)
1.0
0.8
0.6
0.4
0 30 60 90 120 150 180
θL (deg)
θL (deg)