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Deexcitation Processes in Nuclear Reactions

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Progress Report for the period May 1, 1976 to July 31, 1977

August 1977

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Abstract

A number of nuclear reaction studies are in progress. Measurements of the energy dependence of recoil properties of ^{131}Ce , ^{131}La , and ^{131}Ba formed in the interaction of ^{238}U with 0.8-400GeV protons are described. Preliminary results on the angular distribution and differential ranges of Sc and Ba nuclides formed in the interaction of ^{238}U with 0.8, 3.0, and 11.5GeV protons are given. Preliminary angular distribution measurements of products formed in the interaction of ^{238}U with 400GeV protons are described. A comparative study of the interaction of silver with 25.2GeV ^{12}C ions and high-energy protons is described and results of the analysis of the proton data are presented. The formation of ^{24}Na in the interaction of gold with protons and π^+ has been studied and preliminary results are reported.

I. Research Activities

During the past year our research program has concentrated on the following areas: studies of deep spallation and fragmentation processes in reactions induced by high-energy protons; a comparative study of the interaction of relativistic heavy ions and protons with silver; studies of the fragmentation process in pion-induced reactions.

A number of the high-energy reaction studies under present investigation are an outgrowth of an important discovery made in our laboratory several years ago¹. It was found in this earlier work that the recoil properties of deep spallation products formed in the interaction of ^{238}U with high-energy protons underwent a transition at 2-3 GeV. The ranges of these products, and hence their kinetic energies, thus decreased by nearly a factor-of-two while the forward-to-backward emission ratios (F/B) went through a pronounced peak at this energy. One of the products exhibiting this behavior was ^{131}Ba . However, since this product was separated from the uranium target several hours after irradiation, it actually represented a weighted average of ^{131}Ba and its isobaric progenitors, i.e. ^{131}Ce and ^{131}La . In order to better understand the nature of this transition we are presently investigating its dependence on isobaric composition by measurement of the energy dependence of the recoil properties of ^{131}Ce , ^{131}La , and ^{131}Ba between 0.8 and 400 GeV. These experiments involve rapid chain-breaking separations and in the past year we have concentrated on the recoil behavior of ^{131}Ce , the most neutron deficient isobar with $A = 131$ amenable to measurement. We have performed experiments with 0.8 GeV protons at LAMPF and with 2-6 GeV protons at the ZGS. The month of June, 1977, was particularly fruitful since we were able to perform 9 ZGS irradiations. A preliminary analysis of the data indicates that the peak in F/B occurs at a higher energy for

^{131}Ce than for the more neutron-rich isobars but a quantitative analysis remains to be performed.

While thick-target recoil studies provide a useful first look at a new mechanism or energy region, a more complete understanding requires more detailed experiments. We are thus in the course of performing a number of angular distribution and differential range measurements in order to obtain a better understanding of the above transition. Two closely related studies involve measurement of the angular distributions and differential ranges (at 90° to the beam) of a number of Ba and Sc nuclides formed in the interaction of ^{238}U with high-energy protons. The experiments are being performed at 0.8 GeV, which is below the transition energy, at the transition energy (3 GeV), and above this energy (11.5 GeV). The experiments on Ba nuclides are designed to provide further information on the types of products discussed above while those on scandium nuclides will provide similar results on the properties of light fragments, whose thick-target recoil properties have previously been investigated². The experiments involve the irradiation of thin ($\leq 300 \mu\text{g}/\text{cm}^2$) targets of UF_4 surrounded by aluminum or Mylar catcher foils. Because of the low activity levels of the products these experiments are being performed in a relatively high-geometry configuration. The analysis of such experiments has been discussed elsewhere³.

Figure 1 shows preliminary results for the angular distribution of ^{131}Ba (cumulative) at these energies. It is seen that the angular distribution changes from one featuring moderate forward peaking at the lowest energy to sideward ($\sim 60^\circ$) peaking at the highest energy. The 3 GeV curve is perhaps the most unusual since it displays the greatest degree of forward peaking while at the same time appearing to drop off at the lowest angles. Since this drop-off is based on a single datum, confirmatory experiments must still be performed.

Previous angular distribution studies at 2 GeV⁴ do not, in fact, reveal such a dropoff but instead yield a curve that is qualitatively similar to the 0.8 GeV angular distribution. At any rate it is obvious that the angular distributions have features that cannot be inferred from the F/B values.

A closely related study involves the measurement of the differential range and angular distribution of ¹³¹Ba (independent), ¹³¹La, and several other Ba nuclides at 11.5 GeV. This experiment is a more detailed version of an interesting study previously performed in our laboratory⁵. In this earlier work we measured the average ranges of 8 isobaric nuclides with A = 131 and found that they fell into three distinct groups: Sb, Te, I, Xe, and Cs had the long ranges characteristic of binary fission; La and Ce had the short ranges associated with deep spallation; and Ba had an intermediate range. This suggested that ¹³¹Ba was formed to a comparable extent by both mechanisms. However, this remains a supposition and additional mechanisms have been proposed⁶. Differential range and angular distribution measurements should clarify this situation since if our original supposition is correct the range and angular distribution of ¹³¹Ba should have comparable contributions from these two mechanisms as given by the results for neighboring deep spallation (¹³¹La) and fission (¹⁴⁰Ba) products. The experiment is a difficult one since it requires breaking the ¹³¹La → ¹³¹Ba decay chain in a time short or at most comparable to the ¹³¹La half-life (59 min) for all 6-12 samples obtained in a given experiment. Corrections for La decay during bombardment and prior to separation introduce sizeable uncertainties thus requiring the performance of a number of replicate determinations. Although difficult, this is an important experiment since it should for the first time indicate unambiguously how many mechanisms are active in complex nuclear reactions at multi-GeV energies.

During this past year work was started on an Argonne-Chicago-Purdue

collaboration to measure the angular distribution of a variety of products formed in the interaction of ^{238}U with 400 GeV protons obtained at Fermilab. Our group was responsible for the design and construction of the target and catcher holder, for the calculation of the solid angles subtended in the rather high geometry of this experiment, and for the separation and assay of palladium nuclides. While several irradiations were performed, this experiment remains in a somewhat preliminary stage due to a variety of difficulties. These were primarily due to the fact that this experiment is being performed on a parasitic basis and we have no control over beam properties or irradiation length.

Considerable effort was devoted this past year to the study of the interaction of relativistic heavy ions with silver and to a comparative study with high-energy protons. Most of the experimental measurements for 25.2 GeV ^{12}C ions obtained at the Bevalac have been completed and we have finished the analysis of the 300 GeV proton data. A preliminary communication has been published⁷.

The proton experiment yielded some 80 cross sections and we expect to obtain a comparable number from the ^{12}C experiments. In addition to a direct comparison of the two sets of cross sections it is desirable to systematize the data in terms of a charge dispersion and mass-yield analysis. This has customarily been done by fitting the measured yields with the Rudstam formula⁸ and using the parameters obtained from the fit to obtain the unmeasured yields. We were unable to obtain an adequate fit with this formulation and attribute this to the fact that at multi-GeV energies the contribution of fragmentation becomes sufficiently large to destroy the usefulness of a formula designed solely for spallation reactions. We have instead chosen to fit the cross sections with a polynomial expression and have used the non-linear least

squares formulation of Cumming⁹ for this purpose. We found that the following 11-parameter expression gave the best fit to the data:

$$\sigma(Z,A) = \exp\{\alpha_1 + \alpha_2 A + \alpha_3 A^2 + \alpha_4 A^3 + (\alpha_5 + \alpha_6 A + \alpha_7 A^2) \cdot |Z_p - Z|^{\alpha_8}\}$$

where Z and A are the atomic and mass number of a given product and the most probable charge at a given mass number, Z_p , is given by the expression $Z_p = \alpha_9 + \alpha_{10} A + \alpha_{11} A^2$. The eleven α parameters are obtained by an iterative procedure in which the cumulative yields are corrected for the precursor contribution. Figure 2 shows the charge distribution fit. The points designated F_{cor} consist of the experimental cross sections, corrected for progenitor contribution wherever appropriate, divided by the total isobaric yield at the mass number in question. Since the width of the charge distribution is mass dependent the points were corrected to a common mass number, $A = 70$, by means of the above expression. The curve is the result of the least-squares fit evaluated at $A = 70$. This particular approach permits the presentation of all the charge-dispersion data on a single graph. It may be noted that the above equation provides a good fit to the data over a two-magnitude range in cross sections and for products extending $2Z$ units on either side of Z_p . It is worthwhile to note that the shape of the calculated curve is determined by α_8 , whose value is 1.50 ± 0.01 . The resulting curve is more sharply peaked but has broader wings than the commonly assumed Gaussman charge distribution, which is obtained when $\alpha_8 = 2.0$.

The mass-yield curve may be obtained by combining the measured cross sections with least-squares values for the unmeasured yields and the results are shown in Figure 3. The points are the sums of the experimental and unmeasured cross sections and the curve is that given by the analytical expression. It is seen that the mass-yield curve decreases exponentially between

$\sim A = 100-60$, then more gradually down to $A \sim 40$, at which point the yields begin to increase. A steeper dropoff in yields may be noted close to the target mass number.

Considerable progress has been made this past year on a study of fragmentation in pion-induced reactions. In this experiment the cross sections for producing ^{24}Na from gold are measured for both incident pions and protons. At bombarding energies of a few hundred MeV these projectiles differ in two ways that are of importance to an understanding of the fragmentation mechanism: first, the momentum of a given energy pion is much lower than that of a proton of the same energy, and second, the total energy that can be transferred to the struck nucleus by a pion is substantially higher because of the possibility of pion absorption. These differences suggest that a comparison of fragment production cross sections in reactions induced by protons and pions should indicate whether fragmentation occurs as a result of high energy transfer, e.g. formation of a nuclear hot spot, or high momentum transfer, e.g. coalescence of correlated nucleons.

The excitation function for the formation of ^{24}Na in reactions induced by 200-800 MeV protons was measured at LAMPF some time ago. This past year we have concentrated on the pion-induced reaction and measured the excitation function for incident π^+ . A preliminary report of this work has been published¹⁰. The results obtained to date are summarized in Fig. 4. It is seen that, at a given bombarding energy, the ^{24}Na production cross section is higher for incident π^+ than for protons. It may be noted that the proton bombarding energy corresponding to a given π^+ cross section is 100-150 MeV higher than the π^+ energy indicating that the pion absorption energy transfer mechanism is of primary importance.

The research performed this past year is in compliance with the contract

requirements and closely follows the outline submitted in the last renewal proposal. The principal investigator has devoted approximately 50% of his time and effort to this project during the present contract year. It is expected that this figure will be maintained at the same level for the remainder of the year.

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Figure 1

Angular distributions of ^{131}Ba (cumulative) from the interaction of ^{238}U with high-energy protons. The forward-to-backward emission ratios (F/B) derived from the distributions are tabulated.

Figure 2

Charge distribution for the interaction of Ag with 300 GeV protons. The

quantity F_{cor} is defined as
$$F_{\text{cor}} = \frac{\sigma(Z,A)_{\text{exp}}}{\sigma(A)_{\text{calc}}} \times \frac{F_{\text{calc}}(Z_p - Z, A=70)}{F_{\text{calc}}(Z_p - Z, A)}$$

where F_{calc} is the calculated fractional mass yield at a given $(Z_p - Z)$ and A value. The various symbols refer to nuclides in different mass intervals:

o, A=20-40; ●, A=40-60; Δ, A=60-80; ▲, A=80-100.

F_{cor}

0.1

0.01

-2.0

-1.0

0

1.0

2.0

$Z_p - Z$

Figure 3

Mass-yield curve for the interaction of Ag with 300 GeV protons. Closed points - experimental cross sections account for $\geq 50\%$ of isobaric yield; open points - 25-50% of isobaric yield is measured. The solid curve is the result of the analytical expression given in the text and the dashed curve shows the behavior close to the target.

Figure 4

Excitation function for the formation of ^{24}Na in the interaction of ^{197}Au with protons (Δ) and π^+ ($\bullet$).

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