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A PROPOSAL FOR THE STUDY OF HIGH-ENERGY REACTION MECHANISMS BY THE MEASUREMENT OF THE ANGULAR AND ENERGY DISTRIBUTIONS OF NUCLEI RECOILING FROM TARGETS BOMBARDED WITH 200-300 GEV PROTONS

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Summary

When energetic particles interact with complex nuclei, a wide variety of product nuclei is formed. In earlier work at FNAL (Experiment E-81), the formation cross sections of a large number of product nuclides formed from various targets were measured, as well as the average recoil properties (mean momentum and forward-to-backward ratio) of some of them. As a result of these initial experiments, some of which are still continuing, it is now proposed to make more detailed measurements of the recoil properties of certain radioactive nuclides. Using a thin target (ca 0.1 mg/cm^2) inside an evacuated chamber surrounded by catcher foils, the angular distribution and the range distribution at specific angles will be determined for specific radionuclides. Such detailed kinematic measurements will aid in the effort to characterize the mechanisms of nuclear reactions at ultra-relativistic energies.

I. Introduction

A large fraction of the experiments proposed by the group of nuclear chemsits associated in Experiment E-81 have been completed, resulting in a number of publications(1-13). Based on these results, it is now possible to propose a series of more detailed experiments in order to clarify further the mechanisms of interactions of multi-GeV protons with complex nuclei. As an introduction, we will briefly review the results obtained by the different groups involved in E-81, in order to give the background of the present proposal.

The first experiments were the measurement of relative cross sections for forming a large number of radionuclides from various targets bombarded with 200-300 GeV protons. The targets included vanadium(1), cobalt(1), silver(2,6), uranium(3,4,8,13) and gold(9,12). The cross sections were measured relative to the monitor reaction ^{27}Al (p,X)^{24}Na, assuming that the monitor cross section was constant. This assumption was confirmed recently by measurement(11) of the absolute cross section for the reaction ^{12}C(p,pn)^{11}C and its ratio to the aluminum reaction.

The results of these experiments show that the formation cross sections show little change between proton energies in the 10-30 GeV range and 300 GeV. For targets of the lighter elements, the cross section ratios σ(300 GeV)/σ(10-30 GeV) average close to unity; for heavy targets, the ratio varies regularly with mass of the product, but still remains within 20-30% of unity for most products. The fission probability of heavy elements has also been found to be essentially the same over this energy range(14). Although these details of the production cross sections are of considerable interest, the overall constancy above 10 GeV bombarding energy implies that the distribution of excitation energy left in the nucleus by the passage of a very relativistic proton is essentially independent of energy above 10 GeV. Since the mean multiplicity of particles formed in proton-proton collisions increases by a factor of three between 10 and 300 GeV, one concludes that these additional particles created in the initial proton-nucleon interaction escape from the nucleus without contributing to the spread of the intranuclear cascade process.

A second type of experiment done concurrently with the cross section measurements was the measurement of the mean momentum of the radionuclides. This was done by determining the fraction of a given nuclide which recoils out of a target foil into a catcher foil in both the forward and backward directions with respect to the beam (integrated over 2π solid angle). These fractions can be related to the mean range of the recoiling nuclide in the target material, which can be converted to mean kinetic energy with standard range-energy tables. Such measurements have been done for targets of aluminum(5), gold(7,9,10,12) and uranium(3,4,7,8,13). In addition to the mean momentum, one can also obtain a crude angular distribution based on the forward-to-backward ratio (F/B) of the recoils. One can see intuitively that the F/B of a product is a measure of the forward momentum imparted to the target nucleus by the incident proton for the set of processes which form that particular product.

The mean momentum of many of the products investigated appears to be independent of bombarding energy above 10 GeV, as were the cross sections. However, certain types of products, such as light nuclides formed from heavy targets, show a decrease of 20-30% in mean momentum at 300 GeV. A more dramatic change was seen in the F/B values of these light nuclides. For example, the F/B values of the nuclides ^{24}Na and ^{28}Mg formed from gold and uranium targets were largest (F/B = 2.0) at a bombarding energy of 3 GeV, and decreased to F/B = 1.25 at 300 GeV. A similar change was found for certain heavy nuclides (e.g., ^{131}Ba) formed from the same targets, while other heavy nuclides (e.g., ^{140}Ba) exhibit a constant F/B = 1.05, independent of bombarding energy. Still another class of nuclides seems to be those of masses A = 40-70 formed from gold and uranium. This latter class has F/B = 1.4-1.6 near 3 GeV, decreasing to F/B = 1.0 at 300 GeV, i.e., they show forward-backward symmetry at the highest bombarding energy.

The interpretation of these results is not clear at present, but it seems to imply that the efficiency of forward momentum transfer by the incident proton to the struck nucleus actually decreases with increasing incident energy for certain products. The present proposal concerns itself with the more detailed investigation of these very interesting phenomena.

II. Details of Proposal

The results summarized above were obtained by experiments done on a parasite basis, using the FNAL Radiation Physics electric train track in the Meson Hall, without interfering with other experiments. They served the valuable purpose of giving us a general survey of the reactions of 300 GeV protons with complex nuclei. Some of these experiments are still in progress, and the availability of 400-500 GeV protons will permit additional measurements at these higher energies, but it is now desirable to propose a new type of experiment to study certain reactions in more detail.

We propose to measure the angular distributions with good resolution of specific radionuclides which recoil out of a thin target upon irradiation with FNAL protons (300-500 GeV). In addition, we will measure the range distributions at specific angles of these nuclides. These experiments will give considerably more detailed information than the simple 2π, forward-backward measurement done so far. The target must be thin compared to the range of the nuclide to avoid smearing of the distributions by scattering, and the catcher foils used for the range measurements will also be thin in order to obtain the momentum distribution of the nuclides, rather than simply a mean value. The target will be uranium, since all of the interesting phenomena have been observed with uranium targets. Furthermore, one can identify certain products which are formed almost entirely by binary fission at low excitation energies (e.g., ^{140}Ba), thus providing an additional basis for comparison.

An evacuated chamber will be placed in an external proton beam, with a thin target (ca 0.1 mg/cm^2) in its center. Foils of aluminum surrounding the target serve as catchers for the recoiling nuclei. The duration of the run will be a function of the half-lives of the nuclides to be studied and their cross sections, and will be from three to six eight-hour shifts.

Following a given run, the catcher foils will be removed, cut into pieces representing different angular intervals (or for the range measurements, the stack of foils at a given angle will be removed), and assayed for the products of interest by counting the radiations. Because of the extremely thin target, only small amounts of radioactivity will be formed, thus requiring a counting method of high efficiency. This rules out the use of Ge(Li) detectors, whose high resolution is off-set by low efficiency. Selected elements will therefore be chemically separated from the catchers, and counted separately,using beta counters or NaI crystals. This will result in a large number of individual samples of low counting rate, and all of the counting facilities of the individual laboratories participating in this experiment will be used simultaneously. Typical radionuclides of interest include ^{32}P, ^{47}Ca, ^{67}Cu, ^{89}Zr, ^{128}Ba and ^{140}Ba.

The results of these measurements will provide a detailed kinematic picture of the various types of products formed in these reactions. From this information we hope to be able to learn whether new reaction mechanisms are involved at ultra-relativistic energies.

III. Beam Requirements

The intensity required for these experiments is $\geq 2 \times 10^{12}$ protons/pulse, i.e., one of the beams in the Proton Laboratory. The spot size required is < 4 mm diameter. Assuming an intensity of 2×10^{12}, the total amount of beam time required is 500 hours. This time should be divided into individual blocks of 24-48 hours each, with blocks separated by one or more months. This spacing is to allow the necessary time to count the large number of samples and to follow the decay curves of the radioactivities.

The chamber will be furnished by the experimenters, and will be adapted from a chamber owned by the ANL group. The only apparatus to be provided by FNAL is the existing counting facilities and Chemistry Laboratory in the Village, and the normal beam monitoring and profile displays.

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