Protons from 2.7-GeV Protons on Ag and Br†

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The cross section for nonelastic collisions of 2.7-GeV protons in Ag and Br nuclei has been determined. Among 3565 such collisions in nuclear emulsions, the tracks of 646 outgoing protons with kinetic energies in the range 80–850 MeV were identified by measurements of ionization and multiple Coulomb scattering. The differential cross sections for proton emission were derived and compared with the predictions of Bertini using the Monte Carlo treatment of the intranuclear cascade. Reasonable agreement has been found.

INTRODUCTION

In the spallation of complex nuclei by bombarding particles with energies in the GeV region, the emission of relativistic products has been broadly distinguished from recoil nucleons and evaporation fragments.[1] The nuclear collisions caused in photographic emulsions by 300–400-MeV protons have been analyzed by a Monte Carlo method,[2] but following this work, the publication of corresponding data for nuclear spallation between 1 and 3 GeV has been sparse.[3] Typically, in two notable papers devoted to interactions in proton targets,[4,5] there are interesting extensions to the products of collisions in complex nuclei. The appearance, therefore, of detailed information[6] regarding the emission spectra of different products arising at laboratory angles of 13° and 93° from Be and Pt targets bombarded by 2.9-GeV protons is timely. Interest in the problem is enhanced through Bertini's development of the Monte Carlo method to describe the intranuclear cascade at energies as high as 3 GeV.[7]

A notable feature in the results of Piroué and Smith is found in the momentum distribution of the emergent protons at both laboratory angles. These spectra exhibit pronounced maxima, at ~0.7 GeV/*c* for 13° and at ~0.35 GeV/*c* for 93°, regardless of the target. This characteristic is contrary to our experience and to the prediction of the intranuclear-cascade program. The effect may be due in part to target absorption. Since nuclear emulsions containing an exposure to 2.7-GeV protons were available and, in the energy region in question, charged pions are readily distinguishable from protons, it was decided to carry out further measurements on emergent protons with energies between 80 and 850 MeV in an attempt to resolve this point.

COMPARISON OF THEORY AND EXPERIMENT

In comparing the predictions of the Monte Carlo calculation with experimental results from nuclear emulsions, the poor statistics for the number of tracks measured in each interval of energy or angle is the most obvious disability. This effect is magnified by the geometric corrections at large polar angles. However, a more fundamental objection enters if it is assumed that the Monte Carlo program for the intranuclear cascade has greater validity in more massive nuclei, so that an attempt is made to exclude from the experiment those collisions that occur in the light nuclei of the emulsion. A criterion for this purpose is described. This procedure, however, along with partial elimination of collisions in light nuclei, also removes those collisions in Ag and Br that result in low ($\gtrsim$ 150 MeV) nuclear excitation, from which the cascade proton spectrum might be harder than average. The experiment, therefore, contains a source of uncertainty which might not only affect the total cross section, but also cause distortion of the differential cross sections. Although this effect is not considered to be large, a method for removing it is being sought. It is also contemplated that in further comparisons with theory, separate cascade calculations will be carried out for Ag and Br, rather than a single calculation for ^{100}Ru.

EXPERIMENTAL

A stack of ten 2×3-in. Ilford G5 emulsions, each 400 μ thick, was exposed in the internal 2.7-GeV circulating proton beam of the Brookhaven Cosmotron. The beam was parallel to the emulsion plane, and the integrated beam intensity was 2.0×10^5 cm^{-2}. The ionization of the beam tracks showed no significant gradient between emulsion interfaces and was consistent in all plates with the ionization minimum for singly charged particles. The kinetic energy of the beam particles has been verified both by multiple Coulomb scattering measurements on the beam tracks and by

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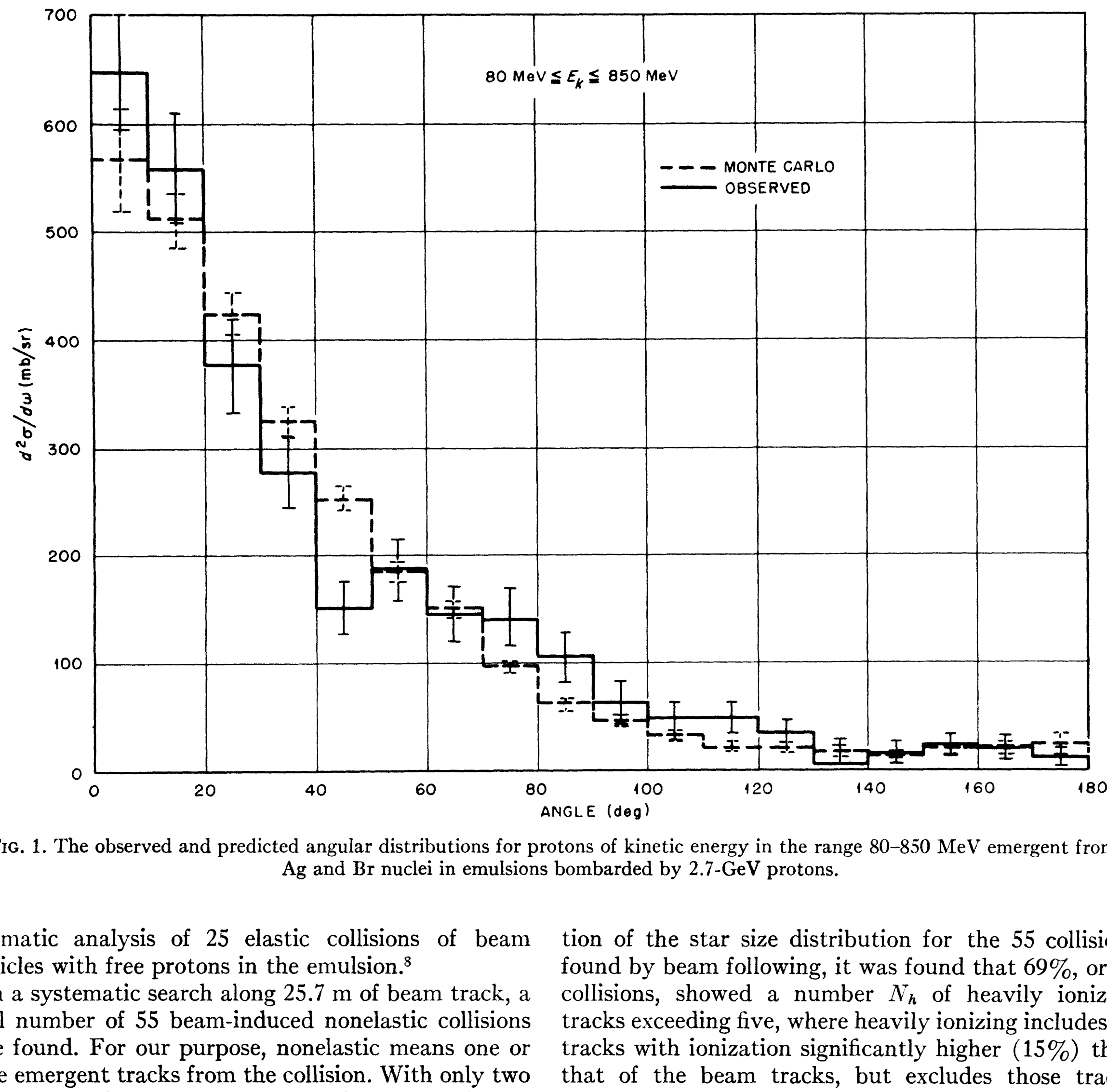

FIG. 1. The observed and predicted angular distributions for protons of kinetic energy in the range 80–850 MeV emergent from Ag and Br nuclei in emulsions bombarded by 2.7-GeV protons.

kinematic analysis of 25 elastic collisions of beam particles with free protons in the emulsion.[8]

In a systematic search along 25.7 m of beam track, a total number of 55 beam-induced nonelastic collisions were found. For our purpose, nonelastic means one or more emergent tracks from the collision. With only two emergent tracks, the star was required to be inconsistent with an elastic proton-proton collision. With only one emergent track, the star was included if that track either showed an ionization significantly greater (15%) than the beam ionization or its polar angle of emission exceeded 10°. From the known constitution of the emulsion and considerations of nuclear radius, it would be expected that 69% of the beam proton collisions occur in Ag and Br nuclei and 31% in the light-emulsion nuclei.[9] The observed mean free path should accordingly be composed of 67±9 cm in Ag and Br, and 154±21 cm in C, N, O, and H. The nonelastic cross section deduced for 2.7-GeV protons on the heavy-emulsion nuclei is therefore 740±100 mb. Furthermore, through inspection of the star size distribution for the 55 collisions found by beam following, it was found that 69%, or 38 collisions, showed a number N_h of heavily ionizing tracks exceeding five, where heavily ionizing includes all tracks with ionization significantly higher (15%) than that of the beam tracks, but excludes those tracks evidently due to pions. The condition $N_h \geq 5$ thus provides a reasonable criterion for collisions of 2.7-GeV protons in Ag and Br, or more accurately, for Ag and Br collisions resulting in nuclear excitation $\gtrsim$ 150 MeV.[1] A similar criterion has been employed for collisions of energetic negative pions.[4]

A systematic examination of all the nuclear collisions in 5.0 cm³ of emulsion was then carried out. A record was kept of those collisions which (a) were caused by a beam particle, (b) showed $N_h \geq 5$, and (c) were located not less than 30 μ from an interface of the emulsion. A total of 3565 such stars were inspected closely. When an emergent track from one of these collisions displayed a visible length exceeding 3.0 mm in a single plate, measurements were made of the grain density, the polar-emission angle, and the multiple Coulomb scattering.[10]

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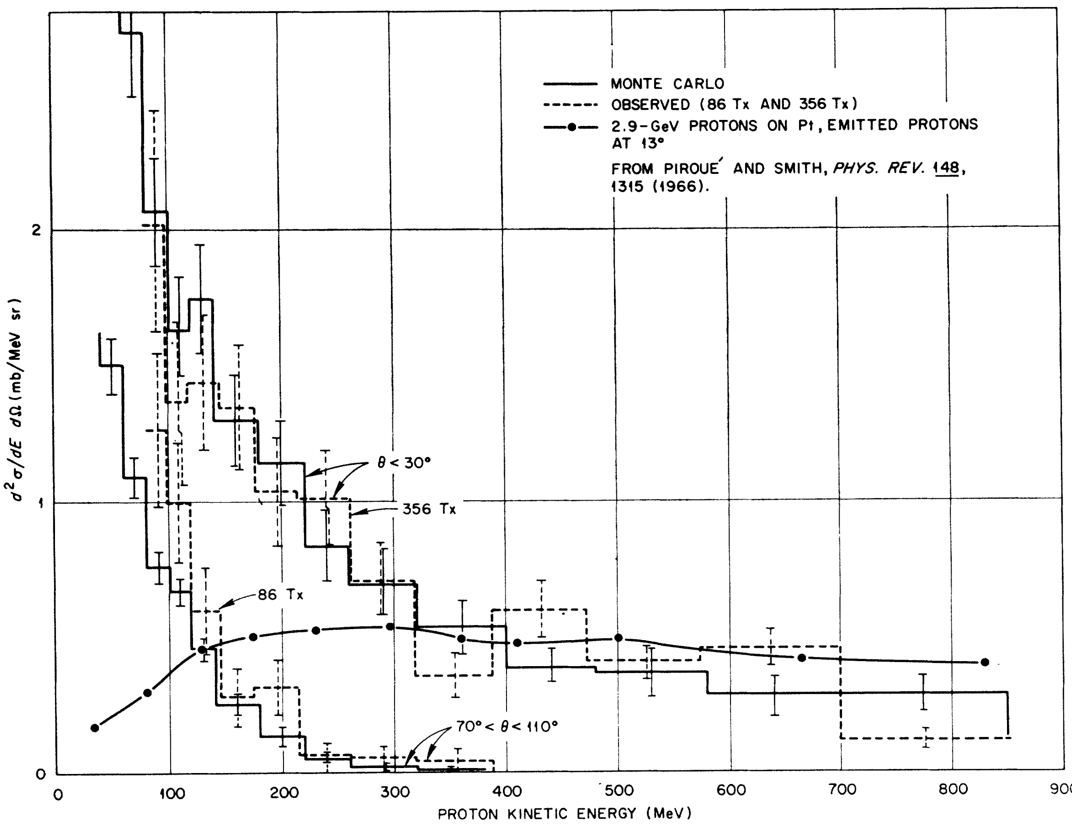

FIG. 2. The observed and predicted energy distributions for protons emergent at angles <30° and 70°–110° from Ag and Br nuclei bombarded by 2.7-GeV protons. The small-angle and large-angle spectra are based on 356 and 86 tracks, respectively.

From the ionization calibration for these emulsions, it is possible to relate those emergent tracks of grain density g in the range $80>g>23/100\,\mu$ with singly charged particle velocities v in the range $0.39c<v<0.85c$.[11] Further comparison of the mean angle of multiple Coulomb scattering with the particle velocity allowed identification of charged pions among the outgoing protons in that velocity range. There is some uncertainty in the differentiation of protons from deuterons, but it is believed that less than 2% of the outgoing proton tracks has been misidentified. The measurements gave data on 646 long tracks of protons emergent with kinetic energies in the range 80–850 MeV from 3565 beam collisions in Ag and Br nuclei. By applying a geometric correction factor based on the track-length condition and the observed emission angles, it was then possible to account for emergent protons with visible track lengths <3 mm. A total of 7260 emergent protons was deduced, corresponding to an average of 2.04 protons (80–850 MeV) from each collision. The corresponding emission cross section is 1500±260 mb.

[11] Particles with charge $>e$ cannot achieve such low values of grain density in these emulsions. For $v>0.85c$, the discrimination of protons from charged pions becomes too uncertain in a 3-mm track.

The angular distribution of the observed emergent protons may be deduced because the track-length condition and the interval of emission angle define an element of emission solid angle. The uncertainties in the experimental result shown in Fig. 1 are due to statistics. For comparison, the angular distribution predicted by the Monte Carlo program developed by Bertini is given in the same figure. The theoretical result is derived from 5000 histories of the intranuclear cascade produced in ^{100}Ru by 2.7-GeV protons and is based on the protons energent between 80 and 850 MeV. The emission cross section in this interval found from the Monte Carlo program is 1460±140 mb; the experimental and theoretical results are evidently in reasonable agreement.

Among the 646 long proton tracks, those 356 which occurred with polar angles <30° were divided among 12 energy intervals in order to examine the forward-angle spectrum. The interval limits were chosen so that approximately the same number of tracks occurred in each interval. For the large-angle spectrum, the 86 tracks between 70° and 110° were divided among eight energy intervals. After appropriate solid-angle corrections, the differential cross sections $d^2\sigma/d\Omega\,dE$ in mb/sr MeV were evaluated as shown in Fig. 2. Again, the indicated error bars are based only on the statistical uncertainties. Also in Fig. 2, the cross sections predicted from the Bertini program are shown. The calculated results are extracted in the same ranges of polar angle as for the experiment. Therefore, it is concluded that at both forward and large angles, the proton spectra decrease rapidly with increasing energy and that the experimental results are in reasonable agreement with the Monte Carlo calculation.

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Study of the Reactions Cd(Ar^{40}, xn)Dy†

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Excitation functions are reported for the reactions of Cd^{114} and Cd^{116} with Ar^{40} to produce Tb^{149}, Dy^{150}, and Dy^{151}. Range measurements in Al for the recoiling Dy products indicate that compound-nucleus formation is the first step in the reaction. From the cross sections, it is concluded that the angular momentum spectrum for the reactions Cd(Ar^{40}, $6n$ and $7n$) is very similar to that for (Ne^{20}, $6n$ and $7n$) reactions. The range measurements extend the span of experimental range-energy information for these nuclei from 4 to 60 MeV. These range data expressed in terms of fractional effective charge [$\gamma = Z_{\rm eff}/Z$] are found to correlate well with data for $Br^{79,80}$, I^{127}, and fission fragments.

I. INTRODUCTION

THE production of Tb^{149}, Dy^{150}, and Dy^{151} nuclei by (HI, xn) reactions has been extensively studied with projectiles as massive as Ne^{22}.[1–5] In the present paper, we report the measurement of excitation functions and ranges in Al for Tb^{149}, Dy^{150}, and Dy^{151} produced by (Ar^{40}, xn) reactions with Cd^{114} and Cd^{116}. Similar measurements have been reported by Kumpf and Karnaukhov[6] who used the internal beam of the Dubna cyclotron. Comparison of these excitation functions with those for (C^{12}, $6n$ or $7n$) and (Ne^{20}, $6n$ or $7n$) reactions suggests that Ar^{40} deposits, on the average, about the same angular momentum spectrum as does Ne^{20}.

The new range data extend the experimental measurements for Dy ranges in Al to 60 MeV. This broad span allows a more direct comparison with range and stopping power information for fission fragments and other heavy nuclei.

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II. EXPERIMENTAL METHODS

Separated isotopes of the following composition were obtained from the Isotope Sales Division, Oak Ridge National Laboratory: cadmium-114 (99.09% Cd^{114}, 0.07% Cd^{116}); cadmium-116 (97.2% Cd^{116}, 1.44% Cd^{114}). Targets were prepared by vacuum evaporation of $Cd^{114}F_2$ and $Cd^{116}F_2$ onto weighed Al discs. Target thicknesses of 30–50 μg/cm² were determined by weight. It is estimated that the uncertainty in determining the average target thickness by this method is $\pm 2\%$.

Stacks of these targets and various catcher foils were mounted on water-cooled copper blocks and irradiated with Ar^{40} beams from the Berkeley HILAC; the copper target assembly served as a Faraday cup. Irradiation energies for each target were calculated from the experimental range-energy curve of Sikkeland for Ar^{40} in Al.[7] The initial energy of the beam was taken to be 10.6 Mev/amu. The energies of the recoiling product nuclei were calculated from the following relationship for compound nucleus formation:

$$E_R = A_b A_R E_b / (A_b + A_T)^2, \quad (1)$$

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