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PRODUCTION OF HIGH-MOMENTUM DEUTERONS FROM NUCLEI BOMBARDED BY 1-BeV PROTONS*

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It has been known[1] for many years that large numbers of deuterons are produced whenever nuclei are bombarded by high-energy protons. In general, the previous data[1] were measured at large angles and low deuteron momenta, with the qualitative results that the ratio of the number of deuterons to protons varied between 1 and 10%. About ten years ago, Azhgirei et al.,[2] in analyzing the high-momentum spectra of particles produced by a 675-MeV proton beam incident on light nuclei, observed a small peak on the high-energy tail of the elastically scattered protons. From the momentum of this peak they concluded that these particles were deuterons resulting from the collision of the incident protons with quasifree n-p pairs in the nucleus.

The data of Ref. 2 were obtained using ^{7}Li, ^{9}Be, ^{12}C, and ^{16}O at only one deuteron-scattering angle, 7.6°, to the incident proton beam. Using a magnetic spectrometer[3] and a time-of-flight system to separate deuterons from protons, we have carried out similar measurements on ^{4}He, ^{6}Li, ^{12}C, ^{16}O, and natural Pb nuclei at several forward deuteron angles, $\theta_L = 5°$, 10°, and 15°. The (1.00 ± 0.01)-BeV proton beam came from the Brookhaven Cosmotron. All of the results are consistent with the reaction $p+(A,Z) \to d+p+(A-2,Z-1)$.

In Fig. 1 we show typical deuteron-momentum spectra for helium and oxygen. The maximum possible deuteron momentum, 2.15 BeV/c, is obtained from the pickup or knockout reaction, $p+{}^{16}\mathrm{O} \to d+{}^{15}\mathrm{O}$, which leaves the residual nucleus in its ground state. No events were observed at this momentum. The peak in the spectra occurs about 20 MeV below the kinematic point for free p-d scattering. This difference is due to the binding energy of the deu-

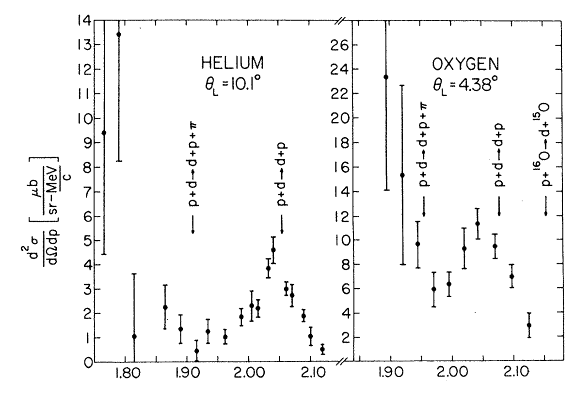

FIG. 1. Typical deuteron-momentum spectra at small angles to the incident proton beam.

teron in the original nucleus. The opening of the pion channel is presumably the cause of the rise in the cross section at the lower momenta. The deuterons from other possible competing reactions, such as $p+p\rightarrow d+\pi$ and $p+n\rightarrow d+\gamma$, would have momenta well below that for $p+d\rightarrow p+d+\pi$.

If we ascribe the width of the peaks to the internal momentum of the nucleon pairs inside the nucleus, and assume that the momentum distribution is Gaussian, then we can determine the average kinetic energies of these two-nucleon clusters. The results are 6, 8, 14, and 29 MeV for ^{4}He, ^{6}Li, ^{16}O, and natural Pb, respectively. These values are in excellent agreement with those obtained at 675 MeV.[2] For comparison, we note that $(p, 2p)$ measurements yield the average kinetic energies of the single nucleons inside the nucleus. For s nucleons in ^{4}He, ^{6}Li, and ^{12}C, the results[4] are 18, 20, and 36 MeV, respectively.

The areas under the peaks in the deuteron-momentum spectra have been integrated to yield the differential cross section for quasifree proton-dinucleon scattering. Figure 2(a) shows that the angular distribution of this cross section is in excellent agreement with the angular distribution for free proton-deuteron elastic scattering.[5] The ratio of quasifree scattering to free p-d scattering, R, is shown in Fig. 2(b) plotted as a function of atomic mass A. This ratio exhibits an $A^{1/3}$ dependency, which implies that the cross section for quasifree scattering is proportional to the nuclear circumference. This result is not at all surprising when one realizes that only those deuterons formed near the surface, and in particular only those near the rim of the nucleus as seen from the beam direction, have much of a chance of being emitted at small laboratory angles, all others being absorbed before they can leave the nucleus.

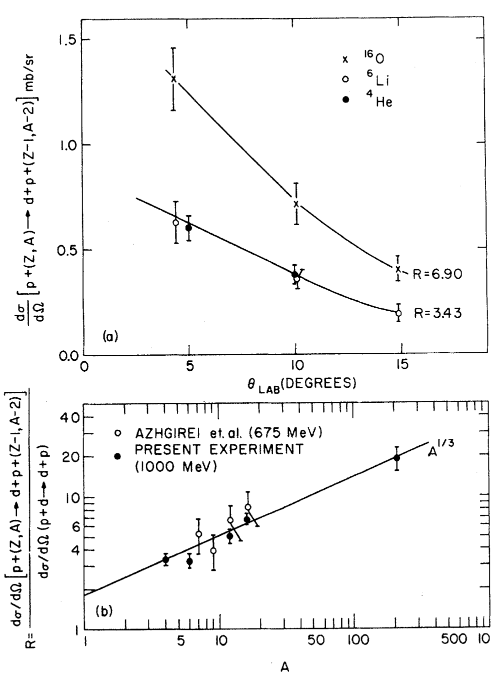

FIG. 2. (a) Angular distributions for quasifree scattering compared with the angular distribution for free proton-deuteron scattering (Ref. 5) (solid line) normalized by the factor R. (b) The ratio of quasifree scattering to free p-d scattering, R, versus atomic mass, A. The solid line is proportional to $A^{1/3}$.

In order to determine in what final state the nucleus was left, we performed a coincidence measurement, using ^{12}C as a target, between the deuterons in the magnetic spectrometer at 8.9° and the protons emitted at the canonical angle for free p-d scattering, 135° (a diagram of the apparatus is given in Ref. 5). The energy of the protons was determined from their pulse height in a NaI counter. The energy calibration for this counter was measured using free p-d scattering at several different coincident angles. A scatter plot of the proton energy versus the deuteron energy exhibits a clear diagonal band of events. A summed energy spectrum of all events for which the ratio of proton to deuteron energy was between 0.084 and 0.145 is shown in Fig. 3. This range of proton-to-deuteron energy ratio corresponds to dinucleon energies inside the nucleus of 0-3 MeV, much less than the average energy of about 14 MeV for these clusters. These results demonstrate that most of the events leave the B^{10} nucleus at or near the ground state. The cross section $d^3\sigma/d\Omega_1 d\Omega_2 dT_p$ for events with summed energy greater than 955 MeV is 7.9 $\pm$ 1.9 μb/sr^2 MeV. This is only about a factor of 10 less than the $(p, 2p)$ cross section for s nucleons in carbon at 160-MeV incident energy.[6]

Regardless of how one views the deuteron production process as occurring (one-neutron exchange, for example), the experimental fact is that the reaction involves a momentum transfer of 1 BeV/c per nucleon, and that therefore the wave function of the nucleons inside the nucleus must have a considerable fraction of 1-BeV/c momentum component. This is only possible if there are strong nucleon-nucleon correlations which bring two nucleons into close

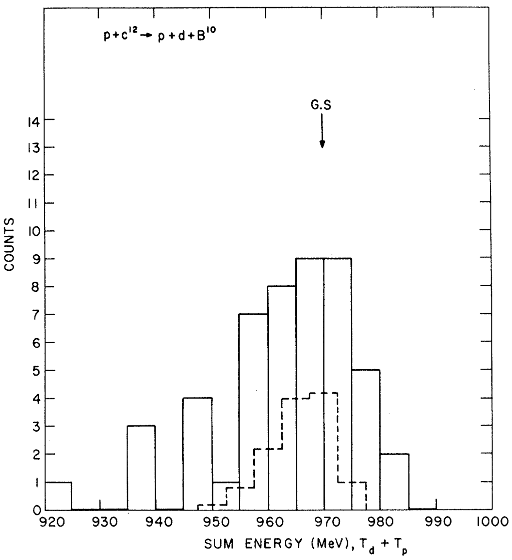

FIG. 3. Sum-energy spectrum, T_p+T_d, for all coincident events in which the ratio of proton to deuteron kinetic energies, T_p/T_d, lies between 0.084 and 0.145. The dashed curve is the sum-energy resolution as determined from free p-d coincidences. This curve has been displaced by 27 MeV, which is the binding energy of the deuteron in the ^{12}C nucleus. The arrow G. S. shows the location of the ground state of B^{10}.

proximity. From the scattering kinematics and the large average kinetic energy of these clusters—about half that of the individual nucleons—we conclude that n-p pairs can move rather freely through the nucleus.

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COMPARISON OF ELASTIC POSITRON-PROTON AND ELECTRON-PROTON SCATTERING CROSS SECTIONS*

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We have measured the ratio of positron-proton and electron-proton elastic-scattering differential cross sections at 1700-MeV incident beam energy. This ratio gives information about the magnitude of the interference term between one- and two-photon exchange amplitudes.

The positron and the electron beams were made by allowing the external bremsstrahlung γ beam from the Cornell 2-GeV synchrotron to strike a one-radiation-length lead target. Electrons or positrons were then selected by a beam transport system which momentum analyzed the particles and focused them to a 46-cm-long liquid-hydrogen target. The transport system (see Fig. 1) is similar to the Stanford Linear Accelerator Center B transport system in design[1] and is free of second-order chromatic aberrations. The image of the pos-

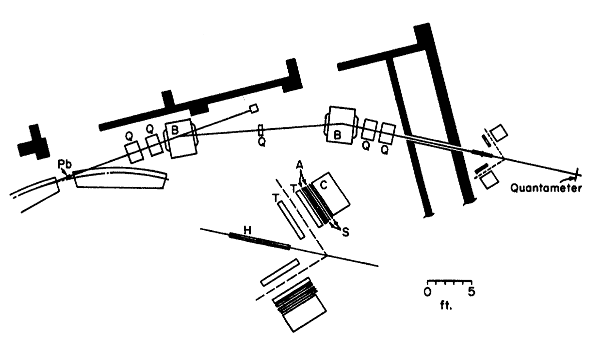

FIG. 1. Schematic drawing of the transport system and the detection apparatus. H, hydrogen target; T, thin-foil optical spark chambers; S, scintillation counters; C, Cherenkov counters.