points to the right of the short cut, some large variation is observed; the Balázs pole residues sometimes show wild variations, even for slight changes in the position of the matching point. This can be traced to the factor $(W-W_R)^{-1}$ in Eq. (24), which changes sign through infinity as W_R crosses the matching point. It therefore seems advisable to match the amplitudes in the other region mentioned. A different matching procedure in this region, namely, matching the amplitude at two points instead of matching the amplitude and its derivative both at one point, showed no appreciable variation of the result.

The authors are grateful to Professor R. C. Majumdar and Professor A. N. Mitra for their kind encouragement. L.K.P. wishes to thank the Council of Scientific and Industrial Research for financial support.

PHYSICAL REVIEW VOLUME 135, NUMBER 4B 24 AUGUST 1964

Electroproduction of Protons at 1 and 4 BeV*

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(Received 19 March 1964)

Protons of energies of 110–450 MeV have been produced by bombardment of targets of lithium-6, carbon, aluminum, and copper by electrons of 1- and 4-BeV energy. It is shown that at this energy and angle the electromagnetic interaction of the virtual photons with the nucleus is consistent with an interaction with one nucleon followed by a subsequent scattering process. This is in contrast to the interaction at lower energies (~100 MeV) where the interaction takes place by absorption from two nucleons in the nucleus simultaneously (quasideuteron model). Deuterons have also been observed and are believed to be produced by a pickup process.

APPARATUS

During an experiment at the Cambridge Electron Accelerator on electron-proton scattering with 1- and 4-BeV electrons,[1] we have studied the production of protons from lithium, carbon, aluminum, and copper targets. The apparatus is shown in Fig. 1.

A target of height $\frac{1}{16}$ in. is placed 0.8 in. from the equilibrium orbit of the circulating electron beam. Positively charged particles are focused in a simple quadrupole spectrometer onto a scintillation counter system consisting of two thin defining counters and a counter thick enough to stop 150-MeV protons. The first two counters were used to define a particle trajectory which had crossed the focal plane, and lay within a momentum band $\Delta p/p \simeq 5.4\%$.

The pulse height from the thick counter was displayed on a 400-channel pulse-height analyzer, and was used to separate deuterons from protons and pi mesons. At the smaller momenta, protons stopped therein and gave bigger pulses than all other particles. At the other momenta, protons passed through, giving a smaller pulse height, and the largest pulses were given by deuterons stopping. Positrons and pi mesons had a smaller ionization loss than the protons and gave a still smaller pulse height. A pulse-height distribution for $E_i=4$ BeV, $\phi=63.1°$, $p_p=794$ MeV/c is shown in Fig. 2.

Some of the photoprotons lost energy by nuclear absorption before passing through the final counter. These then gave too small a pulse height and were not identified as protons. A nuclear absorption correction

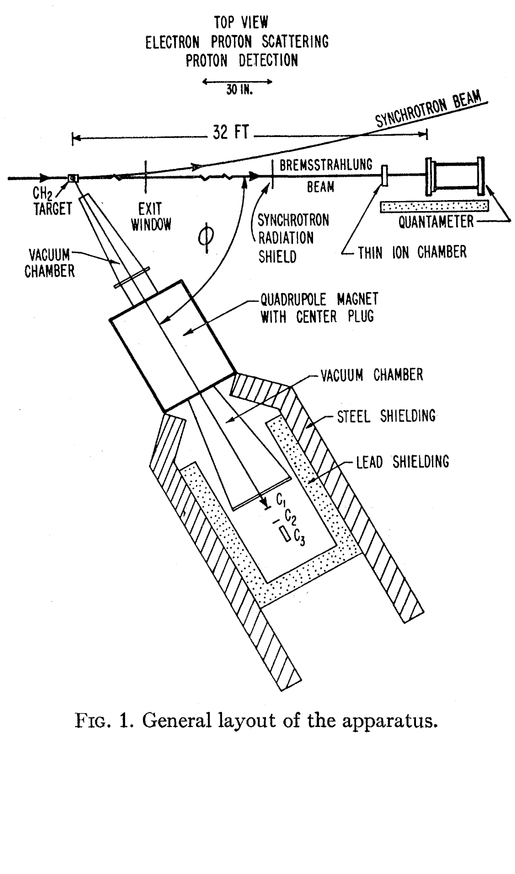

Fig. 1. General layout of the apparatus.

* Work supported by the U. S. Atomic Energy Commission.
† National Science Foundation Predoctoral Fellow.
[1] J. R. Dunning, Jr., K. W. Chen, N. F. Ramsey, J. R. Rees, W. Shlaer, J. K. Walker, and Richard Wilson, Phys. Rev. Letters **10**, 500 (1963).

was evaluated from known absorption coefficients for protons.

The uniform background under these pulses is due to those protons and pions which have produced nuclear reactions in the scintillator. The amplifier system used saturates sharply at channel 95, so that it is not possible to give accurately the numbers of deuterons.

The beam intensity was obtained by measuring the total intensity of bremsstrahlung produced by the interaction of electrons with the target by means of a quantameter.[2] This gives a measure of the total interaction rate of electrons with the target nuclei independent of the number of traversals of the target by the electrons of the beam.

The targets were chemically pure. The worst impurity was $1\frac{1}{2}\%$ oxygen in the lithium (isotope six) used. The targets had a thickness of 0.008 radiation length. It was possible for electrons to radiate in the first part of the target and for the photons thus produced to produce photoprotons in the second part of the target. In order to give a measure of this effect, at one angle, 72.1°, and at an electron energy of 4 BeV and a proton energy of 124 MeV, several target thicknesses were used from 0.0025 to 0.05 radiation length. The apparent cross section is plotted as a function of the target thickness in Fig. 3. The electron cross section is clearly the extrapolation to $t=0$.

The thickness of radiator which, placed in an electron beam, doubles the electron-induced rate is a quantity of some interest and we define it as N_e radiation lengths. Since only half of the target is such a radiator, this is 0.025 radiation length for the data of Fig. 3. According to the theory of electromagnetically induced processes, given for example by Dalitz and Yennie,[3] a 4-BeV electron gives counts equivalent to a radiator N_e of 0.019 radiation length for a virtual photon energy of 3800 MeV and assuming only transverse-photon reactions. For a virtual photon energy of 250 MeV, the virtual radiator is 0.037 radiation length; this number, however, includes large momentum-transfer events which are reduced by form factors. N_e is, therefore, reduced to a number closer to 0.02. Unfortunately, it is not certain that the electron beam traversed the entire thickness of the target; the value 0.025 must, therefore, be considered an upper limit; moreover, a measurement was made for only one set of energies and angles. These data have none the less been used as the basis of a 15% correction of all data to zero target thickness. In the extreme, but unlikely, case of the data at some angle being entirely due to electrons, this procedure could over-correct by 15%.

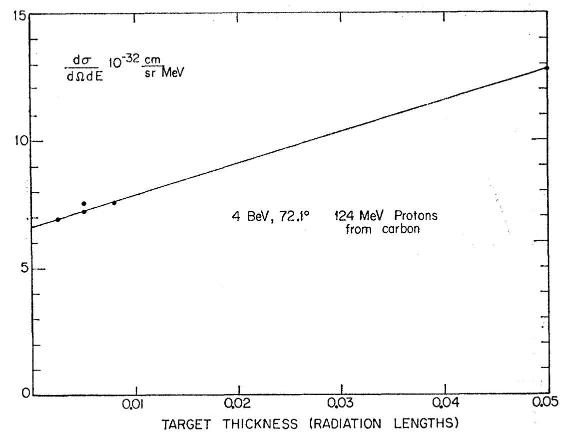

FIG. 3. Apparent cross section as a function of target thickness. Carbon target; 72.1°; 124-MeV protons. Incident electron energy 4 BeV.

Only the tip of the target was irradiated; 1 mm was illuminated at 124 MeV and 3 mm at higher proton energies. The electron beam was prevented from striking the rest of the target by a clipper located an integral number (4) of betatron oscillations upstream from the target.

We therefore find negligible corrections due to absorption or slowing down in the target and due to multiple scattering. However, due primarily to the uncertainties in monitoring procedure, we assign 10% error to each point, though the statistical error is much smaller.

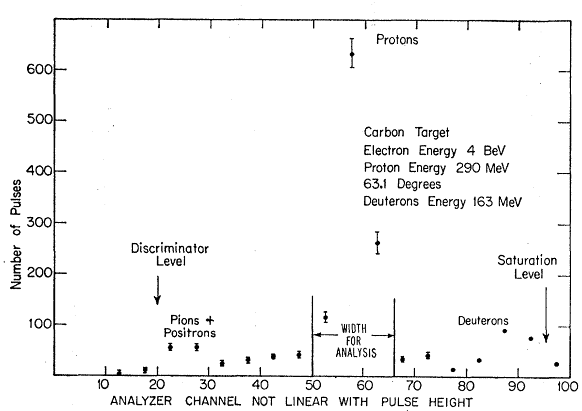

FIG. 2. Pulse-height distribution for electron energy 4 BeV, angle 63.1°, particle momentum 794 MeV/c.

RESULT AND DISCUSSION

The cross sections are tabulated in Table I. Some proton cross sections divided by A are plotted in Fig. 4 versus A.

The deuteron/proton ratio is about 5–10% for all elements and momenta. This ratio is in reasonable agreement with other measurements,[4] at lower momenta. The accuracy is no better than a factor of 2. This ratio is in general agreement with the view that the deuterons are produced by a pickup of a neutron by

[2] R. R. Wilson, Nucl. Instr. Methods **1**, 101 (1957).
[3] R. H. Dalitz and D. R. Yennie, Phys. Rev. **105**, 1598 (1957). See particularly Eq. (1.7).
[4] V. Parikh, Nucl. Phys. **38**, 529 (1962).

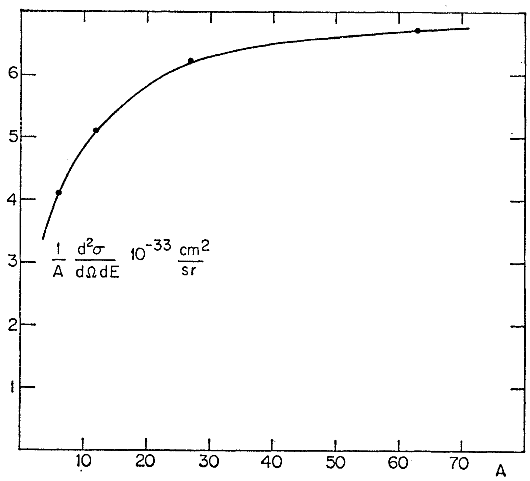

FIG. 4. Cross section, divided by A, as a function of A, for producing protons of 124 MeV from 4-BeV electrons at 72.1°.

a proton of the same momentum or pickup of a proton by a neutron. The same order of magnitude is found in the d/p ratio in secondary particles from 30-BeV proton bombardment,[5] and presumably has the same origin.

The graph of Fig. 4 shows that the cross section for proton production increases faster than A. An examination of the data in Table I shows that this tendency is true for all energies and angles measured, and is a little stronger for 4 BeV than for 1 BeV.

A cross section varying faster than A suggests at first a coherent process. This we cannot conceive at these energies and angles.

The theory of photon absorption of Levinger,[6,7] the quasideuteron model, suggests that absorption of photons, virtual or real, of energy of 50 MeV and higher, should take place only when two nucleons are close together in the nucleus. Absorption on one nucleon alone is likely to be small when the only absorptive process is nucleon Compton scattering. Yet the photon has a wavelength smaller than the internucleon spacing so that interaction with the smallest possible number of nucleons is preferred. The cross section predicted by the quasideuteron model varies with atomic number as $Z(A-Z)/A$. Previous measurements[8,9] show indeed this dependence for light nuclei, and quite detailed fits to the quasideuteron theory. For heavier nuclei (copper $A=63$) absorption processes could reduce this dependence.

We might, on the other hand, consider the protons recoiling from electron-proton scattering; then the cross section should vary as $Z(=A/2)$. In either case, the observed dependence is hard to understand.

We suggest the following qualitative picture. All the photon energies and angles studied here are close to those of eleastic $e-p$ scattering, as can be seen by a comparison of the $e-p$ scattering kinematics in Table I. Let us consider protons recoiling from an electron or photon interaction with a single stationary proton. There is a peak at the elastic-scattering momentum and a continuum from π production being below this momentum. Above this kinematic limit there are no protons. In a nucleus we may expect protons above this limit from either of two causes: firstly, the internal momentum distribution, and secondly, subsequent scatterings inside the nucleus. The second process will

TABLE I. Cross sections for production of protons by electrons.

Electron target	Energy angle (deg)	4 BeV proton energy (MeV)	$d^2\sigma/d\Omega dE$ 10^{-32} cm²/sr MeV
H	59.8	374	3.8[a]
Li_6	59.8	448	0.082
Li_6	59.8	368	0.175
Li_6	59.8	332	0.280
C	59.8	374	0.425
Al	59.8	374	1.19
H	63.1	291	7.5[a]
Li_6	63.1	355	0.146
Li_6	63.1	319	0.204
Li_6	63.1	290	0.313
C	63.1	291	1.01
Al	63.1	291	2.42
H	67.1	208	16[a]
Li_6	67.1	226	0.6
Li_6	67.1	206	0.92
C	67.1	209	2.37
Al	67.1	209	6.4
H	72.1	124	46[a]
Li_6	72.1	166	1.20
Li_6	72.1	144	1.53
Li_6	72.1	124	2.46
Li_6	72.1	119	2.80
Li_6	72.1	109	2.90
C	72.1	123	6.6
Al	72.1	124	16.9
Cu	72.1	124	42.3
H	44.8	291	2.9[a]
Li^6	44.8	337	0.16
Li^6	44.8	293	0.29
C	44.8	291	0.76
Al	44.8	291	1.58
H	52.3	208	8.5[a]
Li^6	52.3	200	0.91
C	52.3	208	2.13
Al	52.3	208	4.95
H	61.1	124	25[a]
C	61.1	145	3.95
C	61.1	124	5.75
C	61.1	115	6.43
Al	61.1	145	10.7
Al	61.1	124	16.0

[a] $d\sigma/d\Omega$ in mb/sr; inside a 5.5% momentum interval.

[5] A. Schwarzschild and C. Zupancic, Phys. Rev. **129**, 854 (1963).
[6] J. S. Levinger, Phys. Rev. **84**, 43 (1951).
[7] K. Dedrick, Phys. Rev. **100**, 58 (1955).
[8] B. T. Feld, R. D. Godbole, A. Odian, F. Scherb, P. C. Stein, and A. Wattenberg, Phys. Rev. **94**, 1000 (1954).
[9] Y. S. Kim, F. F. Liu, F. J. Loeffler, and T. R. Palfrey, Phys. Rev. **129**, 1362 (1963).

increase with the size of the nucleus and, therefore, with A.

This mechanism of a single-particle photon absorption plus a subsequent scattering is the only one that we can find to fit the observed A dependence. The proton energy is much lower than the kinematic limit for a quasideuteron process.

In general, a single-particle process dominates a many-particle process at high energies. The reason for the model of Ref. 6, is the smallness of the elastic-scattering cross section for photons. Above meson threshold, other single-particle processes occur.

The single-particle absorption process cannot be all elastic scattering, for there is considerable enhancement by photoprocesses as shown in Fig. 3. Nor is it single π^0 production from a proton, for this is known to give a small number of recoil protons compared to elastic scattering.[1] It is quite likely, however, to be π^- production from the neutron according to the mechanism

$$\gamma+n\rightarrow\pi^-+p.$$

This process has a strong peak in the forward direction for the pion[10] which corresponds to the sideways protons observed here. This large forward π^- cross section is attributed to processes where the photon interacts with the π charge, and cannot occur for π^0 mesons.

The virtual photon energy for producing 124-MeV protons will be about 250 MeV for the quasideuteron model. The equivalent radiator N_e derived from Fig. 3 was 0.025, whereas the number expected for a virtual photon energy of 250 MeV is 0.036. This could, of course, be reduced if most of the photons came from secondary reactions, or by form-factor effects. The number of virtual photons (N_e) expected for a virtual photon energy closer to the incident electron energy is 0.019 which agrees better with experiment, and allows a margin for some events due to elastic scattering which contributes solely to reactions by longitudinal photons.

Another feature of the cross sections shows that they cannot be explained on the quasideuteron model[6,7] so successful at lower energies. Table II shows the electroproduction cross sections for 144-MeV protons from lithium by incident electrons of 4 and 1 BeV; the cross sections for photoproduction with a bremsstrahlung spectrum of end point 335 MeV have been made in Ref. 9; we interpolate to compare at the same angles. Also, we assume that only the transverse photons affect the electroproduction by the quasideuteron theory to obtain the equivalent electroproduction cross section for comparison. This is shown in Table II. We see that at 1 BeV, the cross section is 4 times that at 335 MeV; at 4 BeV, 6 times. According to the quasideuteron model, protons of 145 MeV are produced by γ rays of energy 250–330 MeV. The number of virtual photons of these energies should not vary appreciably as the electron energy is increased, and, therefore, these factors should be close to unity. Our results are thus consistent with a transition to a single-particle absorption above 335 MeV which is almost complete by 1 BeV. The π^- cross section of Ref. 10 would lead to only a slow rise in cross section from 1 to 4 BeV, as found.

[10] R. B. Blumenthal, W. L. Faissler, P. M. Joseph, L. J. Lanzerotti, F. M. Pipkin *et al.*, Phys. Rev. Letters **11**, 496 (1963).

TABLE II. Cross section for $T_p=145$ MeV, lithium target.

	θ	$d^2\sigma/d\Omega dE$ (cm²/sr MeV)
Bremsstrahlung energy, 335 MeV	72.1[a]	0.13×10^{-30}
(cross section per Q)	61.1[a]	0.20×10^{-30}
Electron energy, 335 MeV	72.1[a]	2.5×10^{-33}
assuming $N_e=0.02$	61.1[a]	4.0×10^{-33}
Electron energy, 1 BeV	61.1[b]	1.8×10^{-32}
Electron energy, 4 BeV	72.1	1.53×10^{-32}

[a] Extrapolated from C, Al data of Table I.
[b] Interpolated from data of Ref. 9.

We note that a transition from a quasideuteron absorption process to a single-particle absorption process is to be expected when the single-particle process has sufficient probability—as is the case above meson threshold. Even above meson threshold, there may be regions where the quasideuteron model still is dominant for the differential cross section; for the production of 500-MeV protons at 60° from a 1-BeV bremsstrahlung beam, for example. Here protons from a single-proton absorption process are kinematically impossible but those from a quasideuteron model are not.

We have made no detailed calculations on this model. We present the data and our qualitative interpretation, in the hope that others may do so. Our model, if correct, would imply that at energies and angles not close to the kinematic limit of single-proton absorption processes, the cross section would not vary faster than A. Since these data were only taken as a by-product of another experiment, we have not studied this.

ACKNOWLEDGMENTS

We would like to acknowledge the help of all the CEA staff without which this experiment would not have been possible.