and Cu. Data were taken at 38°, 90°, and 142° to the beam axis. These targets were cylindrical to minimize asymmetrical neutron scattering in the target. Of the elements investigated, the photoneutrons were given off with spherical symmetry except for deuterium, carbon, and sulfur. The yield from carbon was down 10 percent at 38° and 142° from what it was at 90°, and from sulfur down 5 percent at the extreme angles. The deuterium results agree, within counting statistics, with the angular distribution reported by Kerst at 22 Mev. Some slight increase in yields was seen at small angles (38°) for some targets, but this appeared to be due to x-rays scattered by the target sample producing neutrons in the counter itself. Counting errors on deuterium ran as high as 25 percent, the others considerably lower.

A Pb transition curve was obtained by determining the yields from lead targets of varying thicknesses. The data were analyzed to give the transition curve shown in Fig. 5. The ordinate corresponds to the neutron yield a unit thickness of lead would give when placed behind the abscissa thickness of lead. There is an error introduced into the curve at larger thicknesses because of the lateral spreading of the shower and the finite diameter of the target. The initial sharp descent found by Strauch[3] to correspond to an 80-Mev process is seen; but this is followed by a broad rise peaked at about 4 shower units, which apparently indicates the usual type of (γ,n) resonance at 15–20 Mev.

We wish to express our gratitude to Professor A. C. Helmholz for his guidance throughout this experiment.

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Production of Protons by High Energy γ-Rays*

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The protons ejected from various nuclei by the gamma-ray beam of the 320-Mev Berkeley synchrotron have been studied with a proportional counter telescope system. The energy distribution of the protons from carbon, copper, and lead from 7 Mev to 70 Mev at 90° was roughly proportional to $1/E^2$. The angular distribution was spherically symmetrical for 10-Mev protons and showed a pronounced forward maximum for protons of about 40 Mev. The cross section per nucleus for the ejection of 40-Mev protons was found to be proportional to Z.

The experimental results indicate that protons above 30 Mev arise primarily from the interaction of the γ-ray with some small subunit of the nucleus rather than through the formation of an excited compound nucleus.

I. INTRODUCTION

SINCE Chadwick and Goldhaber[1] demonstrated the photodisintegration of the deuteron in 1935, much work has been devoted to the study of γ-ray induced nuclear reactions. Studies have been made using various target nuclei bombarded with γ-rays from several radioactive sources[2] and from the $Li^7(p,\gamma)Be^8$ reaction.[3,4] Recently, the work has been extended to the high energy regions using the γ-ray beams from the high energy electron accelerators.[5,6] Most of the experiments have been studies of the radioactive end products of the reactions, so that total cross sections as a function of γ-ray energy and target nucleus have been obtained. This has led to rather conflicting evidence about the mechanism for inducing these reactions. For example, it seems difficult to reconcile the ratio of (γ,p) to (γ,n) cross sections[3,6] with an evaporation process unless one supposes a rather special character for the transitions allowed by γ-rays.[7] However, the resonances found for the reactions at about 20 Mev[5,6] can be understood as the excitation of nuclear dipole oscillations with the

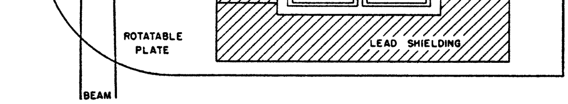

FIG. 1. Geometry of apparatus.

* This work was performed under the auspices of the AEC.
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1 J. Chadwick and M. Goldhaber, Proc. Roy. Soc. (London) **151**, 479 (1935).

2 Russell, Sachs, Wattenberg, and Fields, Phys. Rev. **73**, 545 (1948).
3 W. Bothe and W. Gentner, Z. Physik **106**, 236 (1937).
4 Huber, Lienhard, Scherrer, and Wäffler, Helv. Phys. Acta **11**, 139 (1944).
5 M. L. Perlman and G. Friedlander, Phys. Rev. **74**, 442 (1948).
6 K. Strauch, thesis, University of California, February (1950)
7 L. I. Schiff, Phys. Rev. **73**, 1311 (1948).

subsequent evaporation of a neutron.[8] The present work consists of measurements of the energy and angular distribution of protons ejected from various nuclei by high energy γ-rays. It was felt that this kind of investigation could yield more detailed information about the mechanism than the method of detecting radioactive end products.

II. EXPERIMENTAL ARRANGEMENT

Measurements were made of the range and angular distribution of the emitted protons with a proportional counter coincidence telescope. The geometry of the apparatus is shown in Fig. 1. The counters had an active cylindrical region $2\frac{1}{2}''$ in diameter and $2''$ deep, and were filled to one-half atmosphere with a 95 percent argon, 5 percent CO_2 mixture. Two-mil Dural was used for entrance and exit windows. To limit the proton to a region well within the active volume of the counters, a collimator consisting of a lead brick with an inch-and-a-quarter diameter hole was placed directly in front of the telescope. At the back of the collimator, a one-quarter-inch recess was milled so that absorbers could be placed adjacent to the counters.

The front of the telescope was six inches from the target, which was large enough to intercept the entire beam. The target thickness was kept small compared with the total range being measured. The telescope and target could be rotated independently about the target center, which was aligned photographically with the beam.

A block diagram of the electronic components is shown in Fig. 2. Since the rise-time of the pulses out of the proportional counters was about 0.3 μsec, one could clip the pulses at 0.4 μsec without destroying the proportionality. The short duration was desirable to minimize the problem of pile-up of electrons. The gate generated by the variable gate circuit, which determined the resolving time of the apparatus, was of 0.5-μsec duration.

For all the measurements the synchrotron beam was spread out to about 2 millisecond duration per pulse. With a repetition rate of 6/sec this gave a duty cycle of about 1/80. With the expanded beam the energy of the electrons striking the internal target varies from 290 Mev to 320 Mev.

III. BACKGROUND

The electron background near the synchrotron beam was eliminated by demanding large pulses out of both counters. The amplifier gains were set so that neither counter could detect any radiation from a one-millicurie radium source. Then the gain on the amplifier connected to the rear counter was reduced by a factor of two. Therefore, for electrons to produce a coincidence, two of them must stop in the rear counter and one in the front counter, all within about 0.5 μsec. Furthermore,

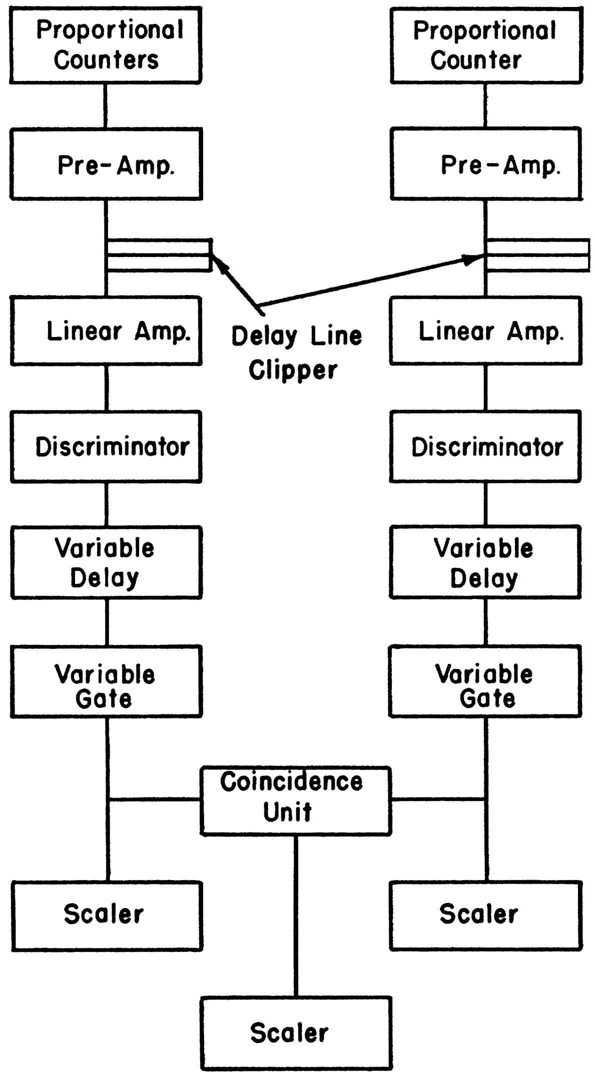

FIG. 2. Block diagram of electronics.

if such an event did occur, as in the case of a shower, it would be equally likely for two electrons to stop in the front counter and one in the rear. However, when the gains on the two channels were reversed, it was found that the counting rate was reduced by about a factor of two, as one would expect if the coincidences were being produced by a single particle.[8a] Further evidence that the coincidences were not produced by electron showers is furnished by the following facts: (a) the relative cross sections are proportional to Z rather than Z^2 (see Fig. 5); (b) the cross section in lead decreases below the proton coulomb barrier (see Fig. 4).

The accidental coincidences were calculated and corrections made for them in all the data. An experimental

[8] M. Goldhaber and E. Teller, Phys. Rev. 74, 1046 (1948).

[8a] The expected reduction of a factor of two arises from the fact that the absorber between the counters was about 30 mg/cm^2 of Al and the residual range on leaving the second counter could be as great at 60 mg/cm^2. (See section on calculation of absolute cross section.)

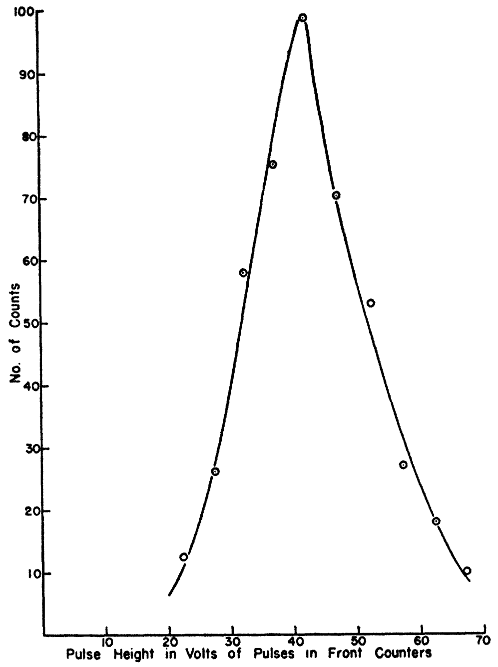

FIG. 3. Pulse-height analysis of counts in the first counter. Energy region observed corresponds to 40-Mev protons. Target is copper.

measurement was made of the ratio of resolving time to duty cycle by introducing a 4-μsec delay into one of the channels, and the measured value used in all calculations. In no case was the correction for accidental coincidences greater than 15 percent.

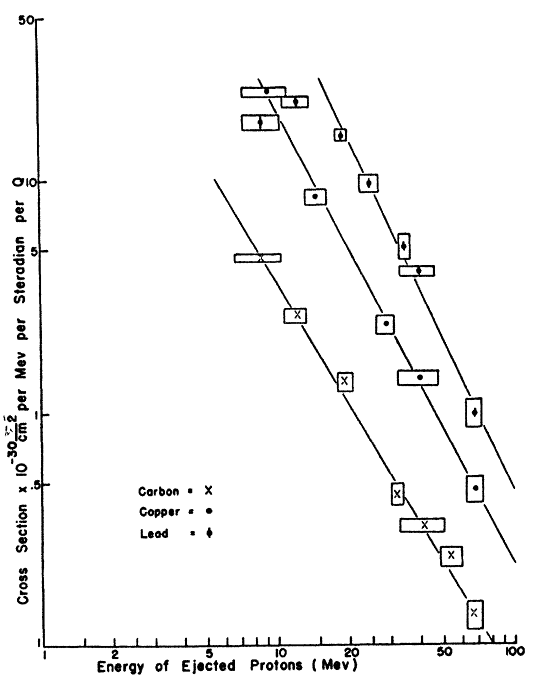

FIG. 4. Energy dependence of the cross section in carbon, copper, and lead at 90° with respect to the beam direction.

The tests described above were sufficient to insure that the coincidence counting rate was due primarily to a single heavy particle. They yield no information about the nature of the particle, that is, whether the particle is a proton, meson, alpha-particle, etc. To obtain such information, a pulse-height analysis was made of the pulses in the first counter which were in coincidence with those of the second counter. For this purpose a ten-channel pulse height analyzer was used. Pulse-height analysis was done using several different targets and absorbers. A typical example is shown in Fig. 3. These results showed that the coincidences were due primarily to a single particle. To check that these were protons, the apparatus was used to detect 30-Mev protons from the Berkeley linear accelerator elastically scattered by carbon. The results of the measurements were sufficient to rule out any background but deuterons.[8b] The resolving power of the apparatus was not sufficient to distinguish protons from deuterons.

IV. CALCULATIONS AND CORRECTIONS

The measurements made gave the number of protons with a range between R and $R+\Delta R$, where R= thickness of the total absorber up to the rear counter and ΔR= maximum residual range on entering the rear counter of a proton which would produce a sufficiently large pulse to register in that counter. ΔR was measured in two independent ways: (a) from the width of the pulse-height curve (Fig. 3); (b) from the fact that a proton had to lose twice the maximum energy possible for an electron in the rear counter in order to register. Method (a) gave $\Delta R=60$ mg/cm^2 of Al; method (b) gave $\Delta R=90$ mg/cm^2 of Al. The former result was considered more reliable and was used in all calculations of the absolute cross section. It is the uncertainty in ΔR which produces the maximum error in the absolute cross section, which is estimated to be accurate to within a factor of two. The cross sections are calculated per "Q," where "Q" = total energy of the beam divided by the maximum energy of the γ-rays = 320 Mev. The conversion from range to energy was made from the range energy relation of Aron, Hoffman, and Williams.[9]

For the low energy region of the energy distribution where very thin targets must be used, the no-target background becomes significant. By means of added shielding, the no-target background was reduced to about 15 percent at the lowest energy point.

There are two other sources of error which must be considered. These are nuclear absorption in the absorber and multiple scattering in the absorber. The correction for nuclear absorption was made assuming an absorption cross section of the geometrical area of the absorbing nucleus. For the highest energy point, this correction was six percent. The correction for multiple

[8b] Only in the cases of a carbon target with no absorber was any substantial alpha-particle component observed. In this case, the alpha-particles contributed about 20 percent of the total number of coincidences.

[9] Aron, Hoffman, and Williams, UCRL-12 (unpublished).

scattering in the absorber was estimated to be five percent at the highest energy.

V. RESULTS

Figure 4 shows the energy distribution on carbon, copper, and lead taken at 90° with respect to the beam direction. The height of the blocks show the standard error due to statistics of counting. The width of the blocks show the energy interval represented by the thickness of the target. The results indicate a differential cross section proportional to E^{-S}, where E=proton energy and $S=1.7\pm0.1$ for carbon, 1.9 ± 0.1 for copper, and 2.2 ± 0.2 for lead. The decrease in cross section in the lead distribution at low energy is presumed to be due to the effects of the coulomb barrier.

The relative cross sections at 40 Mev were taken for Be, C, Al, Zn, Cu, Ag, Pb, and W. This was done at 90° using targets of equal stopping power. The measurements were taken on the same day with all conditions remaining fixed. The results are shown in Fig. 5. As may be seen in the curve the cross sections are proportional to Z, to the accuracy obtained in the experiment.

The angular distributions shown in Figs. 6 and 7 were taken for Be, C, and Cu at 10 and 40 Mev. The 90°, 112°, and 135° points were taken with the target normal to the 112° point. The 90° point was repeated for the forward angles, where the target was rotated so that it was normal to the 67° point.

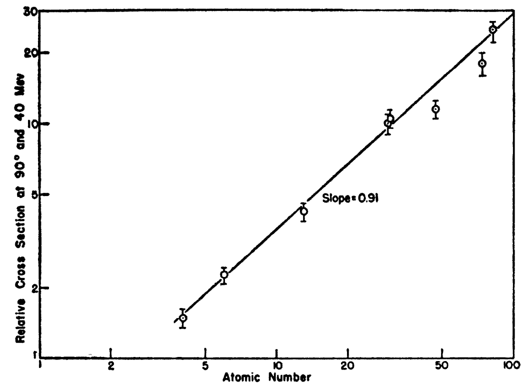

FIG. 5. Relative cross section as a function of atomic number. The slope of 0.91 indicates a cross section closely proportional to Z.

VI. DISCUSSION OF RESULTS

In trying to understand the mechanism for the ejection of protons from nuclei by γ-rays, two possibilities suggest themselves. One is that the γ-ray is absorbed by the nucleus, exciting it to the energy of the γ-ray with the subsequent loss of excitation by emission of a proton. The other is that the γ-ray interacts directly with some subunit of the nucleus, e.g., proton, deuteron, alpha-particle, etc., of which the proton is a constituent. The experimental indication is that the latter process is predominant for protons of energies above about 30 Mev and that the former process gives rise, primarily, to protons below that energy. The evidence for this conclusion is the following. The cross section is a much more slowly varying function of energy than one would predict from an evaporation process regardless of how the absorption cross section for γ-rays varies with energy.[9a] Further evidence against an evaporation process is the fact that the angular distribution at 40 Mev has a forward peak (Fig. 7). It seems difficult to understand any pronounced deviation from spherical symmetry at these energies if one assumes an evaporation process. The simplest assumption one can make about the process is that the γ-ray interacts directly with the protons. With this assumption one can calculate the cross section for the process if the initial wave function of the proton in the nucleus is known; or, what amounts to the same thing, if one knows the momentum space wave function. Assuming that the

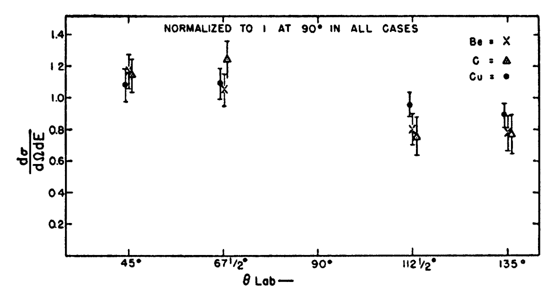

FIG. 6. Angular distribution of 10-Mev protons from Be, C, Cu.

transition is an electric dipole transition the cross section is given by[10]

$$\sigma = 8\pi^3 e^2 \nu c^{-1} |Z_{0e}|^2, \tag{1}$$

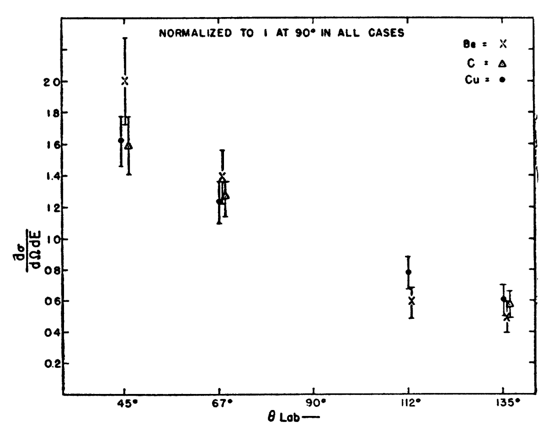

FIG. 7. Angular distribution of 40-Mev protons from Be, C, Cu.

[9a] Even under the assumption that the absorption cross section is a step function, zero everywhere except at and above the maximum beam energy (this assumption leads to the most high energy protons) one can still not account for the observed high enery protons by an evaporation process.

[10] H. A. Bethe and R. Peierls, Proc. Roy. Soc. (London) **A148**, 146 (1935).

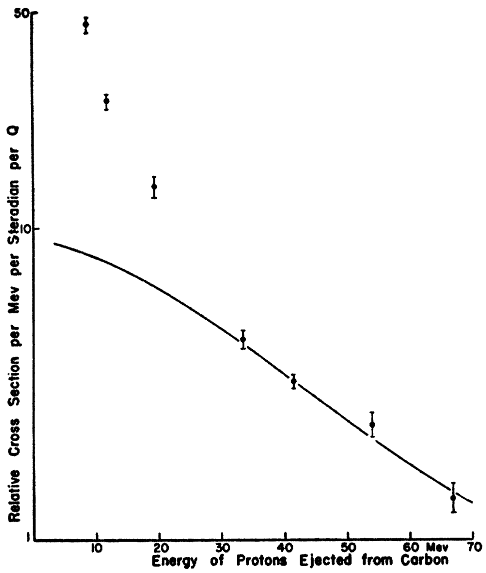

FIG. 8. Energy dependence of cross section. Solid curve is calculated as described in text. Points are experimental.

$$|Z_{0e}|^2=[Mk/(2\pi)^3\hbar^2]\int d\Omega\left|\int d\tau U_0 Ze^{i\mathbf{k}\cdot\mathbf{r}}\right|^2. \quad (2)$$

However,

$$\int d\tau U_0 Ze^{i\mathbf{k}\cdot\mathbf{r}}=i(2\pi)^{\frac{3}{2}}\partial\phi_0(k)/\partial k_Z, \quad (3)$$

where $\phi_0(k)$ is the initial wave function of the proton in wave number space. Thus, one can write

$$\sigma=(8\pi^3e^2\nu Mk/c\hbar^2)\int d\Omega|\partial\phi_0(k)/\partial k_Z|^2. \quad (4)$$

To find $\phi_0(k)$ we proceed as follows: Chew and Goldberger,[11] using the data of York[12] on the production of fast deuterons by neutrons, deduce a momentum distribution for protons in carbon given by

$$N_0(k)=\phi_0^*(k)\phi_0(k)=\alpha_p\pi^{-2}(\alpha_p^2+k^2)^{-2}, \quad (5)$$

where $\alpha_p^2=2M\epsilon_p/\hbar^2$ and $\epsilon_p=18$ Mev gives the best fit to the data of York.

This determines that $\phi_0(k)$ must be of the form

$$\phi_0(k)=\alpha_p^{\frac{1}{2}}\pi^{-1}(\alpha_p^2+k^2)^{-1}e^{if(k)}. \quad (6)$$

[11] G. F. Chew and M. L. Goldberger, Phys. Rev. 77, 470 (1950).
[12] J. Hadley and H. York, Phys. Rev. 80, 345 (1950).

Unfortunately, the phase factor is undetermined. Since the cross section involves the derivative of $\phi_0(k)$, the phase enters in an essential way unless, $f(k)=$ constant. Hence, we make the assumption that $f(k)=$ constant.[12a] The cross section is then given by

$$\sigma=16\pi e^2(h\nu/\epsilon_p)\gamma^{\frac{3}{2}}/3\hbar c\alpha_p^2[1+\gamma]^4, \quad (7)$$

where $\gamma=E_p/\epsilon_p$, and $E_p=$ proton energy.

We take $\epsilon_p=18$ Mev and $h\nu=E_p+25$ Mev, as given by Chew and Goldberger.[11] The solid curve shown on Fig. 8 is a plot of this cross section multiplied by the bremsstrahlung spectrum as given by Heitler.[13] The experimentally observed cross section is shown on the same curve for comparison. The two are made to coincide at 41.5 Mev. It is seen that in the region from 30 Mev to 70 Mev the calculated and observed cross sections agree very well. Below this energy, the experimental cross section is higher than the calculated one. This can be understood by assuming that most of the low energy protons are due to an evaporation process. This is consistent with the fact that the angular distribution is spherically symmetric at energies about 10 Mev.

The absolute values of the observed and calculated cross sections at 41.5 Mev are

$$\sigma_{\text{calc}}=8.3\times10^{-28}\text{ cm}^2,$$
$$\sigma_{\text{obs}}=3.1\times10^{-28}\text{ cm}^2.$$ [13a]

The value of σ_{calc} per nucleus is determined by multiplying the value obtained from Eq. (7) by $Z=6$.

Probably both the energy distribution and the absolute cross sections agree more closely than one might reasonably expect from the crude choice of initial proton wave functions.

It is a pleasure to thank Professors W. K. H. Panofsky and A. C. Helmholtz for their frequent advice and guidance. Thanks are also due Professor E. M. McMillan for his continued interest in this work and the synchrotron crew under W. A. Gibbons for their complete cooperation at all times.

[12a] This choice of $f(k)$ leads to a configuration space wave function of the form $U^0=e^{-\alpha r}/r$. This is equivalent to the assumption that the proton is in an S-state in a well of zero range.
[13] W. Heitler, *The Quantum Theory of Radiation* (Oxford University Press, London, 1944), p. 170.
[13a] The observed cross section now has no ambiguity, since we assume a proton of energy E produced by a γ-ray of energy $E+25$ Mev.