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Low-Energy Proton Production by 160-Mev Protons*

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Energy and angular distributions of emitted protons in the energy range 5 to 23 Mev from lead, tantalum, tin, and zinc when bombarded by 160-Mev protons were obtained. A peak was obtained in each of the energy distributions slightly below the Coulomb barrier of each element. The magnitude of the peaks increased with a decrease in the Coulomb barrier of the element. The angular dependence of the heights of the peaks for all of the elements was approximately isotropic. The angular distributions of the emitted protons with energies above the Coulomb barrier increased in the forward direction. The results are compared with previous related experiments and possible sources of disagreement are discussed.

I. INTRODUCTION

THERE have been several experiments performed in which incident nucleons greater than 20 Mev were used, and where the emitted protons examined were in the energy region of the Coulomb barrier of the target element. In this reaction, there is sufficient excitation for two or more nucleons to be emitted. A large forward peak in the angular distribution of the emitted protons would be evidence for a direct reaction taking place. An energy distribution of the emitted protons with small dependence on the Coulomb barrier of the target element would indicate a direct reaction occurring near the surface of the target nucleus. An angular distribution symmetric about 90° and an energy distribution that has a strong dependence on the Coulomb barrier of the target element indicates many collisions taking place inside the nucleus and possible compound nucleus formation.

Waniek and the emulsion group did an experiment using wire-imbedded emulsions in which the wire targets were bombarded with neutrons at incident energies of 40 Mev, 70 Mev, and 110 Mev.[1–4] The outstanding characteristic of each energy distribution of emitted protons obtained was a sharp peak far below the Coulomb barrier of the target element. All angular distributions were peaked in the forward direction and had sharp minima at 90°.

Energy and angular distributions of lead, gold, tantalum, and tin were measured by Igo and Eisberg, using a 31-Mev incident proton beam.[5,6] The energy spectra and the angular distribution of the four elements were very similar. The energy spectra were not appreciably changed by the differences of the Coulomb barrier of the target elements. The angular distributions of the emitted protons were strongly peaked in the forward direction.

The results of these two experiments indicate a reaction which has essentially little if any dependence on the Coulomb barrier. This is a very interesting result if confirmed.

Cohen and Rubin[7] studied inelastic proton scattering using incident proton energies between 11 and 23 Mev in elements of atomic number 22 to 30. They found that there were no large deviations from isotropy in the angular distributions of the low-energy portion of the proton spectra between 45 and 135°.

The experiment reported in the present paper was designed to make a careful investigation of this reaction using a high-energy proton beam (160 Mev) incident on a number of target elements (Pb, Ta, Sn, and Zn), and examining the low-energy emitted protons at a number of angles (120°, 90°, and 60°). The work is described in greater detail in a thesis by one of us (R.F.).[8]

II. DESCRIPTION OF APPARATUS

A. General

An ionization chamber and a Faraday cup were used to monitor the 160-Mev incident proton beam. A range telescope determined the range distribution of the charged particles emitted from the target. In addition to a range condition, a magnetic rigidity requirement was set on the emitted particle by an analyzing magnet so that the identity of the particle and its energy was determined.

The geometry of the equipment is shown in Fig. 1. The scattering chamber magnet, magnet chamber, and range counter were all mounted on a gun carriage. The proton beam from the cyclotron entered one of the ports of the scattering chamber and left by the port diagonally opposite. The target was suspended in the center of the scattering chamber by means of 3-mil tungsten wires. It was suspended $6\frac{1}{8}$ in. below the holder

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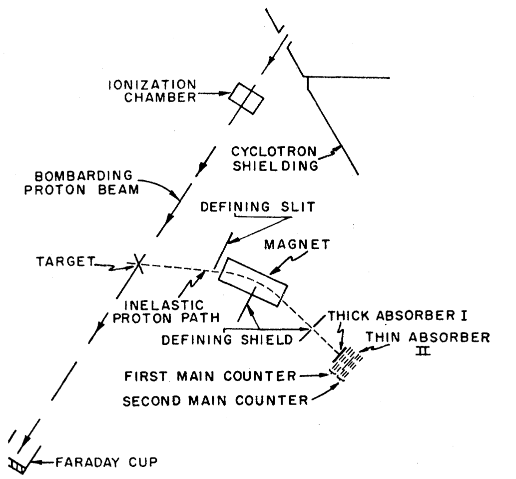

FIG. 1. Block diagram of the experimental geometry.

to which the 3-mil tungsten wires were fastened. The target was always aligned so that its normal bisected the largest angle between the incident beam path and the line defined by the target and the entrance slit to the magnet.

After the equipment was assembled and placed in the experimental area and the initial alignment was made with the proton beam, the equipment was undisturbed until the final run was completed.

An ionization chamber and a Faraday cup were used as monitors of the 160-Mev proton beam. The Faraday cup was always used as the reference for absolute measurement. The ionization chamber readings were measured by the electrometer described by Lewis and Collinge.[9] The Faraday cup readings were measured with an Applied Physics Electrometer.

B. Range Counter

The range telescope consisted of proportional counters[10] containing a gas mixture of 95% argon and 5% nitrogen. The counters were operated in the proportional region so that most of the neutron background could be biased out. There were two main counters used. Each of the main counters consisted of three narrow counters, wired in parallel.

The difference in count rate between the two main counters, using a target-in target-out subtraction determined the number of protons emitted from the target in a given range interval.

A side and top view of one of the three narrow counters which comprised a main counter is shown in Fig. 2. The design of the counter was simple. The counter was easy to construct and, in the event of trouble, was easy to fix.

Because of its hydrogen content, plastic was not used anywhere in the range counter. For a neutron of about 1 Mev, the cross section for the production of low energy protons is the order of barns for a hydrogenous material. It is on the order of millibarns for carbon and higher Z elements.[11] Teflon was used as the insulator of the counters since it is the only common plastic insulator containing no hydrogen.

Three-mil tungsten wires were used as the positive collecting electrode. A conducting foil was fastened to the faces of each of the narrow component counters to isolate the counters physically as well as electrically. Aluminum electroscope foil, the average thickness of which was 0.12 milligrams per cm^2, was used.

The 5.3-Mev alpha particles from polonium 210 were used to test the counters.

The pulse from the gas counter was amplified by a preamplifier and fed into the electronic system which was located in the control room. The first stage of the preamplifier was a cascode circuit.[12,13] Half of the cascode circuit was mounted directly onto the gas counter. This kept the input capacity of the system to a minimum since the lead which connected the counter to the first stage of the preamplifier was very short.

The noise from the electronics and the gas counters was small. For example, out of an ungated background count of 826, 10 counts were due to noise. When the cyclotron gate pulse was used, the count due to noise was 0.

C. The Magnet

The magnetic fields that were needed to deflect the inelastic protons into the range counter were determined by a floating-wire technique, which used the well-known principle that a given current and tension on a light flexible wire in a magnetic field has a magnetic rigidity corresponding to a proton of a particular energy. The calibration of the magnetic fields using this method reproduced to $\pm 0.3\%$.

The magnet settings obtained by this method were checked during a cyclotron run with inelastic protons emitted from a target. The energies of the protons being examined were determined by the range counter. The magnet setting of the center of the peak checked with the magnet setting determined by the floating-wire technique.

The resolution of the magnet was determined and found to be low. When examining a proton of energy E, the highest energy proton that could enter the range counter was $1.36E$, and the lowest energy proton $0.80E$. The corresponding momentum values are $1.17P$ and $0.89P$, respectively, where P is the momentum of a

[9] I. A. D. Lewis and B. Collinge, Rev. Sci. Instr. **24**, 1113 (1953).

[10] D. H. Wilkinson, *Ionization Chambers and Counters* (Cambridge University Press, New York, 1950).

[11] *Neutron Cross Sections*, compiled by D. J. Hughes and R. Schwartz, Brookhaven National Laboratory Report BNL-325 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1958), 2nd ed.

[12] A. B. Gillespie, *Signal, Noise and Resolution in Nuclear Counter Amplifiers* (McGraw-Hill Book Company, Inc., New York, 1953).

[13] G. E. Valley, and H. Wallman, *Vacuum Tube Amplifiers* (McGraw-Hill Book Company, Inc., New York, 1948).

proton having an energy E. The change of the accepted solid angle with energy of the magnet was found to be negligible.

For a given range, the particles which have a radius of curvature nearest to that of protons are deuterons and He^3's. The relationships between the radii of curvature of protons, deuterons, and He^3's of the same range are

$$R_d = 1.65 R_p,$$
$$R_{He^3} = 1.62 R_p,$$

where R_p, R_d and R_{He^3} are the radii of curvature of the proton, deuteron, and He^3, respectively. The magnetic resolution used is seen to have been such that only protons were detected.

The magnetic field as a function of magnet current was checked and found to be stable and reproducible. Since the magnetic field as a function of magnet current had a high degree of reproducibility, it was regulated by regulating the magnet current. The ripple in the magnetic field was checked and found to be less than 0.01% of the central field for all the magnet currents used. The residual magnetic field was measured and found to be two gauss. The smallness of the residual magnetic field is attributed to the Armco iron that was used for the pole core and pole pieces and to the relatively large magnet gap (3 in.) that was used.

III. SPECIAL PROBLEMS AND ESTIMATED ERRORS IN THIS EXPERIMENT

A. Angular Spread of Protons in the Range Counter

The total angular spread of the protons in the range counter was due to: (1) the angular spread of the protons at the entrance of the range counter, (2) the multiple scattering due to the entrance foil, and (3) multiple scattering by the absorbers and gas in the range counter.

The total angular spread of the protons at the entrance of the range counter was composed of the angular spread between the target and the range counter defined by the area of the defining slit; the angular spread between the target and the range counter defined by the area of the beam radiating the target; and the angular spread due to the spread of the radii of curvature of the protons accepted by the entrance of the range counter.

The largest total spread of the protons, made up mainly of the angular spread at the entrance of the range counter plus the multiple scattering in the range counter, occurred when 5-Mev protons were examined. In this case, the second main counter in the range counter would still have accepted all of the protons defined by the defining slit even if the spread due to multiple scattering in the range counter was increased threefold. The loss of counts due to protons scattering out of the counters was thus negligible.

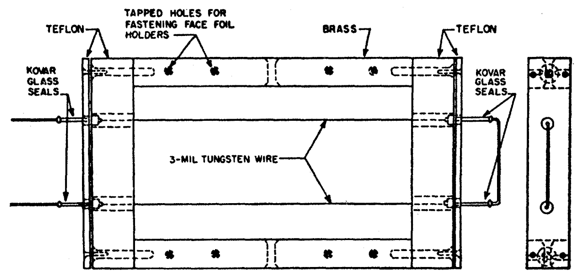

FIG. 2. Side and top view of one of the proportional counters.

B. Solid Angle Definition

The defining slit was between the magnet and the range counter. Thus, the definition of the solid angle was a function of the focusing properties of the magnet. The magnet was assumed to have no focusing in the determination of the absolute cross sections. As checked with the floating-wire technique, the uncertainty in the absolute cross sections due to changes in the focusing properties of the magnet was ±5%.

C. Nuclear Absorption in the Range Counter

In the energy range which was dealt with, the total cross section for proton-induced nuclear reactions in aluminum is approximately 1 barn. When examining 14-Mev protons, 0.6% of the number of protons counted were lost due to nuclear scattering. When examining 8-Mev protons, 0.2% were lost. This is a negligible loss of counts.

D. Angular Alignment of Targets

To keep the target position reproducible, the data for each element were taken separately. At the beginning of each run, the target position and the target alignment were adjusted. During a run, the target spent an equal amount of time in the target-in position and in the target-out position. The alignment was checked during and after the run.

Two of the ports of the scattering chamber had Plexiglas windows. The angular position of the ports of the scattering chamber that had Plexiglas windows was known with respect to the entrance of the magnet. The targets were aligned by eye such that only the edge of the targets could be seen. The horizontal dimension of the target was $2\frac{1}{2}$ inches. The edges of the target could be superimposed to within $\frac{1}{16}$ of an inch. This gave an uncertainty in the angular position of the target of ±1.4°, and a resultant uncertainty in the absolute cross sections of ±1.3% at 60° and 120° and ±1.7% at 90°.

E. Counting Procedure

The target-in, target-out data for a particular energy, target and angle did not vary as a function of

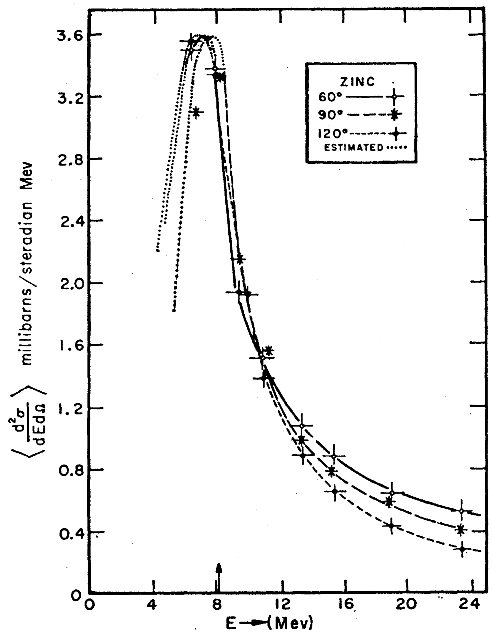

FIG. 3. $\langle d^2\sigma/dEd\Omega\rangle$ for zinc plotted as a function of the emitted proton energy E for the 60°, 90°, and 120° data.

time. However, the target-out counting rate occasionally varied outside of the statistical standard deviation.

To guarantee that there was no error due to the variations in the background count, a target-out count was taken before and after each target-in count for a particular energy, target and angle. The average of the two target-out counts was used as the background count. If the change in the two counts was slightly outside of the statistical standard deviation, the difference of the two counts, rather than the standard deviation, was used as the statistical fluctuation. If the difference was appreciably outside of the standard deviation of the statistics, which was rarely the case, the entire system was rechecked.

F. Low-Energy Target-Associated Sources of Background

The major background problem associated with this type of an experiment is the degrading of the high-energy protons into low-energy protons and these protons appearing as spurious inelastic data. These spurious low-energy protons are particularly objectionable when they appear when the target is in place and disappear when it is removed.

The spurious low-energy protons can come from many sources. The incident proton beam at the target holder in general has an intensity of only 1% or less of its maximum intensity. The targets used in this type of experiment are a few mils thick. If the target holder is much thicker than the targets, then it might make up in thickness as a source of low-energy protons what it lacks in beam intensity. High-energy protons coming from the target can be degraded and scattered by the walls of the scattering chamber, by objects in the scattering chamber, and by slits and then enter the range counter as low-energy protons. The low-energy protons present in the beam can be scattered by the target into the counter. A bombarding proton beam is never monoenergetic. The beam scrapes past slits, chambers, and pipes and creates a low-energy component. This low-energy spectrum has a high probability for large-angle scattering.

The equipment was designed such that few of these low-energy protons were detected. Three-mil tungsten wire was used as the target holder in this experiment. The targets used were $2\frac{1}{2}$ in. wide and $1\frac{1}{2}$ in. high. They were threaded $\frac{1}{8}$ in. from the top of the target with the tungsten wire and suspended by the wire from the top of the scattering chamber. Tungsten has a high atomic number and thus its low-energy proton cross section can be expected to be comparable to that of lead or tantalum and less than that of tin and zinc. The low-energy protons coming from the target holder were thus negligible. The apparatus was designed so that few high-energy protons coming from the target could degrade and scatter into the counter. Calculations were made and under all conditions for this experiment the contribution of spurious low-energy protons from this source was found to be negligible. The incident proton beam was defined with a lead slit which was 17 ft from the target. The beam did not touch the brass pipes anywhere between the defining slit and the target. High-energy protons degrading and scattering in the defining slit of the incident beam were the major source of low-energy contamination in the beam. Lead has a

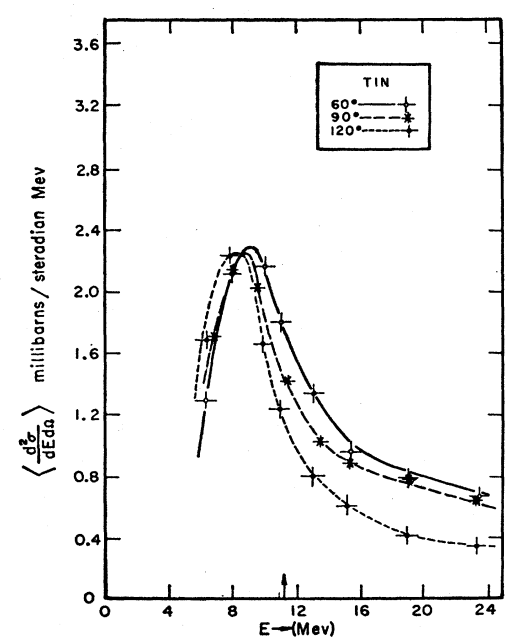

FIG. 4. $\langle d^2\sigma/dEd\Omega\rangle$ for tin plotted as a function of the emitted proton energy E for the 60°, 90°, and 120° data.

TABLE I. $\bar{\sigma}_t$ for the production of protons from 0 to 25 Mev. Cross sections (in millibarns)

Lead	104±15
Tantalum	171±20
Tin	267±40
Zinc	384±80

large scattering cross section. This caused a minimum of low-energy protons to be scattered by the lead slit into the solid angle defined by the target. The great distance between the defining slit and the target, coupled with the large scattering cross section of lead, caused only a small number of low-energy protons to strike the target. Rutherford scattering has a $Z^2[E^2 \sin^4(\theta/2)]^{-1}$ dependence, where Z is the atomic number of the target element and θ is the angle of scattering. The largest number of spurious low-energy protons was therefore expected to appear when the lowest energy (5 Mev) protons were examined from the highest Z target (lead) with the equipment set at the lowest angle (60°). The low-energy component of the beam was magnetically analyzed. The 5-Mev component in the beam was measured at 60°, and the ratio of spurious to true inelastic 5-Mev protons was found to be 0.01%. Thus, at the angles observed in this experiment, spurious counts due to low-energy protons contaminating the incident beam were negligible.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

1. Results

There are many possible nuclear reactions leading to low-energy proton emission when a high-energy incident

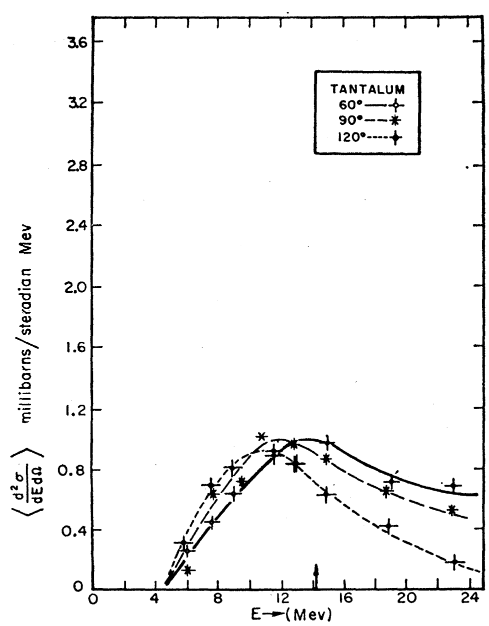

FIG. 5. $\langle d^2\sigma/dEd\Omega\rangle$ for tantalum plotted as a function of the emitted proton energy E for the 60°, 90°, 120° data.

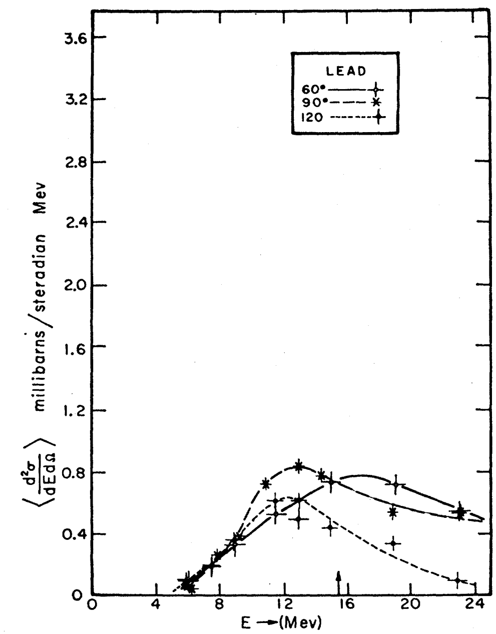

FIG. 6. $\langle d^2\sigma/dEd\Omega\rangle$ for lead plotted as a function of the emitted proton energy E for the 60°, 90° and 120° data.

beam, such as 160 Mev, is used. We define a differential scattering cross section $\langle d^2\sigma/dEd\Omega\rangle$, which is the differential scattering cross section for the emission of a proton from a target of a given energy per Mev per steradian times the average number of protons emitted at that energy.

The differential scattering cross section $\langle d^2\sigma/dEd\Omega\rangle$ obtained in this experiment is plotted against proton energy in Figs. 3–6 for the target elements used, zinc, tin, tantalum, and lead, respectively, for the detected angles 120°, 90°, and 60°.

Table I gives the average total cross section $\bar{\sigma}_t$ obtained, which is defined by

$$\bar{\sigma}_t = \int_0^{25} \int_0^{4\pi} \left\langle \frac{d^2\sigma}{dEd\Omega} \right\rangle dEd\Omega.$$

To obtain the $\bar{\sigma}_t$ for these elements, the plots of $\langle d^2\sigma/dEd\Omega\rangle$ were extrapolated to zero energy. The uncertainty of $\bar{\sigma}_t$ was estimated to be 20% for zinc, 15% for tin and lead, and 10% for tantalum.

Approximate Coulomb barriers of the target elements are 15.6, 14.2, 11.2, and 8.3 Mev for lead, tantalum, tin, and zinc, respectively, for a nuclear radius equal to 1.3×10^{-13} cm times the cube root of the mass number of the element. These Coulomb barriers are shown in Figs. 3 to 6 by a vertical arrow on the energy axis.

The major characteristics of the experimental results are:

(1) The energy spectra are peaked slightly below the barrier of each element.

(2) The heights of the peaks of the energy spectra show an approximate isotropic angular distribution.

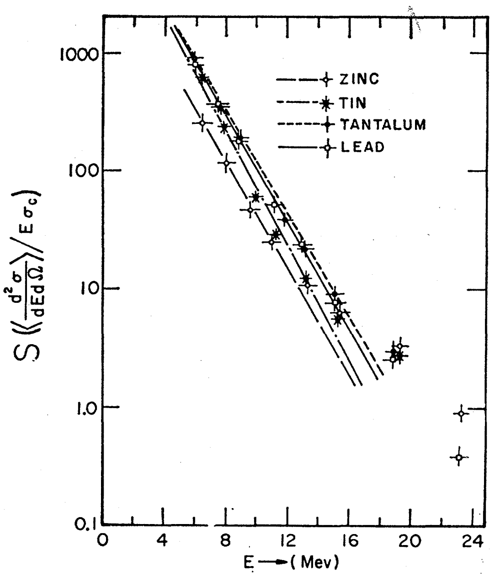

FIG. 7. S plotted as a function of E for the data of zinc, tin, tantalum, and lead.

(3) The peaks of the spectra decrease in height as the atomic number of the target nucleus increases.

(4) The angular distributions of the emitted protons with energies above the Coulomb barrier show an increase in intensity in the forward direction.

2. Discussion of Results and Comparison with Previous Experiments

It is reasonable that incident protons and incident neutrons with energies much greater than the proton Coulomb barrier of the target nucleus should induce similar reactions. However, the energy and angular distribution of the present experiment do not agree with the distributions obtained in the neutron experiments of Waniek *et al.*[1–4] and in the proton experiments of Igo and Eisberg.[5,6] On the other hand, the present results are consistent with those of Gugelot[14] and of Cohen and Rubin[7] at lower proton energies and with those of Graves and Rosen[15] at lower neutron energies. Possible sources of the discrepancies between the present experiments and those of Waniek *et al.*[1–4] and of Igo and Eisberg[5,6] include possible reactions in the insensitive emulsion volume surrounding the target wires in the former case and possible low-energy contamination of the incident beam in the latter case, as has been discussed in greater detail in reference 8.

[14] P. C. Gugelot, Phys. Rev. **81**, 51 (1951).

[15] E. R. Graves and L. Rosen, Phys. Rev. **89**, 343 (1953).

The essentially isotropic angular distributions of the emitted protons obtained in the present experiment in agreement with the results of Cohen and Rubin[7] indicate possible compound nucleus formation. If this is so, the detected protons come from different compound nuclei of different excitation energies.

Let S equal to $\langle d^2\sigma/dEd\Omega\rangle$ divided by E, the energy of the emitted proton, and by σ_c the total black nucleus cross section for an incident proton of energy E. S is a function of the level density and excitation energy of the average residual nucleus, as predicted by the statistical model of the compound nucleus.[16] The values of σ_c used were obtained from reference 16. S is plotted semilogarithmically in Fig. 7 using the 120° data for each of the elements studied. The curves appear to be approximately straight.

S thus has an exponential dependence on the ratio of (E/T). T is a constant for each element and is equal to 1.2 ± 0.3 Mev, 1.0 ± 0.3 Mev, 1.1 ± 0.2 Mev, and 1.2 ± 0.2 Mev for the targets zinc, tin, tantalum, and lead, respectively.

This energy dependence of S is the same as that found by Gugelot[14] and by Graves and Rosen[15] using incident nucleons of much lower energy. Gugelot used a 16-Mev incident proton beam while Graves and Rosen used a 14-Mev neutron beam. The average T obtained in the latter two experiments was 1.4 ± 0.4 Mev for atomic mass numbers 60 to 210. This is approximately the same T as obtained in this experiment. The protons produced in this experiment may be the result of a two-step process. The nucleus is struck by a 160-Mev proton and immediately emits a number of high-energy nucleons. A compound nucleus results at a high excitation. The decay of this compound nucleus results in the emission of one or more low-energy protons. The excitation of this compound nucleus can be comparable to the excitation of the nuclei capable of being produced by incident nucleons of much lower energy as indicated by the results of Gugelot and Graves and Rosen.

ACKNOWLEDGMENTS

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[16] J. M. Blatt, and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1953).