Inelastic Scattering of 96-Mev Protons*

K. STRAUCH AND F. TITUS
Harvard University, Cambridge, Massachusetts
(Received June 7, 1956)

Using incident 96-Mev protons, the energy spectra of protons scattered into a laboratory angle of 40° have been obtained from the following elements: Li, Be, B, C, N, O, F, Na, Mg, Al, Si, P, S, Cu, Ag, Pb, and Bi. All targets had natural isotopic constitution. All spectra shown an elastic peak and an inelastic continuum. Threshold considerations indicate that this continuum is often due to unresolved peaks at the very high-energy end. In addition, the spectra from the lighter elements show large inelastic peaks corresponding to the direct excitation of nuclear states in the target nucleus. Systematic trends are discussed.

I. INTRODUCTION

IN a previous article[1] we have reported measurements of the elastic and inelastic scattering of 96-Mev protons from carbon. In addition to the elastic peak and inelastic continuum, the energy spectra of scattered protons show sharp inelastic peaks which are due to protons that have excited the target nucleus to known energy states. In the forward direction, the coherent elastic scattering dominates. As the scattering angle approaches the region of the first diffraction minimum, the elastic peak and nearest inelastic peak become of comparable magnitude. Only after careful separation of elastic from inelastic protons was it possible to observe a faint first and second diffraction "minimum." The angular distribution of inelastic protons, both in the continuum and under the peaks, is peaked in the forward direction.

The importance of "slightly" inelastic events in proton scattering from carbon, that is, events leading to the excitation of low-lying nuclear levels in the target, prompted the present survey. Bombarding a wide variety of targets with protons of about 96 Mev, energy spectra of particles scattered into a laboratory angle of 40° have been obtained. This angle corresponds to the region of the first diffraction minimum for light elements. It was chosen because the elastic scattering cross section is low enough so as not to interfere with the inelastic measurements, while the inelastic scattering cross section is large enough for reasonable counting rates. The scattered particles were detected with a range telescope. The energy resolution of the experiment varied from 3.0 Mev at the highest scattered energy to 7 to 19 Mev at the lowest energy detected for the thinnest and thickest target respectively. A detailed discussion of the experimental arrangement and method of data analysis is given in reference 1. Pertinent additional details are given under the corresponding element heading in the following section. All targets were of natural isotopic constitution.

* Supported by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

[1] K. Strauch and F. Titus, Phys. Rev. **103**, 200 (1956).

II. RESULTS

The measured energy spectra are presented in Figs. 1–16. All plots are in the proton-target element (most abundant isotope) center-of-mass system. Each figure shows the center-of-mass scattering angle averaged over the energy of detected protons, and numbered arrows indicate the position of the highest energy proton that could have originated in the following reactions: $2(p,np)$; $3(p,2p)$; $4(p,dp)$; $5(p,\alpha p)$; $6(p,3\alpha dp)$; $7(p,4\alpha p)$; and $8(p,4\alpha tp)$. The arrow labeled **d** corresponds to the energy of protons having the same range as pickup deuterons that leave the residual nucleus in its ground state. (The detection telescope measures only ranges.) Lines indicate the energy position of protons that could have left the target nucleus in energy states listed for the most abundant isotope in recent compilations.[2–4] The highest energy line indicates the expected energy (center-of-mass system) of an elastically scattered proton as calculated from the energy of the incident beam. For the heavier elements, only low-lying states are indicated. The experimental points were taken in two groups called "normal" and "shifted" in reference 1: these are indicated by dots and crosses, respectively. A full line connects the points. The experimental points are not corrected for absorption of the scattered beam in the telescope. Where important, the correction for telescope absorption is shown by a dotted line. Representative statistical errors are indicated throughout.

Lithium

The 0.99-g/cm^2 Li target was sealed in an argon-filled thin-window aluminum container. The background from this container amounted to up to 10% of the Li counting rate and was substracted as follows. A range spectrum was obtained with an empty container. To take into account the additional energy lost in the lithium-filled container, the range scale was reduced by the effective target thickness before subtracting the corrected background spectrum from the range spec-

[2] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

[3] P. M. Endt and J. C. Kluyver, Revs. Modern Phys. **26**, 95 (1954).

[4] *Nuclear Data*, National Bureau of Standards Circular No. 499 (U. S. Government Printing Office, Washington, D. C., 1950).

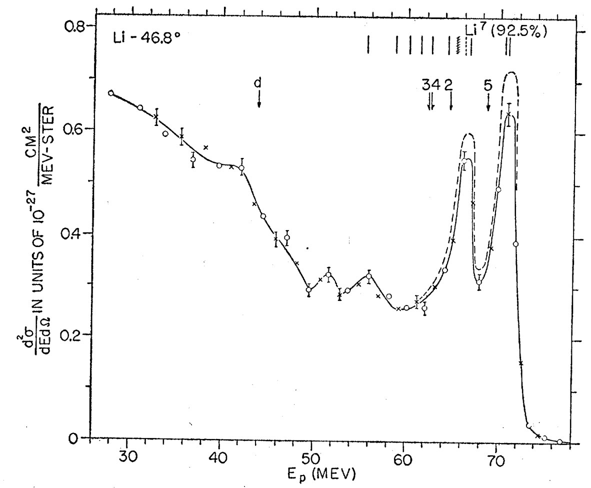

FIG. 1. Energy spectrum of protons scattered from lithium (center-of-mass system). See first paragraph of Sec. II for complete description.

trum observed with the filled container. We estimate that the error introduced by this procedure is smaller than the statistical uncertainty. The thickness of the Li target was measured by comparing its stopping power to that of Al. The same portion of the target was used for the scattering measurement and the stopping power comparison to minimize errors due to target inhomogeneity. As a result, we estimate that the target thickness is known to $\pm 1.7\%$.

The 70.8 ± 0.4 Mev peak in Fig. 1 represents elastically scattered protons and possibly contains protons that have excited the target nucleus to the 0.477-Mev level. The width of the peak is the same as the purely elastic peak of C^{12}: this fact, and the cross section suggest that the inelastic contribution is appreciably smaller than the elastic one. The 66.4 ± 0.4 Mev peak corresponds to the strong excitation of the 4.61-Mev level of Li^7, and its low-energy tail suggests the weaker excitation of one or more levels between 5 and 9 Mev. The 55.5 ± 1-Mev peak should be classified as probable. It corresponds to a nuclear excitation of 18 ± 1.4 Mev, and could correspond to the 17.5-Mev level excited by γ rays.[5] The 51.5 ± 1 Mev peak is uncertain, it would correspond to a level at 22 ± 1.4 Mev. The bump at 42 Mev is presumably due to pickup deuterons.

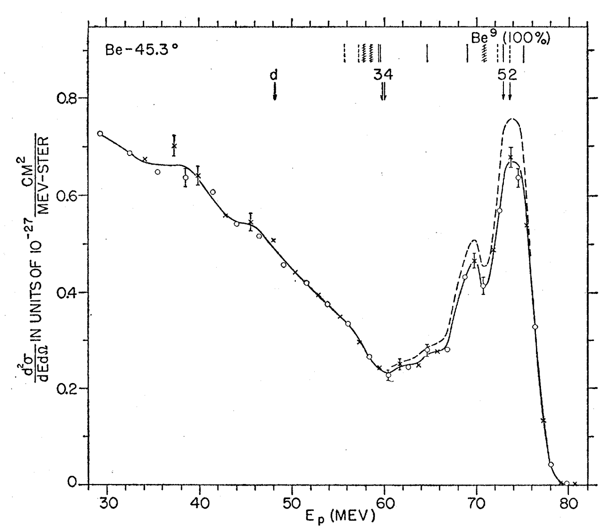

FIG. 2. Energy spectrum of protons scattered from beryllium (center-of-mass system).

Beryllium

The spectrum obtained with a 1.00-g/cm^2 Be target is shown in Fig. 2. The energy position and the width of the first peak at 74.0 ± 0.5 Mev indicates that it consists of a mixture of elastic and inelastically scattered protons: one or more of the low-lying levels of Be^9 are excited. The peak at 69.8 ± 0.5 Mev corresponds to the excitation of the 6.8-Mev level, and probably also of the 7.9-Mev level. The shoulder at 65 Mev indicates the possible excitation of the 11.3-Mev level. The bumps at 47 Mev and 37 Mev correspond to the two pickup deuteron groups that have been observed by Selove.[6] The rapid increase of the continuum below the energy corresponding to "inner core" breakup by $(p,2p)$ and (p,dp) reactions should be noted.

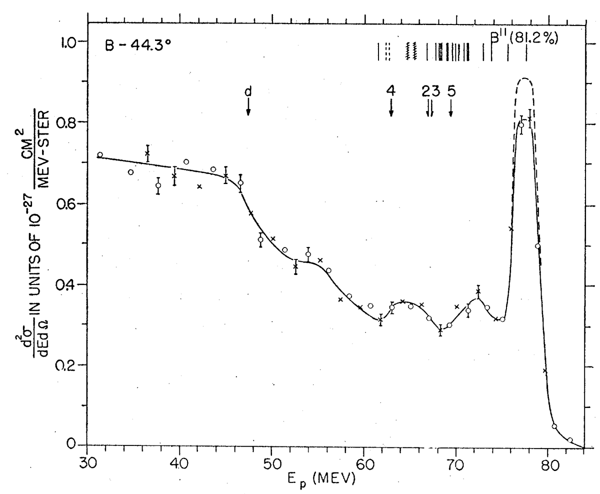

FIG. 3. Energy spectrum of protons scattered from boron (center-of-mass system).

Boron

The 1.08-g/cm^2 B target was made of powder contained in a thin-walled aluminum box. Background subtraction and target thickness were obtained as in the case of Li. The spectrum shown in Fig. 3 contains only one prominent peak at 77.5 ± 0.5 Mev which is mainly due to elastic protons. All inelastic protons above 69.6 Mev must be the result of level excitation,

[5] J. Goldemberg and L. Katz, Phys. Rev. **95**, 471 (1954).
[6] W. Selove, Phys. Rev. **101**, 231 (1956).

however the energy resolution of this experiment makes identification difficult. The two broad peaks at 73 Mev and 65 Mev, and a possible bump at 55 Mev all suggest that many levels of B are excited, but none as strongly as some of the low-lying levels of the two neighboring elements.

Carbon

For the sake of completeness, the 43.9° spectrum of C of reference 1 is reproduced in Fig. 4. The reference contains a detailed discussion of this spectrum, in addition to angular distribution measurements.

Nitrogen

The N spectrum of Fig. 5 was obtained by using a 0.74-g/cm² NaN_3 target, and subtracting from it the spectrum obtained simultaneously with a 1.03-g/cm² Na target. Since the stopping power of the two targets were slightly different, it was necessary to shift the energy scale of the Na spectrum by this small difference before carrying out the subtraction. It is not believed that this procedure introduced any appreciable experimental uncertainty. Both the NaN_3 and Na targets were kept in thin-walled aluminum containers. The background subtraction and the target thickness measurement were carried out as with Li.

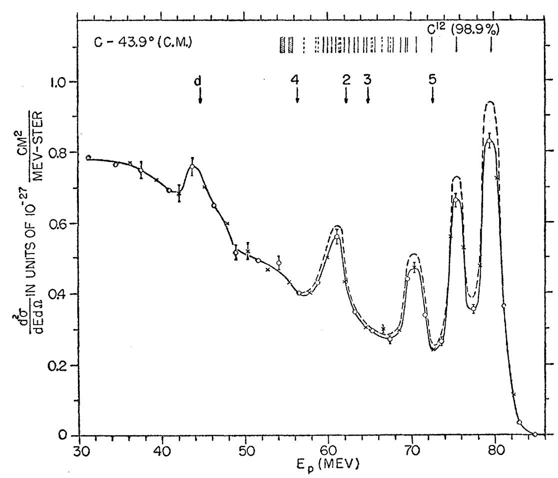

FIG. 4. Energy spectrum of protons scattered from carbon (center-of-mass system).

The 81.5±0.4 Mev peak contains mainly elastic protons: this fact follows from the energy position and width. Excitation of some of the low-lying levels of N^{14} occurs, as is shown by the presence of inelastic protons above 74.6 Mev and the broad peak centered at 76 Mev. The valley between the elastic and broad inelastic peaks corresponds to the energy of protons that would have excited the 2.31-Mev $T=1$ state of N^{14}: this level seems to be at most weakly excited. None of the low-lying energy states appear to be excited as strongly as those of the neighboring elements. A broad peak appears at 64 Mev—it corresponds to a nuclear excitation of 19 Mev where no levels have yet been reported. The probable structure at 44 Mev is presumably caused by pickup deuterons. The position of this peak would be consistent with deuterons that have removed an "inner-core" neutron and thus leave N^{13} in an excited state: such a narrow group has been observed for Be.[6]

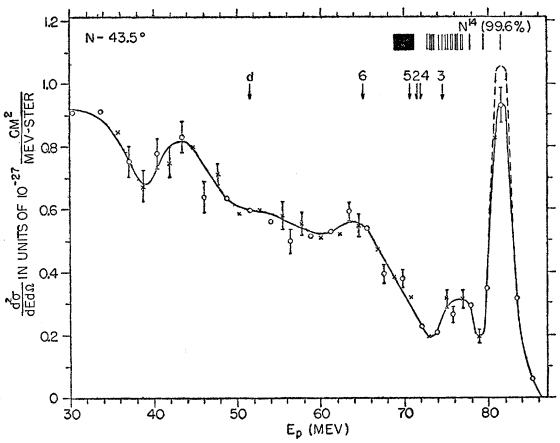

FIG. 5. Energy spectrum of protons scattered from nitrogen (center-of-mass system).

Oxygen

A 0.82-g/cm² H_2O target was used in a thin-walled aluminum container. Target thickness and background were obtained as with Li. The spectrum shown in Fig. 6 contains a purely elastic peak at 82.3±0.4 Mev since no excited levels below 6.06 Mev are known. The strong inelastic peak at 76.0±0.4 Mev could have contributions from protons that have excited any of the 6.06-, 6.14-, 6.91-, or 7.12-Mev levels. There is evidence for structure at lower energies, especially a broad peak at

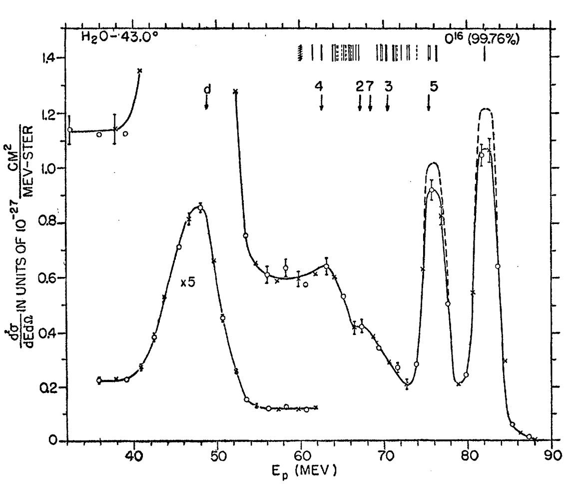

FIG. 6. Energy spectrum of protons scattered from water (proton-oxygen center-of-mass system).

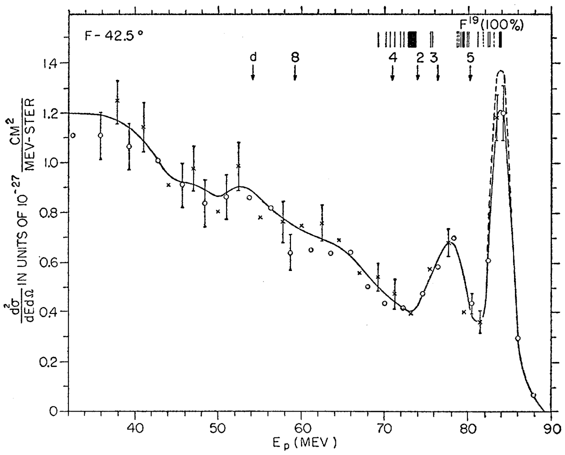

FIG. 7. Energy spectrum of protons scattered from fluorine (center-of-mass system).

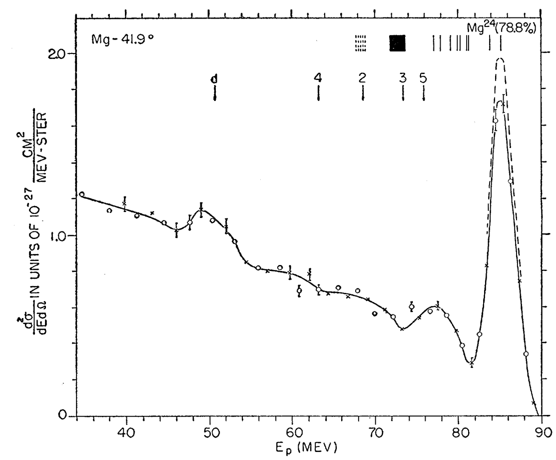

FIG. 9. Energy spectrum of protons scattered from magnesium (center-of-mass system).

63 Mev corresponding to a nuclear excitation of 20.3 Mev. The peak at 48 Mev is due to recoil protons from the *p-p* interaction: it provides a convenient check of our beam calibration and the agreement is satisfactory with the results of Kruse *et al.*[7]

Fluorine

Figure 7 shows a F^{19} spectrum obtained with a 0.89-g/cm^2 NaF target after the Na and background contributions had been subtracted as explained for the N data. The width and position of the 83.8±0.4 Mev peak is consistent with elastic protons only. However, several known low-lying energy levels could have been excited by protons contained in this peak. The width of the 78.0±0.5 Mev peak is too broad to correspond to the excitation of one level only. Its position corresponds to a nuclear excitation of 6.1 Mev, a region in which no levels have as yet been reported. The statistical accuracy of the F results is poorer than for other elements due to the target subtraction.

Sodium

A 1.03-g/cm^2 Na target sealed in an argon-filled thin-walled aluminum container was used to obtain the results of Fig. 8. Only an elastic peak, with possible contributions from protons exciting the 0.439 Mev-level, is prominent. That some of the low-lying levels are excited is shown by the presence of inelastic protons below the threshold for breakup of the target nucleus. However, the cross section per level is smaller than for some of the prominent peaks in the lighter elements. The absence of inelastic peaks in the Na spectrum makes this a favorable spectrum to subtract from compound spectra such as NaN_3 and NaF.

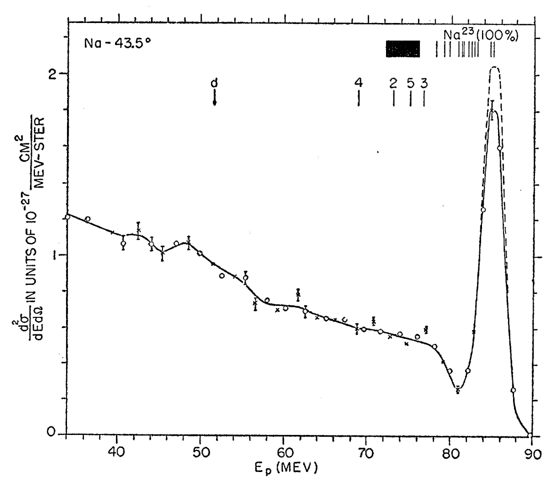

FIG. 8. Energy spectrum of protons scattered from sodium (center-of-mass system).

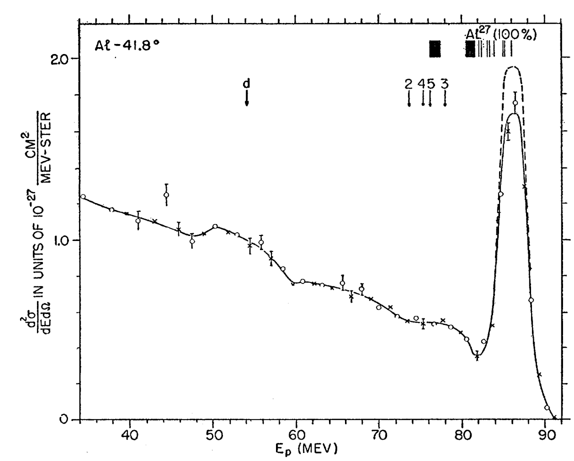

FIG. 10. Energy spectrum of protons scattered from aluminum (center-of-mass system).

[7] Kruse, Ramsey, and Teem, Phys. Rev. **101**, 1079 (1956).

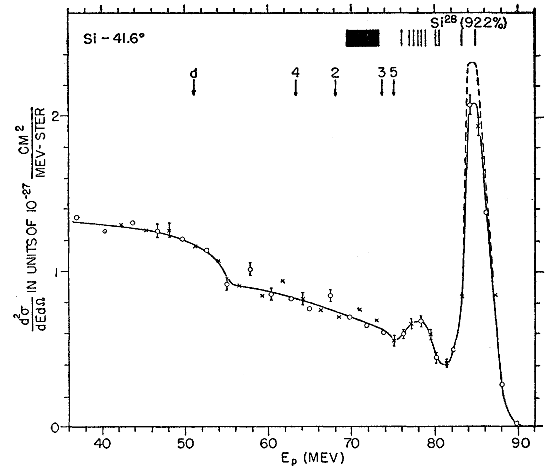

FIG. 11. Energy spectrum of protons scattered from silicon (center-of-mass system).

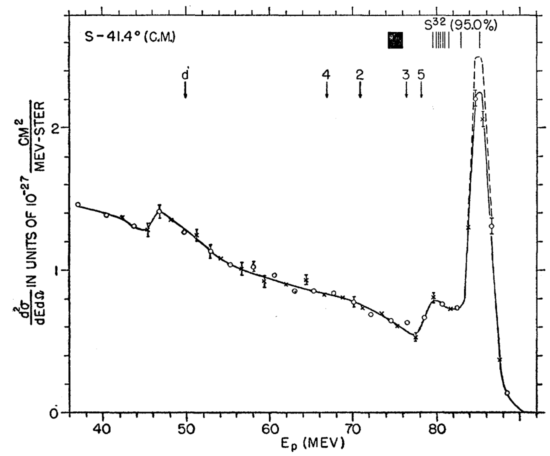

FIG. 13. Energy spectrum of protons scattered from sulfur (center-of-mass system).

Magnesium, Aluminum, Silicon, Phosphorus, and Sulfur

Figures 9–13 show the spectra obtained with Mg(1.10 g/cm^2), Al(1.07 g/cm^2), Si(1.39 g/cm^2), P(1.56 g/cm^2), and S(1.43 g/cm^2) targets. These spectra all show the elastic peak (more or less pure) followed by a region of inelastic scattering which from threshold considerations must correspond to level excitation of the target nucleus. Some structure is seen in the high-energy portion of the inelastic continuum of Si and S. Excepting the P spectrum, there is a good correlation between dips in the inelastic scattering cross section and the absence of known levels. However, the maximum value to which the inelastic scattering cross section rises does not appear to depend strongly on the level density. Thus between 4–6 Mev nuclear excitation, respectively 4, 14, and 2 levels are known in Mg^{24}, Al^{27}, and Si^{28}. The inelastic scattering cross sections for the corresponding energy region are 0.43 mb/sterad, 0.48 mb/sterad and 0.51 mb/sterad, respectively. The structure in these spectra in the 50-Mev region can be consistently interpreted as due to pickup deuterons.

Copper, Silver, Lead, and Bismuth

Figures 14–17 show the spectra obtained with Cu(1.35 g/cm^2), Ag(2.57 g/cm^2), Pb(3.79 g/cm^2), and Bi(3.705 g/cm^2) targets. Within the experimental accuracy, no structure in the inelastic continuum is observed with any of these targets. The inelastic continuum runs smoothly into the elastic peak. Here again, threshold considerations indicate that the portion of the apparent continuum which is located close to the elastic peak is due to protons having excited levels in the target nucleus. After subtracting the continuum, the width of the high-energy peaks is that expected for purely elastic protons.

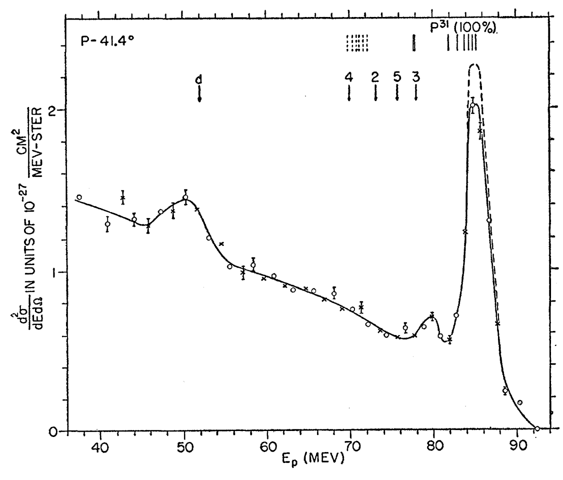

FIG. 12. Energy spectrum of protons scattered from phosphorous (center-of-mass system).

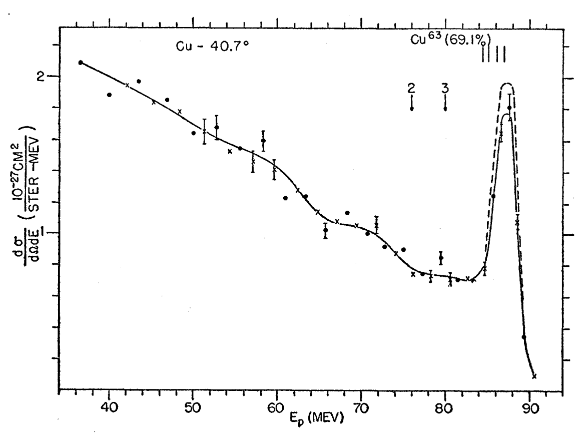

FIG. 14. Energy spectrum of protons scattered from copper (center-of-mass system).

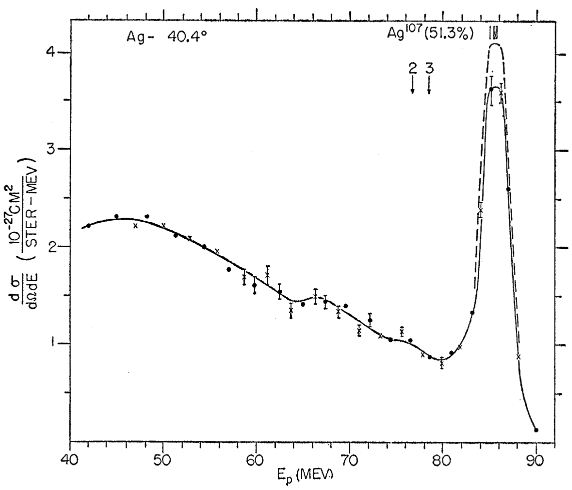

FIG. 15. Energy spectrum of protons scattered from silver (center-of-mass system).

III. DISCUSSION

The spectra presented in the preceding section have many common characteristic features.

(1) The highest energy peak includes elastically scattered protons. In the case of C and O, the energy difference between the ground and first excited states is large enough so that it is certain that only truly elastic protons are included. In most other spectra, the width of the high-energy peak is that expected of elastically scattered protons. However, the existence of low-lying levels which could not be resolved make it impossible to know with certainty the composition of protons in these peaks. For the heavier elements the inelastic contribution would be small if the cross section for the excitation of the low-lying levels is similar to those in the 3–4 Mev region. At least for rotational states this is not expected to be the case.[8]

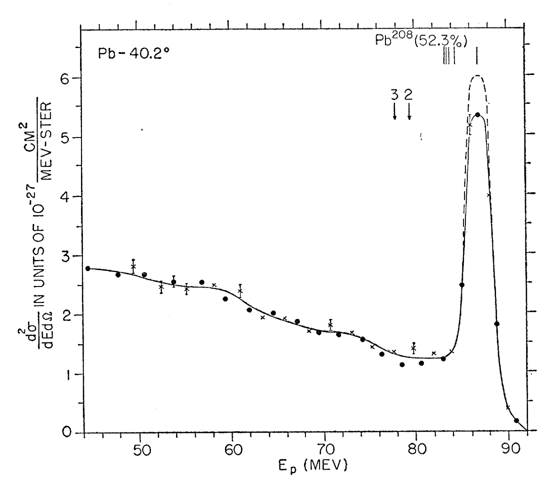

FIG. 16. Energy spectrum of protons scattered from lead (center-of-mass system).

[8] S. I. Drozdov, J. Exptl. Theoret. Phys. (U.S.S.R.) 28, 734 (1955).

(2) Most of the spectra from the light elements show one or more inelastic peaks. Their widths are usually determined by the energy resolution of the experiment.

(3) All spectra show an inelastic continuum which decreases in cross section with increasing proton energy. That portion of the continuum which consists of protons whose energy is too high to have originated in a breakup of the target nucleus must be composed of unresolved peaks. Inelastic protons originating from nuclear breakup have a genuinely continuous distribution. The portion of the continuum just below the energies at which nuclear breakup becomes possible are probably composed partically of unresolved peaks and truly continuous protons. For instance, the Li, C, and O spectra all show strong inelastic peaks at energies lower than correspond to possible $(p,\alpha p)$ protons, and C has an inelastic peak in a region where $(p,2p)$ and (p,np) protons are possible.

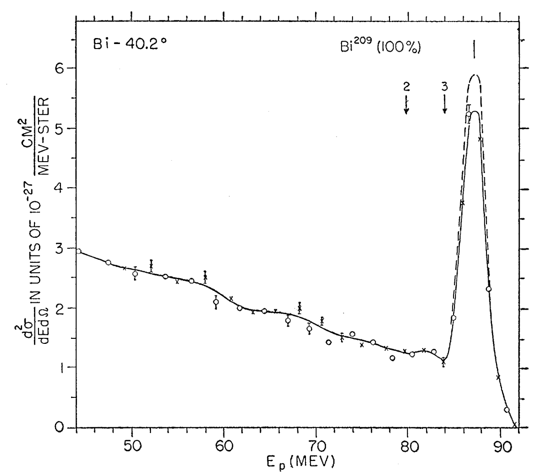

FIG. 17. Energy spectrum of protons scattered from bismuth (center-of-mass system).

Some general properties of these features will now be examined.

A. Excited Energy States

The inelastic peaks are most prominent with elements of mass number $A \leqslant 19$. For a given element, if a level is excited at all, its excitation is in general stronger the closer it lies to the ground state. With two exceptions, the prominent peaks are at higher energies than those possible for protons from $(p,2p)$ or (p,np) reactions. The exceptions are Be with one very loosely bound neutron, and C which has one or more strongly excited levels at 20.8 Mev. Several strongly excited levels lie above the $(p,\alpha p)$ threshold.

Certain elements, such as B and N, have no levels that are excited as strongly as some of the levels of neighboring elements. This conclusion is not based on the absence of prominent inelastic peaks, which could well be smeared out by the experimental energy resolution, but on the smaller magnitude of the apparent continuum. If many unresolved levels were excited strongly, then this continuum would be higher. On the whole, levels seem to be excited more strongly if they are in a region of low level density. The most prominent exception to this observation is the 60-Mev peak in carbon.

As discussed in some detail in reference 1, the success of the individual-particle model in explaining many of the features of the excited states of light nuclei[9] suggests the desirability of an analysis of the nature of the levels that are found to be excited strongly by 96-Mev protons in terms of their individual-particle description. Such an analysis can only be speculative since the assignment of a given level to a certain configuration is generally uncertain.[9] With this understanding the following two remarks are consistent with observations:

(1) Levels that are strongly excited appear to result from "simple" rearrangements of the ground state structure. "Simple" rearrangement means a change in coupling of a given configuration, or the transition of one nucleon only to a higher shell state.

(2) Not all levels that can be reached from the ground state by a "simple" rearrangement are observed to be strongly excited, and this failure cannot always be ascribed to poor energy resolution or to competition from nuclear breakup.

B. Inelastic Continuum

The spectra shown in Figs. 1–17 all have an inelastic continuum which decreases in cross section with increasing proton energy, agreeing in form with the predictions of Goldberger[10] based on the nuclear cascade model. In order to compare the inelastic continua from the various targets, a K_AEe^{-E/k_A} dependence of the inelastic scattering cross section has been assumed E is the center-of-mass energy of the scattered protons, and K_A and k_A are constants to be determined in each case by a best fit to the observed spectrum. The only justification for the use of this particular form is that in the energy region available, it gives a good representation of the inelastic spectra, and that it conviently determines a constant k_A measuring the shape and another constant K_A proportional to the cross section. Other functions could have been used with equal success.

Figures 18 and 19 show the values of K_A and k_A as a function of atomic weight. The limits of errors indicated correspond to the minimum and maximum values of K_A and k_A which will permit a fit of the assumed function to the experimental data. It can be seen that the cross section parameter K_A varies about as $A^{\frac{1}{2}}$. Such a dependence is reasonable if it is remembered that our observations cover only the high-energy part of the inelastic continuum. Heavy elements favor a larger energy degradation of cascade particles: the yield

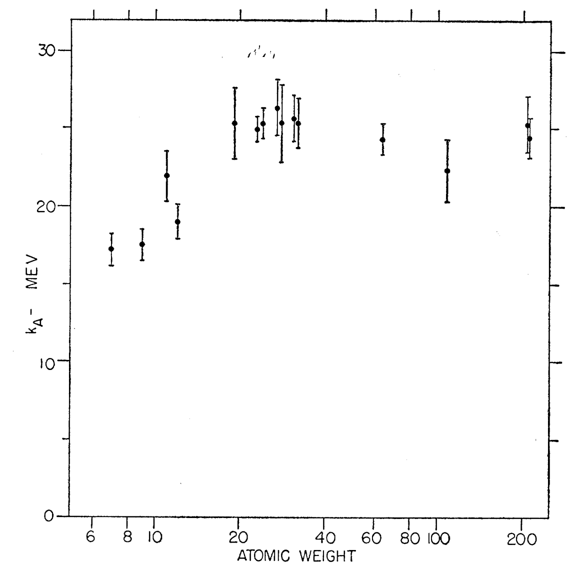

FIG. 18. Variation of the shape constant k_A with mass number A.

of fast secondaries is thus expected to increase more slowly than the absorption cross section.[11] The shape factor k_A appears to remain quite constant for $A>19$.

Hofmann and Strauch[12] have observed the energy spectra of neutrons ejected from several nuclei by 95-Mev protons. The angles of observation varied from 0° to 28° in the laboratory system. The shape of the neutron spectra, at the larger scattering angle, are quite similar to the shape of the proton continuum. Extrapolations of the neutron continuum cross sections to 40° are in good agreement with the observed proton continuum cross sections. These results indicate that there is no appreciable difference in the production of inelastic neutrons and protons by 96-Mev protons. The fact that inelastic peaks have been observed in the proton spectra and not in the neutron spectra can be

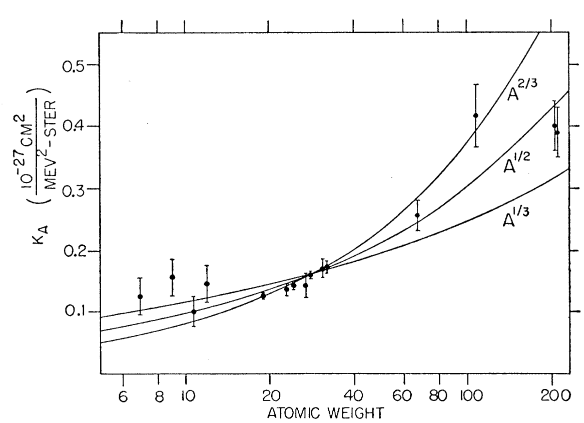

FIG. 19. Variation of the cross-section constant K_A with mass number A.

[9] D. R. Inglis, Revs. Modern Phys. 25, 390 (1953).
[10] M. L. Goldberger, Phys. Rev. 74, 1269 (1948).
[11] T. B. Taylor, Phys. Rev. 92, 831 (1953).
[12] J. A. Hofmann and K. Strauch, Phys. Rev. 90, 449 (1953).

explained by the much poorer energy resolution of the neutron experiments.

IV. CONCLUSION

It has been found that the inelastic scattering of 96-Mev protons results in the direct excitation of many levels in the target nucleus. Strong excitation of certain levels takes place in the light elements, and several of these have been identified with known excited states. Thus in the high-energy region, a careful separation of inelastic from elastic protons is required in experiments dealing primarily with elastic scattering. The present survey suggests the desirability of increasing the experimental energy resolution for more detailed studies with high energy protons. Such an increase in energy resolution is possible with the more nearly monoenergetic proton beams from a linear accelerator or from a cyclotron with a regenerator-type of external beam. Finally the possibility of using polarized protons, which can be easily produced at high energy, should be noted.

We wish to thank G. P. Calame, F. Federighi, G. Gerstein, and J. Niederer for their valuable help in taking data and calculating the spectra. We are much indebted to the entire staff of the Cyclotron Laboratory for their generous help and assistance.

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Yields of the $O^{18}(p,\alpha)N^{15}$ and $O^{18}(p,n)F^{18}$ Reactions for Protons of 800 kev to 3500 kev*

H. A. HILL AND J. M. BLAIR
Department of Physics, University of Minnesota, Minneapolis, Minnesota
(Received April 23, 1956)

The yield of the $O^{18}(p,\alpha)N^{15}$ reaction was observed at 90° with respect to the ion beam for protons from 800 kev to 3500 kev. Resonances in the yield located fifteen energy levels in F^{19} not previously observed. Neutrons from the $O^{18}(p,n)F^{18}$ reaction were observed in the forward direction above the threshold ($E_p=2577\pm8$ kev). Simultaneous observation of alpha particles and neutrons showed that the resonance energies for the two reactions agree in some cases but not in others.

INTRODUCTION

A STUDY of the yield of the reaction $O^{18}(p,\alpha)N^{15}$ as a function of proton energy will provide information concerning the existence of energy levels in the compound nucleus F^{19}. This reaction has previously been studied by Seed,[1] Mileikowsky, and Pauli,[2] and Cohen.[3] Cohen observed resonances for proton energies of 640±5 and 850±5 kev. The present work was undertaken to extend such measurements to higher energies, since nothing was known about levels in F^{19} from the upper level found by Cohen (excitation level of 8.76 Mev in F^{19}) up to the $O^{18}(p,n)F^{18}$ threshold (excitation level of 10.47 Mev in F^{19}). The $O^{18}(p,n)$ reaction has been studied by a number of investigators.[4–6] Above the (p,n) threshold the (p,α) and (p,n) reactions were observed simultaneously so that a detailed comparison of the variation of their yields with proton energy could be made.

EQUIPMENT

The protons used in this work were accelerated by the Minnesota electrostatic generator.[7] After passing through a 90° magnet, the proton beam was refocused by means of two sets of quadrupole electrostatic lenses[8] fourteen feet apart, and then entered the target chamber. The slightly converging proton beam was defined by a tantalum collimating aperture before hitting the target foil. Particles leaving the target at 90°±1.5° with repect to the beam direction passed into a proportional counter through an aluminum window. The undeflected proton beam struck an insulated current collector cup. A magnetic field was provided around the mouth of the collector cup to eliminate current measurement errors due to secondary electrons. The beam current was measured with an integrator circuit which automatically placed a shutter in the ion beam and shorted the input lead to the scaling circuits when a condenser became charged to a predetermined potential. The neutron flux in the forward direction was intercepted by a conventional "long counter."[9] After suitable amplification, the pulses

* This work was supported in part by the Office of Naval Research.
1 J. Seed, Phil. Mag. 42, 566 (1951).
2 C. Mileikowsky and R. T. Pauli, Arkiv Fysik 4, 299 (1952).
3 A. V. Cohen, Phil. Mag. 44, 583 (1953).
4 Richards, Smith, and Browne, Phys. Rev. 80, 524 (1950).
5 Blaser, Boehm, Marmier, and Scherrer, Helv. Phys. Acta 24, 465 (1951).
6 H. Mark and C. Goodman, Phys. Rev. 101, 768, (1956).
7 Williams, Rumbaugh, and Tate, Rev. Sci. Instr. 13, 202 (1942).
8 E. L. Hubbard, and E. L. Kelly, University of California Radiation Laboratory Report 2181, 1953 (unpublished).
9 A. O. Hanson and J. L. McKibben, Phys. Rev. 72, 673 (1947).