Inelastic Scattering of Protons by Ca^{40}†

C. M. BRAAMS*
Physics Department and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received December 2, 1955)

The inelastic scattering of protons by Ca^{40} was investigated with the MIT-ONR electrostatic generator and a 180-degree magnetic spectrograph. Bombarding energies from 6.54 to 8.15 Mev were used, targets were made of calcium, and the reaction angle was 90 degrees. Excited states of Ca^{40} were found at 3.348 ±0.004, 3.730±0.004, 3.900±0.004, 4.483±0.005, 5.202±0.008, 5.241±0.006, 5.272±0.006, 5.606±0.009, 5.621±0.008, 5.901±0.008, and 6.029±0.008 Mev.

I. INTRODUCTION

IN the *j-j* coupling shell model,[1,2] the protons and neutrons from the twenty-first to the twenty-eighth occupy the $1f_{7/2}$ shell. The nucleon number 20 has long been accepted[3,4] as "magic," mainly because of the stability and abundance of isotopes with 20 protons or neutrons. Recent studies of nuclear binding energies[5–11] have shown that 28 like nucleons also form a particularly stable configuration, and some authors[5,8] even find evidence against 20 as a magic number.

Closed shells at 2, 8, 20, 40, and so on, can be explained[3] by taking the orbits of individual particles, moving in a harmonic-oscillator potential well as a first approximation; whereas 28, 50, 82, and 126 follow from the assumptions that the potential is intermediate between the harmonic oscillator and the square well and that the spin-orbit coupling brings the state of highest *j* from each harmonic-oscillator shell down to the next lower one. At the present time, the most generally accepted picture[2,12–15] seems to be that the $1f_{7/2}$ state is brought down to about halfway between the $1d_{3/2}$ and the $2p_{3/2}$ states, thus forming a shell between nucleon numbers 20 and 28 which contains only one *j* value.

This model leads to a number of predictions about the excited states of nuclei with proton and neutron numbers from 20 to 28, which can be tested experimentally.

1. The first excited states of nuclei with magic proton and neutron numbers should lie relatively high.[16–19] The doubly magic nuclei in this region which are accessible to experimental investigations are ${}_{20}Ca_{20}{}^{40}$ and ${}_{20}Ca_{28}{}^{48}$.
2. The first excited state should also be high in nuclei with closed shells plus or minus one $1f_{7/2}$ particle, because it involves either raising a $1f_{7/2}$ particle to the next higher shell, or raising a particle from the next lower shell to the $1f_{7/2}$ state. The nuclei in this class which are accessible are ${}_{20}Ca_{21}{}^{41}$, ${}_{21}Sc_{20}{}^{41}$, ${}_{21}Sc_{28}{}^{49}$, ${}_{20}Ca_{27}{}^{47}$, and ${}_{27}Co_{28}{}^{55}$.
3. The nuclei with proton and neutron numbers from 20 to 28, which have two or more particles or holes in the $1f_{7/2}$ shell, can only have low-lying excited states of the same configuration as the ground state. These multiplets have been studied theoretically,[20–22] and the experimental evidence for their existence has been recently reviewed.[23,24] This class of nuclei ranges from ${}_{20}Ca_{22}{}^{42}$ to ${}_{27}Co_{27}{}^{54}$. Their spectra may become very complex if both protons and neutrons are involved, so that in the present stage of nuclear spectroscopy, the most interesting members might be those with one closed shell. These are the calcium isotopes from ${}_{20}Ca_{22}{}^{42}$ to ${}_{20}Ca_{26}{}^{46}$, and ${}_{22}Ti_{28}{}^{50}$, ${}_{23}V_{28}{}^{51}$, ${}_{24}Cr_{28}{}^{52}$, ${}_{25}Mn_{28}{}^{53}$, and ${}_{26}Fe_{28}{}^{54}$.

This paper is the first in a series on the energy levels of the calcium isotopes. The MIT-ONR electrostatic generator and two magnetic spectrographs have been used to study the (d,p) and (p,p') reactions on the stable Ca isotopes 40, 42, 43, 44, and 48. Groups of alpha particles from the $Ca^{40}(d,\alpha)K^{38}$, $Ca^{42}(p,\alpha)K^{39}$, and $Ca^{43}(p,\alpha)K^{40}$ reactions were also observed. In addition to information about the excited states of Ca^{40}, Ca^{41}, Ca^{42}, Ca^{43}, Ca^{44}, Ca^{45}, Ca^{48}, and Ca^{49}, this work therefore yields relations between the atomic masses of Ca^{40}

† This work has been supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

* Present address: Physisch Laboratorium, Utrecht, Netherlands.

1 Haxel, Jensen, and Suess, Z. Physik **128**, 295 (1950).
2 M. G. Mayer, Phys. Rev. **78**, 16 (1950).
3 H. A. Bethe and R. F. Bacher, Revs. Modern Phys. **8**, 82 (1936).
4 M. G. Mayer, Phys. Rev. **74**, 235 (1948).
5 C. H. Townes and W. Low, Phys. Rev. **79**, 198 (1950); and W. Low and C. H. Townes, Phys. Rev. **80**, 608 (1950).
6 J. A. Harvey, Phys. Rev. **81**, 353 (1951).
7 H. E. Duckworth and R. S. Preston, Phys. Rev. **82**, 468 (1951).
8 A. H. Wapstra, Phys. Rev. **84**, 838 (1951).
9 Collins, Nier, and Johnson, Phys. Rev. **86**, 408 (1952).
10 N. Feather, Advances in Phys. **2**, 141 (1953).
11 K. Way and M. Wood, Phys. Rev. **94**, 119 (1954).
12 P. F. A. Klinkenberg, Revs. Modern Phys. **24**, 63 (1952).
13 Haxel, Jensen, and Suess, Ergeb. Exakt. Naturwiss. **26**, 244 (1952).
14 B. H. Flowers, Progr. Nuclear Phys. **2**, 235 (1952).
15 M. H. L. Pryce, Rept. Progr. Phys. **17**, 1 (1954).
16 P. Staehelin and P. Preiswerk, Helv. Phys. Acta **24**, 623 (1951).
17 A. H. Wapstra, Physica **18**, 799 (1952).
18 F. Asaro and I. Perlman, Phys. Rev. **87**, 393 (1952).
19 G. Scharff-Goldhaber, Phys. Rev. **90**, 587 (1953).
20 D. Kurath, Phys. Rev. **91**, 1430 (1953).
21 I. Talmi, Helv. Phys. Acta **25**, 185 (1952).
22 A. R. Edmonds and B. H. Flowers, Proc. Roy. Soc. (London) **A215**, 120 (1952).
23 Nussbaum, van Lieshout, and Wapstra, Phys. Rev. **92**, 207 (1953).
24 R. H. Nussbaum, thesis, Amsterdam, 1954 (unpublished).

through Ca^{45} and the potassium isotopes. Unfortunately, Ca^{46} was not available in concentrations sufficient for these experiments.

Preliminary reports about our work on Ca^{40}, Ca^{41}, Ca^{43}, and Ca^{45} have already appeared.[25–28] The present paper describes the inelastic scattering of protons from targets of natural calcium. This reaction was observed previously by Harvey,[29] who used the MIT cyclotron and range measurements. With a bombarding energy of 7.7 Mev, he observed one level at 3.8 Mev, which he ascribed to Ca^{40} because of its 97 percent abundance.

II. EXPERIMENTAL PROCEDURE

Thin targets of natural calcium were prepared by evaporating the metal onto Formvar films supported by a $\frac{1}{2}$-in.$\times\frac{3}{4}$-in. wire frame. The targets oxidize at once when air is let into the evaporator and presumably turn into $CaCO_3$ within weeks. As it was found that a metallic layer on the target greatly increases the permissible beam intensity, the Formvar was backed with gold foil. The Formvar was picked up with the wire frame from a water surface in the usual way, and the frame was dipped once more to pick up a piece of gold foil which had been cut to size and floated on the water. From an analysis of the spectrum of elastically scattered protons, it was found that the beaten gold leaf contained appreciable amounts of silver and copper. Some targets were therefore made with a backing of evaporated gold. During the evaporation, however, the Formvar tends to shrink and break off the wire frame so that these targets are much more delicate than the ones with gold leaf. Some good targets were also obtained by inadvertently letting the calcium, evaporated onto unbacked Formvar, absorb some mercury vapor before letting air into the evaporator.

The weight of a typical target may be: $CaCO_3$, 0.05 mg/cm²; Formvar ($C_5H_7O_2$), 0.02 mg/cm²; Au (including some Ag and Cu), 0.2 mg/cm². According to Nier,[30] the abundances of the isotopes in natural calcium are as listed in Table I.

The targets were placed in the field of the 180-degree annular magnetic spectrograph[31] and bombarded with

TABLE I. Isotopic abundances of natural calcium.

Calcium isotope	40	42	43	44	46	48
Natural abundance in percent	96.96	0.64	0.145	2.06	0.0033	0.185

[25] Braams, Bockelman, Browne, and Buechner, Phys. Rev. **91**, 474(A) (1953).
[26] C. M. Braams, Phys. Rev. **94**, 763(A) (1954).
[27] C. M. Braams, Phys. Rev. **95**, 650(A) (1954).
[28] P. M. Endt and J. C. Kluyver, Revs. Modern Phys. **26**, 95 (1954).
[29] J. A. Harvey, Phys. Rev. **88**, 162 (1952).
[30] A. O. Nier, Phys. Rev. **53**, 282 (1938).
[31] Buechner, Strait, Stergiopoulos, and Sperduto, Phys. Rev. **74**, 1569 (1948).

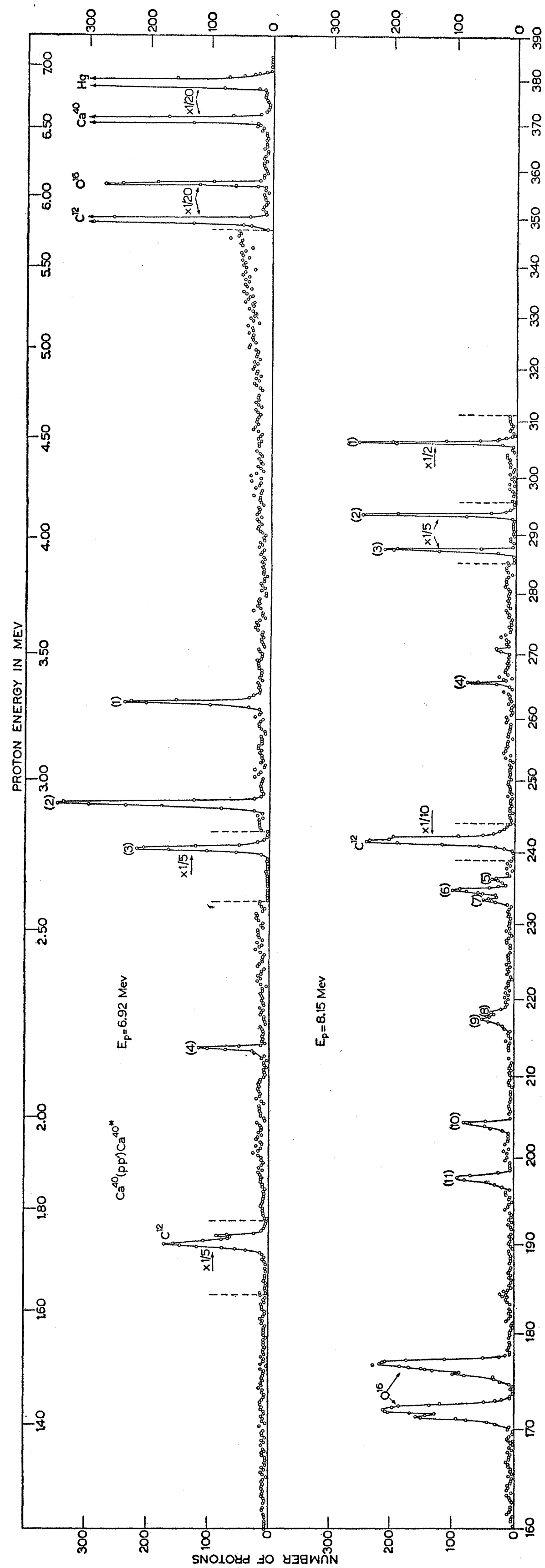

FIG. 1. Proton groups from a calcium target bombarded with 6.92- and 8.15-Mev protons. Reaction angle 90 degrees.

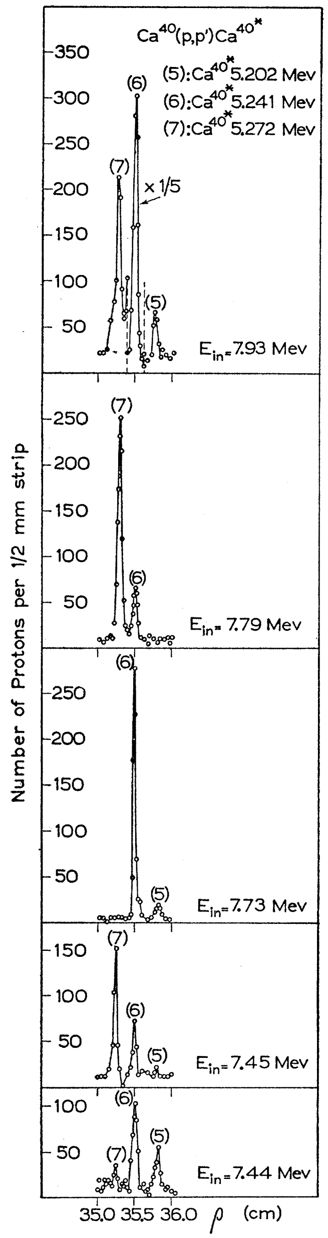

FIG. 2. Intensity variations of three proton groups from Ca^{40} as a function of incident proton energy.

protons from the MIT-ONR electrostatic generator.[32] The proton beam was analyzed with a 90-degree magnetic analyzer with 60.4-cm radius, which has an energy resolution better than 1 part in 1000. The energies of scattered protons were determined by locating their tracks in Eastman N.T.A. nuclear plates, placed in the focal plane of the spectrograph. Each exposure covers a momentum range of about 5 percent; for a complete survey of the spectrum, a series of plates has to be taken in which the magnetic field is varied in steps of about 4.5 percent.

The assignment of proton groups was made primarily on the basis of measurements of their energies as a function of the bombarding energy. The differential energy shift, $d^2E_{out}/dMdE_{in}$, near mass number 40, is 1.2 kev per mass unit per Mev. This method is generally accurate to within a few mass units, which, for strong groups, is sufficient to exclude possible target contaminants. It does not apply, however, to low-energy groups from highly excited states, which are observed only with bombarding energies near the upper limit of the operating range of the generator. In these cases, the assignment was based on the intensities of the groups, together with the consideration that the Coulomb barrier excludes heavy nuclei; while the spectra of the light target materials, C^{12} and O^{16}, are well known in the region covered by this work. An analysis of the target provided by the elastically scattered protons, is very helpful in determining which target materials have to be taken into account. Further details about the experimental method are given in previous publications from this Laboratory.[33–35]

III. RESULTS

Surveys of the spectra of scattered protons were taken at bombarding energies of 6.92, 7.32, and 8.15 Mev. The result of the 6.92-Mev bombardment on a target reinforced with mercury is shown in the upper part of Fig. 1. The high-energy part of the spectrum shows protons scattered elastically from Hg, Ca^{40}, O^{16}, and C^{12} and indicates the absence of contaminants in appreciable amounts. The exposures for this part were chosen 20 times shorter than for the rest of the spectrum to keep the elastic group from Ca^{40} countable; the peak height is 2600 protons per $\frac{1}{2}$-mm strip, while the background between the Hg and O^{16} groups varies around 10. The spectrum below the elastic group from C^{12} was taken with exposures of 300 microcoulombs. The whole spectrum from $B\rho=160$ to 385 kilogauss-centimeters is composed of 19 plates taken with different fields. Four inelastic groups from Ca^{40}, as well as the group from the well-known 4.43-Mev level in C^{12}, are seen. The lower part of Fig. 1 shows the result of the 8.15-Mev bombardment from the first excited state of Ca^{40} down. Seven new groups from levels in Ca^{40} appear, while two more

TABLE II. Energy levels of Ca^{40}.

Level	Energy in Mev	Level	Energy in Mev
1	3.348±0.004	7	5.272±0.006
2	3.730±0.004	8	5.606±0.009
3	3.900±0.004	9	5.621±0.008
4	4.483±0.005	10	5.901±0.008
5	5.202±0.008	11	6.029±0.008
6	5.241±0.006		

[32] Buechner, Sperduto, Browne, and Bockelman, Phys. Rev. **91**, 1502 (1953).

[33] Buechner, Strait, Sperduto, and Malm, Phys. Rev. **76**, 1543 (1949).

[34] Strait, Van Patter, Buechner, and Sperduto, Phys. Rev. **81**, 747 (1951).

[35] Sperduto, Buechner, Bockelman, and Browne, Phys. Rev. **96**, 1316 (1954).

groups can be ascribed to the 6.05- and 6.13-Mev levels in O^{16}.

Seven series of exposures at bombarding energies between 6.54 and 8.15 Mev were taken with the purpose of accurately measuring the excitation energies of the first four levels in Ca^{40}. Each series consisted of at least one exposure for the elastic group from Ca^{40} and each excited state. The fourth level was not seen at bombarding energies below 6.9 Mev. It was found that the energy difference between the elastic group and the group from an excited state reproduces with a mean deviation of 2 kev, so that the probable random error in the final numbers for the excitation energies is of the order of 1 kev for the first four levels. The final stated errors are arrived at by quadratically adding 0.1 percent of the excitation energy to account for possible systematic errors, such as discussed by Buechner *et al.*[32,33] Results, together with those for the higher levels, are listed in Table II.

The three closely spaced groups at $B\rho=235$ in the 8.15-Mev bombardment showed remarkable variations in their relative intensities when observed at other bombarding energies, and in preliminary experiments this led to some uncertainty regarding their mass assignments. Thirteen exposures at energies between 7.17 and 8.00 Mev were taken to investigate these groups in some detail. Typical results are shown in Fig. 2. From these measurements, it is concluded that all three groups correspond to levels in Ca^{40} and that resonances in the compound nucleus exist in the region of excitation between 8.8 and 9.6 Mev. In this connection, it may be noted that the excitation energy of the compound nucleus is relatively low when a proton is added to Ca^{40}, as can be seen in Table III, in which the stable calcium isotopes are compared. It is conceivable that the level density at a given excitation energy is also relatively low in Sc^{41} because of its closed-shell-plus-one structure. The groups at $B\rho=204$, 217, and 218 kilogauss-cm in the lower part of Fig. 1 have also been observed at $E_{\text{in}}=7.73$ Mev. The assignment of these groups and the one at $B\rho=198$ kilogauss-cm to Ca^{40} seems reasonably certain in view of their intensities.

IV. DISCUSSION

The 3.8-Mev level reported by Harvey has been resolved into levels at 3.730 and 3.900 Mev, both of which are represented by strong proton groups. In addition, a weaker group from a level at 3.348 Mev and groups from eight higher excited states were found. The 3.348-Mev level was also found in two recent experiments, which showed that it has spin zero and decays by pair emission. The 3.46±0.1 Mev pairs were found by Bonner *et al.*[36,37] who excited this level by inelastic scattering of 4.8-Mev protons; while Day[38] found the 0.5-Mev annihilation gamma ray from the inelastic scattering of neutrons of energies higher than 3.36±0.05 Mev (in the center-of-mass system). Gamma rays of 3.74±0.03 and 3.9±0.1 Mev were also found by Day, in good agreement with the present work. A 3.75-Mev gamma ray was also found[39,40] in the β^+ decay of Sc^{40}; no information on the excited states of Ca^{40} is obtained from the decay of K^{40}, which goes directly to the ground state.[28]

TABLE III. Excitation energy in compound nucleus upon addition of a 7.4-Mev proton to a calcium isotope.[a]

Target nucleus	Ca^{40}	Ca^{42}	Ca^{43}	Ca^{44}	Ca^{48}
Compound nucleus	Sc^{41}	Sc^{43}	Sc^{44}	Sc^{45}	Sc^{49}
Excitation in Mev	9.0	12.3	14.1	14.3	17.0

[a] A. H. Wapstra, Physica 21, 385 (1955).

The most interesting level of Ca^{40} is certainly the first one. It lies about two times higher than the first excited states of other even-even nuclei in the same mass region, and it also makes an exception to the rule that the spins and parities of these states are 2^+. In both respects, Ca^{40} resembles other double closed-shell nuclei.[19,37,41]

The author wishes to thank the Elsevier study fund for a grant which made possible his stay at the Massachusetts Institute of Technology. He is grateful to Professor W. W. Buechner, who suggested the investigation of Ca^{40}, and to him and the staff of the High Voltage Laboratory, in particular A. Sperduto, C. K. Bockelman, C. P. Browne, and M. M. Elkind, for the help and advice that made this work possible. Thanks are also due to W. A. Tripp, Janet L. Frothingham, Lillian A. Stone, and Iris Saltsburg for their careful scanning of the photographic plates.

[36] Bonner, Bent, and McCrary, 98, 1198(A) (1955).
[37] Bent, Bonner, and McCrary, Phys. Rev. 98, 1325 (1955).
[38] R. B. Day, Geneva Conference, 1955 (to be published) and private communication.
[39] N. W. Glass and J. R. Richardson, Phys. Rev. 93, 942 (1954).
[40] N. W. Glass and J. R. Richardson, Phys. Rev. 98, 1251 (1955).
[41] Johnson, Johnson, and Langer, Phys. Rev. 98, 1517 (1955).