# Energy Levels of Calcium Isotopes. $Ca^{40}(d,p)Ca^{41}$ Reaction*

C. M. BRAAMS†
*Physics Department and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts*
(Received May 28, 1956)

The $Ca^{40}(d,p)Ca^{41}$ reaction was investigated with the MIT–ONR electrostatic generator, a 180-degree magnetic spectrograph, and a magnetic broad-range spectrograph. Bombarding energies from 2.5 to 7.0 Mev were used; targets were made of natural calcium; and the reaction angle was 90 degrees. The $Q$ value for the transition to the ground state of $Ca^{41}$ is 6.140±0.009 Mev. Twenty-five excited states of $Ca^{41}$ were found in the region of excitation from 1.947 to 4.194 Mev.

## I. INTRODUCTION

EARLY work on the $Ca^{40}(d,p)Ca^{41}$ reaction was done with the Yale cyclotron by Davidson[1] and later by Sailor.[2] Davidson measured $Q$ values for the transitions to the ground state and the first excited state; Sailor remeasured these $Q$ values and found six more partly resolved proton groups from higher excited states. Holt and Marsham,[3] using the Liverpool cyclotron, measured $Q$ values of eight proton groups and angular distributions of six. In all these investigations, the energy of the protons was measured by their range in aluminum.

With the Chalk River pile as a source of neutrons, Kinsey *et al.*[4] measured the high-energy gamma rays from the thermal neutron capture in natural calcium, while Braid[5] found a 1.93-Mev gamma ray with a scintillation spectrometer.

Levels in $Ca^{41}$ at 1.95 and 2.47 Mev were found both in the $(d,p)$ and in the $(n,\gamma)$ work. The gamma transitions from the neutron-capturing state $(\frac{1}{2}^+)$ to these levels are of the $E1$ type,[6] so that their spins and parities are $\frac{1}{2}^-$ or $\frac{3}{2}^-$. No direct ground-state transition was observed. This is in agreement with the work by Holt and Marsham who find angular distributions indicating $l_n=3$ for the ground state and $l_n=1$ for the 1.95- and 2.47-Mev levels. They suggest $7/2^-$, $\frac{3}{2}^-$, and $\frac{1}{2}^-$, respectively, for these states because of relative intensities and shell-model predictions.

Recently, the $Ca^{40}(n,\gamma)Ca^{41}$ reaction was also studied by Demidov *et al.*[7] with a magnetic Compton-electron spectrometer. Most of the gamma rays found by Kinsey or Demidov can be fitted into the level scheme for $Ca^{41}$; and, from an experiment with enriched $Ca^{40}$, Demidov concludes that 90% of the integrated gamma spectrum of natural calcium is indeed associated with the capture of a neutron in $Ca^{40}$. This is in disagreement with measurements[8] of the capture cross section of enriched $Ca^{42}$, which would lead to the conclusion that about half of the neutron captures in natural calcium should occur in that isotope.

## II. EXPERIMENT

The major part of our work on the $Ca^{40}(d,p)Ca^{41}$ reaction was done with the equipment described in the first paper of this series.[9] The analyzed deuteron beam of the MIT–ONR electrostatic generator was used to bombard targets of natural calcium, and the proton spectrum was measured with the 180-degree magnetic spectrograph.

Partial surveys of the spectrum were taken at bombarding energies of 6.0, 5.4, 5.0, and 2.9 Mev. Diatomic ions were accelerated through 5.8 million volts to obtain a beam of 2.9-Mev deuterons. The 6.0-Mev survey covered the range of proton energies corresponding to $Q$ values of the $Ca^{40}(d,p)Ca^{41}$ reaction below 5 Mev; the region below $Q=2$ Mev was observed again in the 5.0-Mev survey, while the 5.4- and 2.9-Mev surveys each covered $Q$ values between 2 and 7 Mev. Above $Q=2$ Mev, most of the groups from the $Ca^{40}(d,p)Ca^{41}$ reaction are well resolved, but the lower part of the spectrum is much more complex and is also partly obscured by very strong groups from the $C^{12}(d,p)C^{13}$ and $O^{16}(d,p)O^{17}$ reactions. We have therefore restricted our further work to $Q$ values greater than about 2 Mev.

The reaction energy of the ground-state transition was carefully measured with an incident beam of 2.9 Mev. The deuteron energy was chosen so low to avoid proton energies that would require a spectrograph field strength higher than 12 kilogauss. The result, 6.140±0.009 Mev, is in good agreement with the measurements of Sailor and of Holt and Marsham. Eighteen more proton groups, corresponding to excited states from 1.947 to 3.95 Mev, were also assigned to $Ca^{41}$ on the basis of their energy shift when the energy

* 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] W. L. Davidson, Phys. Rev. **56**, 1061(L) (1939).
[2] V. L. Sailor, Phys. Rev. **75**, 1836 (1949).
[3] J. R. Holt and T. N. Marsham, Proc. Phys. Soc. (London) **A66**, 565 (1953).
[4] Kinsey, Bartholomew, and Walker, Phys. Rev. **85**, 1012 (1952).
[5] T. H. Braid, Phys. Rev. **91**, 442(A) (1953).
[6] B. B. Kinsey and G. A. Bartholomew, Phys. Rev. **93**, 1260 (1954).
[7] A. M. Demidov (private communication); see also Groshev, Adyasevich, and Demidov, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955* (United Nations, New York, 1956), Vol. 2, Paper No. 651.
[8] H. Pomerance, Phys. Rev. **88**, 412 (1952).
[9] C. M. Braams, Phys. Rev. **101**, 1764 (1956).

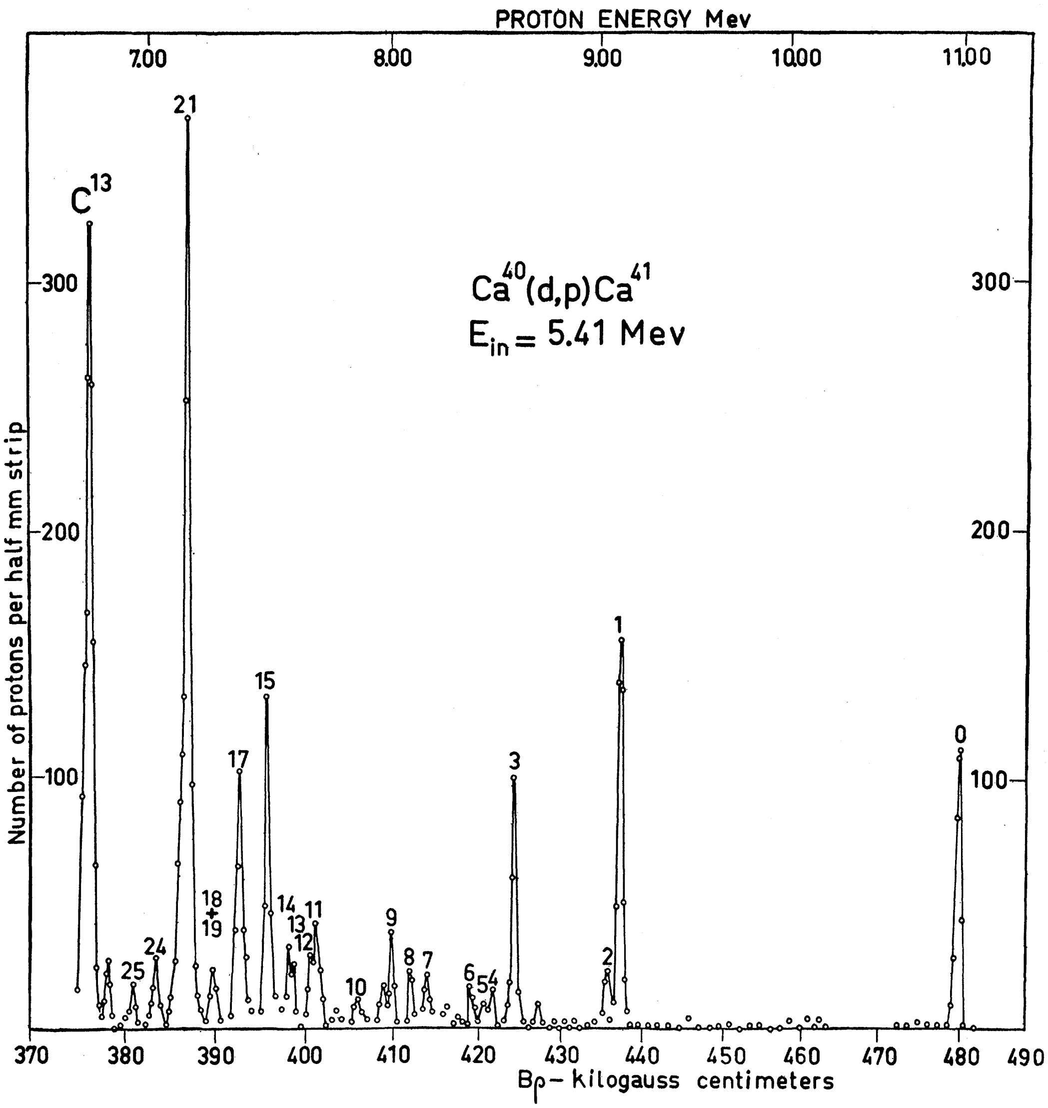


FIG. 1. Spectrum of proton groups obtained with 180° magnetic spectrograph. The angle of observation was 90°.

of the incident beam was varied. For some portions of the spectrum, this required exposures at incident energies of 2.5 and 7.0 Mev.

The 5.4-Mev spectrum taken with the 180-degree spectrograph is shown in Fig. 1. The results obtained with this instrument prior to January, 1954 are given in Table I. A new magnetic spectrograph[10] has since become available in this Laboratory, and we have used this instrument to review the $Ca^{40}(d,p)Ca^{41}$ reaction at incident energies of 6.5 and 7.0 Mev. The superior resolution of this instrument has made it possible to obtain better energy measurements on proton groups which were not completely resolved by the old spectrograph and to find more groups than had been seen before. The 7.0-Mev spectrum is shown in Fig. 2. Numerical results are listed in Table I.

A comparison between the second and the third column of Table I shows that, apart from random differences between the results of the two spectrographs, there is a systematic deviation, reaching a maximum of about 6 kev at 2.5 Mev. It seems unlikely that such a systematic error could occur in the measurements with the 180-degree spectrograph because the measured $Q$ values are averaged from three or more measurements taken at different bombarding energies with different targets and showing a mean deviation of the computed averages of about 2 kev. The adopted $Q$ values in the fourth column of Table I are derived from the assumption that the measurements of energy differences between neighboring peaks are more accurate with the broad-range spectrograph, because of its higher dis-

[10] Buechner, Browne, Enge, Mazari, and Buntschuh, Phys. Rev. **95**, 609(A) (1954); and Buechner, Mazari, and Sperduto, Phys. Rev. **101**, 188 (1956).

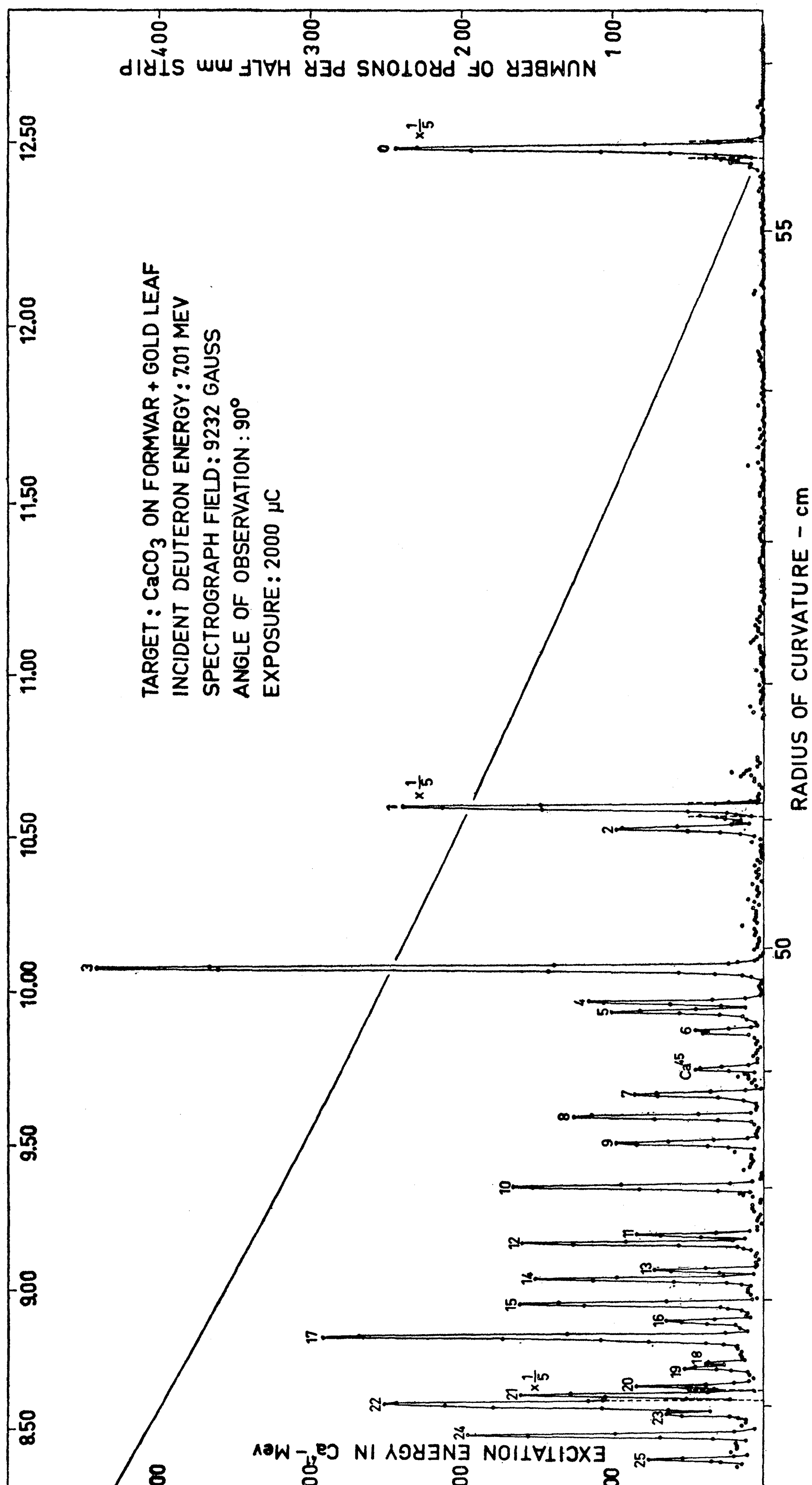


FIG. 2. Spectrum of proton groups obtained with broad-range magnetic spectrograph.

persion, but that systematic errors are smaller with the 180-degree spectrograph because of its more direct calibration. The quoted errors include a random error of about 3 kev and a systematic error of 0.15% of the excitation energy.

## III. DISCUSSION

The 1.947- and 2.469-Mev levels are probably the ones that were observed by Sailor, Holt and Marsham, and Kinsey and Bartholomew. At 90 degrees to the incident beam, these are by far the strongest groups in their region of the spectrum, and, since Holt and Marsham report angular distributions showing a definite $l$ value of the captured neutron, it is likely that the same two proton groups are predominant at all angles. The assignment of $p_{\frac{3}{2}}$ and $p_{\frac{1}{2}}$ orbitals to these states, suggested by Holt and Marsham, has raised the question of the position of the $f_{\frac{5}{2}}$ state predicted by the shell model. This orbit is filled between the $p_{\frac{3}{2}}$ and $p_{\frac{1}{2}}$ states,[11] and it is reasonable to look for it in that part of the $Ca^{41}$ spectrum. From this point of view, it is encouraging that we have found a new level at 2.014 Mev. Because the first excited state of $Ca^{40}$ lies at 3.35 Mev, one would not expect to find low-lying excited states in $Ca^{41}$ that are formed by excitation of the 20–20 core. This would support the hypothesis that the 2.014-Mev level is indeed a single-particle state which puts the first core-excited state of $Ca^{41}$ at 2.584 Mev.

On the other hand, the intensity at 90 degrees of the proton group from the 2.014-Mev level, in comparison with that from the ground state, is much lower than would be expected from the statistical factor $2j+1$, which should govern their relative intensities if these states form the $f_{7/2}-f_{5/2}$ doublet. Furthermore, not enough data are available on the position of single-particle levels in nuclei of different mass numbers to support the assumption that the order in which the $j$ values occur as ground states in a given mass region should also be the order of the single-particle states in a much lighter nucleus. Recent calculations by Bleuler and Terreaux[12] show that, in particular, the relative position of the $1f_{\frac{5}{2}}$ and $2p_{\frac{3}{2}}$ states may be a function of the mass number. In light nuclei, however, the $1f_{\frac{5}{2}}$ state is expected to lie between the $2p_{\frac{3}{2}}$ and $2p_{\frac{1}{2}}$ states. High-resolution measurements of angular distributions of the proton groups from the $Ca^{40}(d,p)Ca^{41}$ reaction are presently being made in this Laboratory[13]; further speculations on the character of the $Ca^{41}$ levels should await these results.

[11] P. F. A. Klinkenberg, Revs. Modern Phys. 24, 63 (1952).

[12] K. Bleuler and Ch. Terreaux, Helv. Phys. Acta 28, 245 (1955).

TABLE I. Energy levels of $Ca^{41}$ from $Ca^{40}(d,p)Ca^{41}$ reaction.

| Ground state Q value (Mev) | 180° spectrograph 6.140 | Broad-range spectrograph 6.141 | Adopted value 6.140±0.009 |
|---|---|---|---|
| Level | Excitation energy (Mev) | Excitation energy (Mev) | Excitation energy (Mev) |
| 1 | 1.947 | 1.943 | 1.947±0.004 |
| 2 | 2.014 | 2.010 | 2.014±0.005 |
| 3 | 2.469 | 2.463 | 2.469±0.005 |
| 4 | 2.582 | 2.578 | 2.584±0.006 |
| 5 | 2.612 | 2.606 | 2.612±0.006 |
| 6 | 2.677 | 2.671 | 2.677±0.006 |
| 7 | 2.890 | 2.885 | 2.890±0.006 |
| 8 | 2.967 | 2.963 | 2.967±0.006 |
| 9 | 3.054 | 3.052 | 3.056±0.006 |
| 10 | 3.207 | 3.204 | 3.206±0.006 |
| 11 | 3.373 | 3.374 | 3.375±0.007 |
| 12 | 3.403 | 3.404 | 3.405±0.007 |
| 13 | 3.500 | 3.499 | 3.500±0.007 |
| 14 | 3.531 | 3.531 | 3.531±0.007 |
| 15 | 3.619 | 3.619 | 3.619±0.007 |
| 16 | | 3.682 | 3.682±0.007 |
| 17 | 3.737 | 3.736 | 3.736±0.007 |
| 18 | | 3.836 | 3.837±0.007 |
| 19 | 3.856 | 3.854 | 3.854±0.007 |
| 20 | | 3.921 | 3.921±0.007 |
| 21 | 3.950 | 3.950 | 3.950±0.007 |
| 22 | | 3.982 | 3.982±0.007 |
| 23 | | 4.023 | 4.023±0.007 |
| 24 | | 4.101 | 4.101±0.007 |
| 25 | | 4.193 | 4.194±0.007 |

## ACKNOWLEDGMENTS

The author wishes to thank the Elsevier study fund for a grant which made possible his stay at M.I.T. He is grateful to Professor W. W. Buechner and to the staff of the High Voltage Laboratory, in particular, A. Sperduto, C. K. Bockelman, and C. P. Browne, for help and advice in various stages of this work. The angular distribution measurements of Dr. Bockelman have helped to remove some uncertainties in the assignment of weak proton groups and, thus, have contributed greatly to the completion of the work. Thanks are also due W. A. Tripp, Janet L. Frothingham, Lillian A. Stone, and Sylvia G. Darrow for their careful scanning of the photographic plates.

[13] C. K. Bockelman (to be published).