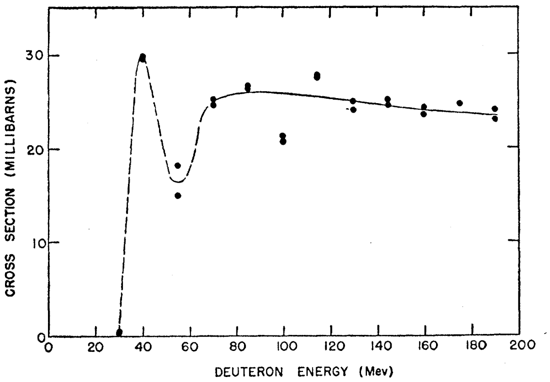

FIG. 1. Cross section of Na^{22} from aluminum as a function of deuteron energy.

conditions, it was only necessary to know the relative counting efficiency of Na^{22} and Na^{24} in order to calculate the Na^{22} cross sections. Na^{22} emits 0.54-Mev positrons and Na^{24} decays with the emission of a 1.4-Mev negatron.[1] The contribution to the activity from the gamma rays emitted by each isotope was small, less than two percent, when counted on a chlorine-argon beta counter and was neglected for monitoring purposes. The total air and window absorbing thickness was 5 milligrams per square centimeter. The correction factor for the air and window absorption for Na^{22} was taken as 1.08 and for Na^{24} as 1.04. These values were determined from absorption curves obtained for each activity. The correction for self-absorption and self-scattering were taken from Nervick's work[3] and were 1.05 for Na^{22} and 1.10 for Na^{24}. Backscattering corrections were taken as 1.28 for Na^{24} from the work of Burtt,[4] and 1.22 for Na^{22} from unreported work done in this laboratory.

The values of the Na^{22} cross section are plotted in Fig. 1 as a function of deuteron energy. In order to obtain low energies in the 184-inch cyclotron, the targets had to be placed close to the center of the tank, where there is an appreciable flux of neutrons with sufficient energy to cause the reaction $Al^{27}(n,\alpha)Na^{24}$. As a result of this reaction, cross sections for Na^{24} below 50 Mev are higher than they should be for deuterons alone.

The cross sections of Na^{22} in this low-energy range are therefore too low. That part of the curve represented by the broken line is only a guess.

The authors would like to express their appreciation to the crew of the 184-inch cyclotron at Berkeley who performed the necessary irradiations.

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Energy Levels in Ca^{42} and Ca^{44}*†

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The $K^{39}(\alpha,p)Ca^{42}$, $K^{41}(\alpha,p)Ca^{44}$, and $Ca^{43}(d,p)Ca^{44}$ reactions were studied and ground state Q-values of -0.19, 0.98, and 9.07 Mev respectively were found. Energy levels in Ca^{42} were found at 1.51, 1.95, 2.29, 2.59, and 3.02 Mev and in Ca^{44} at 1.13, 1.92, 2.28, 2.58, 2.97, and 3.17 Mev. An anomalously low cross section was observed for the $Ca^{43}(d,p)Ca^{44}$ reaction.

I. INTRODUCTION

PRELIMINARY work on the $K^{39}(\alpha,p)Ca^{42}$ reaction has been reported previously.[1] Since that time an increase in the cyclotron beam currents available and the installation of a magnetic beam analyzer have made a more accurate study of this reaction possible. Work was also done on reactions providing information on the level structure of Ca^{44}.

II. EXPERIMENTAL METHOD

The 4.15-Mev deuteron beam and the 8.22-Mev alpha-particle beam of the Yale cyclotron were used in these investigations. Thin targets of the isotopes under study were placed in the analyzed particle beam. Protons from the target were slowed down in aluminum absorbers and then detected in argon filled proportional counters. "Peaking" of the group structure was achieved by setting the discriminator circuit biases to permit only the highest pulses to be recorded. These were caused by particles stopping at the end of the counter and thus causing maximum ionization at the end of their range. The recorded pulses thus provided a differential absorption curve of the proton spectrum. The

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[1] J. P. Schiffer and E. Pollard, Phys. Rev. 91, 474(A) (1953).

electronic circuits used in this method have been described previously by several investigators from this laboratory.[2,3]

Targets were evaporated on Au or Ta backing. Instead of using pure K or Ca targets, it was found more convenient to use KI and CaI, these compounds being more stable under atmospheric conditions than the pure metals.

III. $\mathrm{K}^{39}(\alpha,p)\mathrm{Ca}^{42}$

Early work on this reaction was done by Pollard and Brasefield[4] with natural alpha sources. With very low yields the Q-values obtained provided more of a qualitative indication than an exact assignment. Siegbahn observed a gamma ray at 1.51 Mev following the beta decay of K^{42}, which was assumed to correspond to the first excited state of Ca^{42}. Stevenson and Deutsch measured the beta-gamma angular correlation for this transition and concluded that the spin and parity of the level was 2^+ in agreement with shell theory predictions for the first excited states of even-even nuclei.

Work on the (α,p) reaction indicated that the state in question was indeed the first excited state of Ca^{42}. The ground state Q-value was found to be -0.19 ± 0.07 Mev. The uncertainty was due to the inaccuracy with which the range of a proton group could be established. Nonuniformity in commercial foils has been found to be a large potential source of error in absorption measurements by some investigators.[5] No large variations were found in the commercial aluminum foils used, but a slight nonuniformity was detected in some gold foils. A further source of error was the lack of accuracy with which the stopping power of gold was known in the energy range studied. These considerations apply to the assignment of errors to all subsequent data.

A typical curve for this reaction is shown in Fig. 1. In calculating the levels of excitation in the nucleus from a curve such as this the errors tend to be smaller than those for the Q-values because when differences between Q-values are taken some of the systematic errors cancel. The values obtained for excited states in Ca^{42} are shown in Table I. Level assignments above 3 Mev, while undoubtedly corresponding to levels in the nucleus, do not necessarily represent all the levels present. Runs at two different beam energies showed an entirely different shape for the proton spectrum in this region. Levels at lower excitation also changed in their relative intensities but no indication of new levels of energy lower than 3.3 Mev was found. It can only be concluded that the level density at higher excitation is greater than the resolution of the equipment used. No particular attempts were made in this investigation to measure levels higher than about the fourth excited state.

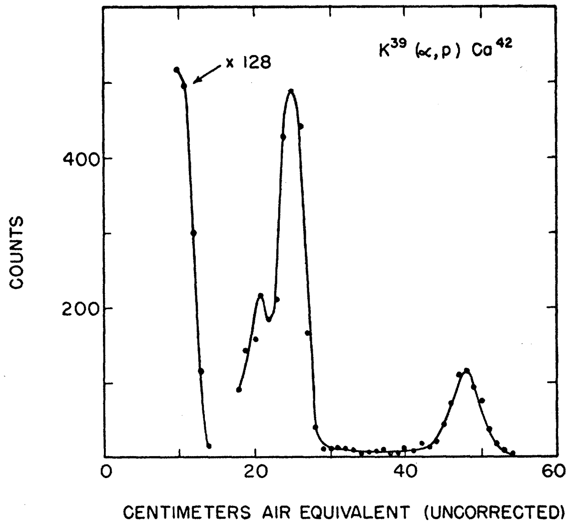

FIG. 1. The proton yield at 0° from $\mathrm{K}^{39}(\alpha,p)\mathrm{Ca}^{42}$. The peak on the left is that due to elastically scattered protons. Other runs, not shown here gave group structure at higher excitation.

TABLE I. Energy levels from the $\mathrm{K}^{39}(\alpha,p)\mathrm{Ca}^{42}$ and $\mathrm{K}^{41}(\alpha,p)\mathrm{Ca}^{44}$ reactions.

Ca^{42}	Ca^{44}
1.51 ± 0.05	$1.13\pm0.05^{\mathrm{b}}$
1.95 ± 0.07	1.92 ± 0.05
2.29 ± 0.05	$2.28\pm0.05^{\mathrm{b}}$
2.59 ± 0.07	2.58 ± 0.05
3.02 ± 0.05	2.97 ± 0.05
$3.30\pm0.10^{\mathrm{a}}$	3.17 ± 0.05
3.75 ± 0.07	
$4.09\pm0.10^{\mathrm{a}}$	

[a] Observed only with a beam energy of 7.75 Mev.
[b] Observed also in the $\mathrm{Ca}^{43}(d,p)\mathrm{Ca}^{44}$ reaction.

The Q-values cited are the result of six independent runs. While some reduction of experimental error would be possible with the accumulation of more data, the present method does not permit much greater accuracy.

IV. $\mathrm{Ca}^{43}(d,p)\mathrm{Ca}^{44}$

Information on the levels structure of Ca^{44} has been known for some time. Hibdon, Kurbatov, and Pool[6] measured the gamma-ray energy following beta decay of Sc^{44} and found it to be 1.33 Mev. Later work found this energy to be 1.18[7] and 1.16[8] Mev. Recent work by Cohen[9] on the decay of K^{44} found evidence of 1.13, 2.07, 2.48, and 3.60 Mev gamma rays. It was also suggested from the shape of the beta decay curve of Sc^{44} that the ground state of Ca^{44} was even in parity and that the 1.13-Mev state was also even, with the gamma ray going by electric quadrupole or magnetic dipole transition. This is consistent with the shell theory prediction

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[2] W. O. Bateson, Phys. Rev. **80**, 982 (1952).
[3] A. B. Martin, Phys. Rev. **71**, 127 (1947).
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[8] J. Bruner and L. M. Langer, Phys. Rev. **79**, 606 (1950).
[9] B. L. Cohen, Phys. Rev. **94**, 117 (1954).

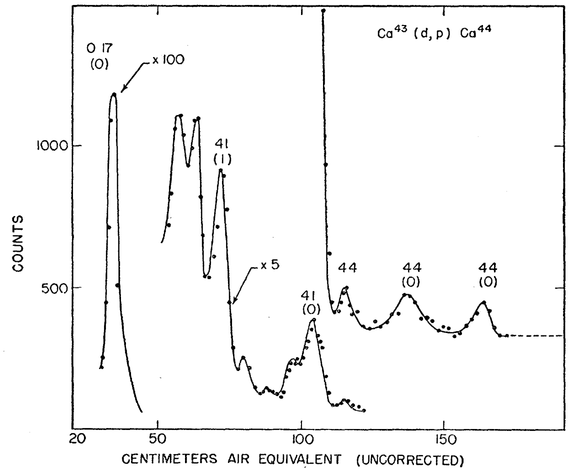

FIG. 2. The proton yield at 90° from Ca^{43}(d,p)Ca^{44}. The target contained 23.4 percent Ca^{40}, 1.6 percent Ca^{42}, 68 percent Ca^{43} and 7 percent Ca^{44}. The numbers above the peaks refer to the product nucleus. The peaks between the ground state and first excited state of Ca^{41} are due to Ca^{43} and Ca^{45}. The oxygen peak is shown for calibration purposes. The dotted line represents the neutron background.

for even-even nuclei to have 0^+ ground states and 2^+ first excited states.

The measurement of levels in Ca^{44} was undertaken by two means. It was thought that the (d,p) reaction on Ca^{43} would be comparable in yield to the Ca^{40}(d,p)Ca^{41} reaction and therefore it was tried first. The Q-value calculated from mass values was 9.20 Mev which was very favorable. Initial attempts, however, failed to show any group structure high enough in energy to be associated with this Q-value.

Because of the large background in counting rates caused by the fast-neutron background associated with the deuteron beam of the cyclotron, a proportional counter telescope was first tried. Pulses from the first counter were used without bias to trigger one-half of a coincidence circuit, the other half of which was triggered by "peaked" counts in the second counter. A target containing 68 percent Ca^{43} and 23 percent Ca^{40} [10] showed group structure associated with the Ca^{40}(d,p)Ca^{41} reaction, but no evidence of higher-energy protons could be found. In order to improve counting rates the solid angle of observation was improved by using a single counter in spite of the background. The difficulty of a slightly varying background was overcome by keeping operating conditions extremely stable. Figure 2 shows the results of the most successful of approximately twenty-five attempts. The proton groups due to the reaction on Ca^{43} are only 20 percent above the background rate, but due to the stability of the background level their positions could be determined reasonably well.

The Q-value of 9.07±0.07 Mev for the ground state peak is in fair agreement with the one calculated from mass values.[11] (See Table II.) Two excited states were observed at 1.15 and 2.28 Mev, in good agreement with (α,p) results. The cross section for this reaction for 90° observation was less by roughly a factor of fifty from that observed for Ca^{40}(d,p)Ca^{41}, considering ground states. Comparing first excited states the ratio of cross sections is a hundred. When comparing the yield to that obtained in the K^{41}(α,p)Ca^{44} reaction, the latter still has a cross section greater by a factor of seventy. Because of the nature of the experiment no reasonable estimates of absolute cross sections can be made. The relative cross sections are accurate within a factor of two.

The peak on the left of Fig. 2 is due to the O^{16}(d,p)O^{17} reaction. Oxygen was present in all targets as a contaminant and the large yield of this reaction provided a convenient means of calibrating the beam energy.

V. K^{41}(α,p)Ca^{44}

The yield from this reaction was perhaps a factor of five below that from K^{39}, but this was still adequate to measure the range of proton groups. A typical run, using a target containing 99 percent K^{41} and 1 percent K^{39} [10] is shown in Fig. 3. The angle of observation here

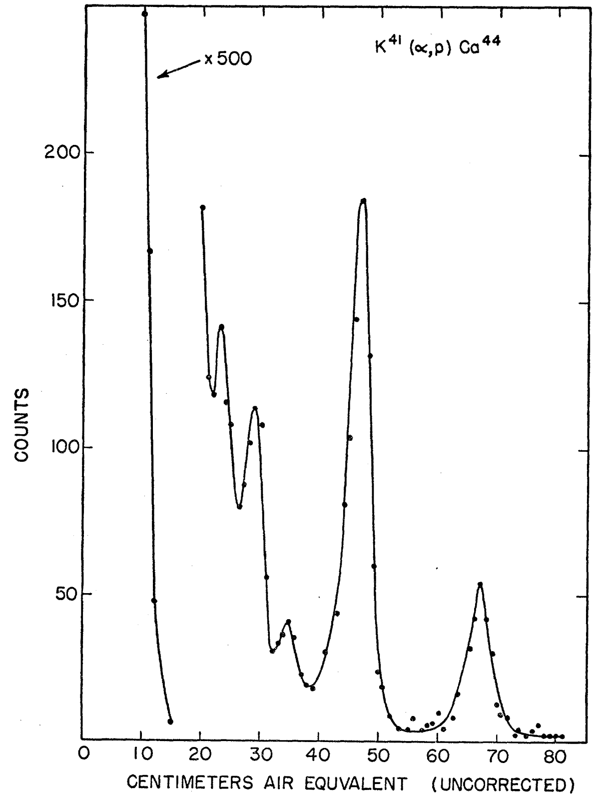

FIG. 3. A typical curve of the proton yield at 0° from K^{41}(α,p)Ca^{44}.

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[10] Separated isotopes were obtained from the Oak Ridge National Laboratory.

[11] Collins, Nier, and Johnson, Phys. Rev. **84**, 717 (1951).

was 0°, with the peak on the left representing protons elastically scattered by the alpha beam from hydrogenous impurities in the target. The Q-value for the ground state was found to be 0.98±0.10 Mev. There is a small discrepancy between this value and the one calculated from mass values of Collins, Nier, and Johnson.[11] Earlier in these investigations it was thought that a level was detected beyond the one assigned to the ground state group, but further data showed that this was a spurious effect due to statistical fluctuations in background rates.

The excited states calculated are shown in Table I. Above the fourth excited state the level density was too high for the resolution of the equipment. The 1.92-Mev state was not seen with the (d,p) reaction, presumably because of its low yield. The gamma rays observed by Cohen, as mentioned in the previous section, could be assigned to the levels measured in this work, within the estimated experimental errors. The 1.13-Mev gamma ray was probably a first excited state to ground state transition, although the third to first excited state spacing of 1.15 Mev could perhaps also account for it. The 2.07- and 2.48-Mev gamma rays were probably due to levels of higher excitation not measured here.

TABLE II. Ground state Q values.

Reaction	Ground state Q (Mev) Measured in present work	Calculated from mass values[a]
$K^{39}(\alpha,p)Ca^{42}$	−0.19±0.07	0.34±0.10
$K^{41}(\alpha,p)Ca^{44}$	0.98±0.10	1.29±0.12
$Ca^{43}(d,p)Ca^{44}$	9.07±0.07	9.20±0.12

[a] See reference 11.

VI. CONCLUSIONS

All available information on the level structure of Ca isotopes is shown in Fig. 4. The data on Ca^{40} were obtained by inelastic proton scattering by Braams.[12] The spin assignments in Ca^{41} are from Holt and Marsham's[13] work on angular distributions. Jeffries[14] determined the spin of Ca^{43} by magnetic moment measurements. The ground state and first excited state angular momentum assignments in Ca^{42} and Ca^{44} have been discussed in Secs. III and V. There is a surprising similarity between the excitation of the second to fifth states in Ca^{42} and Ca^{44}.[15] The level structures of Ca^{41}, Ca^{43}, and Ca^{45} are from work done by Braams[16] using magnetic analysis. The ground state angular momenta are in agreement with shell theory, which predicts that the independent particle is in an $f_{7/2}$ state between neutron number 20 and 28. The first excited state spacings show the predicted decrease with increasing neutron number above the closed shell at 20, if even-even and even-odd nuclei are viewed separately.

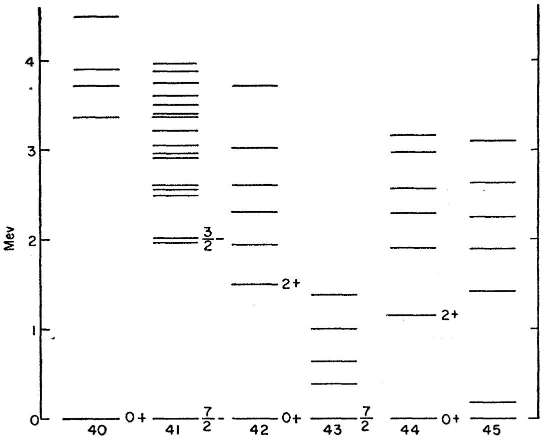

FIG. 4. Level structure in Ca isotopes. Levels in Ca^{42} and Ca^{44} are from the present work; the other isotopes were measured by Braams (see references 11 and 14). The first excited states decrease gradually above the doubly magic Ca^{40}.

The anomalously low cross section for the Ca$^{43}(d,p)$ Ca^{44} reaction remains unexplained. The spin change involved is the same as that in the Ca$^{40}(d,p)$Ca^{41} reaction. A shift in the angular distribution could account for only a very small fraction of the observed decrease in yield. Runs were also tried at 0° and 45° without success.

VII. ACKNOWLEDGMENTS

The author would like to express his appreciation to Professor Ernest C. Pollard for his suggestion of this problem and his advice in the course of this work.

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[14] C. D. Jeffries, Phys. Rev. **90**, 1130 (1953).

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