duced to 0.02. For a given sample of material, the relative intensities were found to remain constant over a period of two months so that the impurity must also have a half-period of about 30 days.

The beta-gamma-coincidence rate of Ce^{141} is shown in Fig. 3 as a function of the surface density of aluminum placed before the beta-ray counter. The constancy of the beta-gamma-coincidence rate shows that the beta-ray spectrum is simple. The absolute magnitude of the coincidence rate is such as to suggest that each beta-ray is followed by a 0.13-Mev quantum. The proposed disintegration scheme for Ce^{141} is shown in Fig. 4.

Beta-beta-coincidences were found in the disintegration of Ce^{141} and are shown in Fig. 5 as a function of the surface density of aluminum placed before both of the beta-ray counters. The coincidence rate is seen to approach zero in the vicinity of 20 mg/cm², showing that the 0.13-Mev quantum is to some extent converted.**

** A small gamma-gamma-coincidence rate, (0.03, 0.01 $\times 10^{-3}$) coincidence per gamma-ray, was noted in the disintegration of Ce^{141}. Since considerable evidence [see Siegbahn and Hedgran, Phys. Rev. **75**, 523 (1949)] has been accumulated to show that such small coincidence rates are sometimes spurious, the observed effect cannot be regarded as genuine. Any geometry dependent effects such as scattering, would be enhanced by the presence of the hard gamma-ray of the impurity.

Pr^{143}

The beta-rays of Pr^{143} were absorbed in aluminum as shown in Fig. 6. The visual end point occurs at 294 mg/cm², 0.835 Mev as calculated by Feather's equation.[8] Best agreement is found with the more recent data of the Ohio State group.[2]

Note added in proof—The spectrometric measurements of L. R. Shepherd [Research **1**, No. 14, 671 (1948)] have just come to the attention of the writers. His data indicate that 70 percent of the disintegrations proceed by way of the disintegration scheme of the present paper and that the remaining disintegrations occur with beta-emission to the ground state of Tr^{141}. The maximum beta-ray energy reported by Shepherd is 0.56 Mev, corresponding to an absorption limit of 200 mg/cm². This end point is not apparent on the absorption curve of Fig. 1 of the present paper.

[8] N. Feather, Proc. Camb. Phil. Soc. **34**, 599 (1938).

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Energy Levels in Ca^{41} and the Mass Difference between A^{40} and Ca^{40} *

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The reaction $Ca^{40}(d,p)Ca^{41}$ was studied and Q-values of 6.17, 4.22, 3.76, 2.31 Mev were found. Four additional Q-values 3.2, 2.9, 2.7, 2.5 Mev are probable. The mass increment $(A^{41}-A^{40})-(Ca^{41}-Ca^{40})$ $=2.54\pm0.03$ mMU was obtained by comparing the end groups of the two reactions $A^{40}(d,p)A^{41}$ and $Ca^{40}(d,p)Ca^{41}$. These data combined with data from two other nuclear reactions give the mass difference $Ca^{40}-A^{40}=0.27\pm0.21$ mMU, indicating that A^{40} is slightly more stable than Ca^{40}. This mass difference is compared with data on the radioactive decay of K^{40}, showing that the assignment of the 1.55-Mev γ-ray to $K^{40}\rightarrow A^{40}$ K-capture process is reasonable.

I. INTRODUCTION

THE mass differences between the three important isobars A^{40}, K^{40}, and Ca^{40} are uncertain. Since Ca^{40} is a closed shell nucleus, it might be expected to be more stable[1] than A^{40}. On the other hand, some experimental evidence[2] seems to contradict this conclusion. If the 1.55-Mev γ-ray accompanying the radioactive decay of K^{40} is assigned to the K-capture process, then A^{40} appears to be more stable than Ca^{40}.

It is possible to obtain the mass difference between A^{40} and Ca^{40} by using the four nuclear reactions: $A^{40}(d,p)A^{41}$, $A^{41}\rightarrow K^{41}+\beta^-$, $K^{41}(p,n)Ca^{41}$ (threshold), and $Ca^{40}(d,p)Ca^{41}$. All four of these reactions have been investigated previously.[3-6]

In order to reduce the uncertainties in two of the above reactions, two studies have been made: (1) the $Ca^{40}(d,p)Ca^{41}$ reaction has been reinvestigated using thin targets, and (2) a direct comparison was made between the end groups of the two reactions $A^{40}(d,p)A^{41}$ and $Ca^{40}(d,p)Ca^{41}$. This was done so that the mass difference $(A^{41}-A^{40})-(Ca^{41}-Ca^{40})$ could be obtained with the uncertainties of beam energy and counter depth eliminated.

II. PROTON ENERGIES FROM $Ca^{40}(d,p)Ca^{41}$

Thin targets were used for the investigation of the proton spectrum from the $Ca^{40}(d,p)Ca^{41}$ reaction. These targets consisted of approximately 0.35 mg/cm² of calcium metal evaporated on gold foil.

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** Assisted by the Joint Program of the ONR and AEC.

[1] L. B. Borst and J. J. Floyd, Phys. Rev. **74**, 989 (1948).

[2] O. Hirzel and H. Wäffler, Phys. Rev. **74**, 1553 (1948).

[3] E. C. Pollard and P. W. Davison, Phys. Rev. **73**, 1241 (1948). Also more complete work on $A^{40}(d,p)A^{41}$ by P. W. Davison, J. O. Buchanan, and E. C. Pollard is in the course of publication.

[4] Bleuler, Bollman, and Zünti, Helv. Phys. Acta **19**, 419 (1946).

[5] H. T. Richards and R. V. Smith, Phys. Rev. **74**, 1257 (1948).

[6] William L. Davidson, Jr., Phys. Rev. **56**, 1061 (1939).

The surface of the target forms CaO on exposure to air. The proton groups from this oxygen can be used as a standard for appraising the accuracy of the Q-values obtained from the calcium.

The procedure for observing the proton yield has been described in detail in previous papers.[7,8] Figure 1 is a schematic diagram of the apparatus. The target was bombarded by 3.90-Mev deuterons from the cyclotron. The target was supported on a C-shaped holder so that the beam strikes only the target. The protons resulting from the reaction were observed at ninety degrees with respect to the incident beam. The yield was determined as a function of the thickness of aluminum plus air between the target and the counter. A proportional counter was used for detection of the protons. A counting level was chosen such that only the largest pulses were recorded, i.e., only those protons near the end of their range and giving maximum specific ionization. The observed yield is shown in Fig. 2.

The spectrum shows four groups which are clearly resolved. In addition, a graphical analysis of the range 40 to 55 cm shows 4 additional poorly resolved groups. The two oxygen groups arising from the CaO layer of the target surface are shown as the dashed curve in Fig. 2. These have been reduced to one-tenth their true size.

To obtain the energy corresponding to each proton group, the extrapolated range is found from Fig. 2. A small correction must be added to the observed range to correct for the variation of the stopping power of Al with proton energy. The corrected range is then converted to energy using Cornell University 1937 range-energy curves.

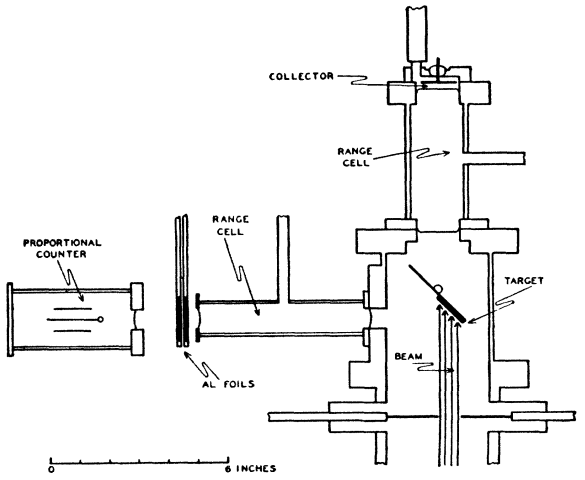

FIG. 1. Schematic diagram of bombardment chamber. The target is mounted on a Wilson seal and may be turned aside. The range cell behind the target is for measuring the energy of the deuteron beam. The range cell at right angles to the beam measures the range of the protons. An automatic foil changer between range cell and counter makes large changes of absorption possible.

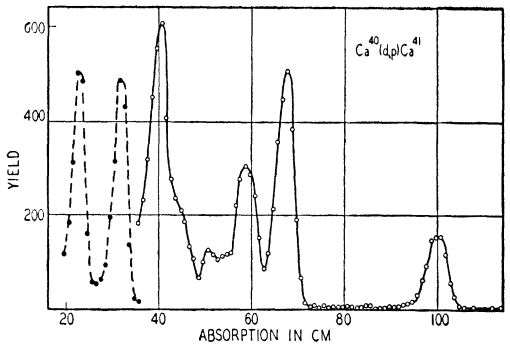

FIG. 2. The proton yield from $Ca^{40}(d,p)Ca^{41}$. Relative yield in arbitrary units is plotted against the total absorption in centimeters air equivalent. The dashed curve is the yield from oxygen in the form of CaO on target surface. It is reduced to one-tenth of its actual yield relative to the calcium.

The beam energy was measured by means of the range cell behind the target (Fig. 1). This was done by turning the target aside and measuring the beam-galvanometer current as a function of the air pressure in the range cell. The extrapolated energy of the deuteron beam was 3.90 ± 0.02 Mev and its half-width was 0.10 Mev. The Q-values were calculated using the extrapolated beam energy and extrapolated proton energy. It was found that the correction resulting from the calculation of the Q-values, using mean beam energy and mean proton energy, was much smaller than the probable errors.

The results are summarized in Table I. The Q-values are in fair agreement with those obtained by Davidson[6] (6.30 and 4.51 Mev), considering that Davidson used a thick target.

The values in Table I in italics are the groups obtained by a graphical analysis of the curve and are less certain than the other groups listed.

Since Ca^{40} is 96.96 percent abundant, it is probable that all of these Q-values should be assigned to the reaction $Ca^{40}(d,p)Ca^{41}$. Any other isotope of calcium would have to have a cross section more than 50 times greater than Ca^{40} to give a comparable yield.

A careful search was made over the range 110 to 200 cm for additional groups, but none were found. It is assumed, therefore, that the Q-value of 6.17 Mev corresponds to the formation of Ca^{41} in the ground state. The mass difference calculated from this Q-value is $Ca^{41}-Ca^{40}=0.99997\pm0.00005$ MU.

A plot of the excitation of the levels is shown in Fig. 3. The thickness of each line in this diagram is proportional to the relative intensity of the group. The spacing of the levels is striking in that the interval between the ground and the first excited

[7] A. B. Martin, Phys. Rev. **72**, 378 (1947).
[8] Pollard, Sailor, and Wyly, Phys. Rev. **75**, 725 (1949).

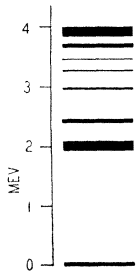

FIG. 3. Energy level diagram for Ca^{41} obtained from $Ca^{40}(d,p)Ca^{41}$. The thickness of each line corresponds to the relative yield of the proton group.

state is unusually large. The spacing between the higher excited states decreases rapidly.

III. COMPARISON OF Q_0 FOR A^{41} AND Ca^{41}

The $A^{40}(d,p)A^{41}$ reaction has been carefully observed and previously reported by Pollard and Davison.[3] However, for the purpose of calculating the mass difference $Ca^{40}-A^{40}$, a comparison of the end groups from the argon and the calcium reactions is needed. Using the same bombardment chamber and taking the measurements in immediate sequence would greatly reduce the error limits in the mass difference $(A^{41}-A^{40})-(Ca^{41}-Ca^{40})$. Such a comparison would eliminate the uncertainty in the beam energy which is ± 0.02 Mev. Also other small uncertainties would be removed such as the effective counter depth, the thickness of the aluminum windows, and the energy loss of the deuterons and protons in the argon-filled bombardment chamber.

To compare the end groups of the two reactions, a gas bombardment chamber was filled with argon and the proton spectrum of argon was observed. The proton group corresponding to the ground state of A^{41} was located. This had previously been identified[3] with reasonable certainty. A calcium target was then introduced into the bombardment chamber, the chamber was refilled with argon to the same pressure as before, and the end group from calcium was observed.

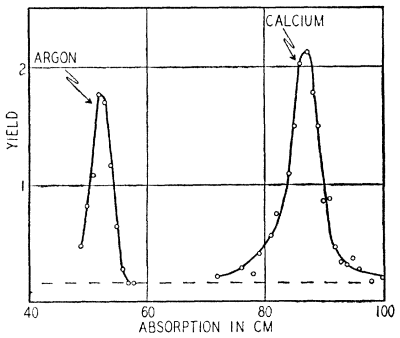

FIG. 4. The end groups from $A^{40}(d,p)A^{41}$ and $Ca^{40}(d,p)Ca^{41}$. These were taken in immediate sequence using the same bombardment chamber, counter setting, and geometric arrangement. The dashed line shows the average neutron background.

The results are plotted in Fig. 4. The difference in the energies of the protons corresponding to the ground state in the two reactions is obtained as shown in Table II.

The mass difference is calculated as follows:

$$\begin{aligned}(A^{41}-A^{40})-(Ca^{41}-Ca^{40}) &= -(Q_0{}^{A}-Q_0{}^{Ca}) \text{ Mev} \\ &= -42/41(E_p{}^{A}-E_p{}^{Ca}) \text{ Mev} \\ &= -42/41(1.074)(E_p{}^{A}-E_p{}^{Ca}) \text{ mMU} \\ &= 2.54\pm 0.03 \text{ mMU}. \qquad (1)\end{aligned}$$

TABLE I. Q-values for $Ca^{40}(d,p)Ca^{41}$ and $O^{16}(d,p)O^{17}$ obtained from Fig. 2, after applying aluminum correction to the observed extrapolated ranges, and using the Cornell 1937 range-energy curves to obtain the proton energy. The energy of the deuteron beam was 3.90 Mev.

	Q	Excitation
	$Ca^{40}(d,p)Ca^{41}$	
Q_0	6.17 ± 0.05 Mev	0.0 Mev
Q_1	4.22 ± 0.05	1.95
Q_2	3.76 ± 0.05	2.41
Q_3	*3.2 ±0.1*	*3.0*
Q_4	*2.9 ±0.1*	*3.3*
Q_5	*2.7 ±0.1*	*3.5*
Q_6	*2.5 ±0.1*	*3.7*
Q_7	2.31 ± 0.05	3.86
	$O^{16}(d,p)O^{17}$	
Q_0	1.95	0.0
Q_1	1.06	0.89

TABLE II. Comparison of the end groups of protons from the two reactions $Ca^{40}(d,p)Ca^{41}$ and $A^{40}(d,p)A^{41}$. The observed extrapolated ranges were obtained from Fig. 4.

	Observed range	Aluminum correction	Corrected range	Proton energy
$Q_0{}^{Ca}$	92.4 cm	3.2 cm	95.6 cm	9.02 ± 0.02 Mev
$Q_0{}^{A}$	55.7	1.2	56.9	6.71 ± 0.02

It should be noticed that the deuteron beam must enter the gas target through an aluminum foil and, therefore, is reduced in energy from 3.90 Mev to 3.26 Mev. This explains why the observed range of the calcium protons is less in this case than in Fig. 2 where full beam energy was used.

As a check of the consistency of these results, $Q_0{}^{A}$ for argon can be computed using $Q_0{}^{Ca}$ for calcium obtained in Section II of this paper:

$$Q_0{}^{Ca}-Q_0{}^{A}=2.37 \text{ Mev},$$
$$Q_0{}^{A}=6.17-2.37=3.80\pm 0.06 \text{ Mev}.$$

This agrees closely to the value $Q_0{}^{A}=3.82\pm 0.05$ Mev reported by Pollard and Davison.[3]

IV. THE MASS DIFFERENCE ($Ca^{40}-A^{40}$)

If the value found in Eq. (1) is combined with the values found by Richards[5] and Bleuler,[4] the

TABLE III. Mass differences and the nuclear reactions from which they were computed, using $H^1=1.008128$, $D^2=2.014718$, $n=1.00897$ mass units.

Nuclei	Calculated mass difference	Reaction	Data used in calculation	Reference
$Ca^{41}-Ca^{40}$	0.99997 ± 5	$Ca^{40}(d,p)Ca^{41}$	$Q_0^{Ca}=6.17\pm0.05$ Mev	This paper
$(A^{41}-A^{40})-(Ca^{41}-Ca^{40})$	0.00254 ± 3	Comparison of end groups of $Ca^{40}(d,p)Ca^{41}$ and $A^{40}(d,p)A^{41}$	$Q_0^{Ca}-Q_0^{A}=2.37\pm0.03$ Mev	This paper
$A^{41}-A^{40}$	1.00249 ± 5	$A^{40}(d,p)A^{41}$	$Q_0^{A}=3.82\pm0.05$ Mev	3
$Ca^{41}-K^{41}$	0.00047 ± 7	$K^{41}(p,n)Ca^{41}$	$E_{thresh}=1.25\pm0.06$ Mev	5
$A^{41}-K^{41}$	0.00274 ± 20	$A^{41}\rightarrow K^{41}+\beta^-$	$\beta^-_{max}=2.55\pm0.2$ Mev	4
$K^{40}-A^{40}$	0.0017	$A^{40}(p,n)K^{40}$	$E_{thresh}=2.4$ Mev	11
$K^{40}-A^{40}$	0.00167 ± 10	$K^{40}\rightarrow A^{40}+\gamma$, K-capture	$\gamma=1.55\pm0.1$ Mev	10
$K^{40}-Ca^{40}$	0.00145 ± 5	$K^{40}\rightarrow Ca^{40}+\beta^-$	$\beta^-_{max}=1.35\pm0.05$ Mev	9

difference in mass between A^{40} and Ca^{40} can be calculated. The data used in this calculation are summarized in Table III.

$$(Ca^{40}-A^{40})=[(A^{41}-A^{40})-(Ca^{41}-Ca^{40})]+(Ca^{41}-K^{41})-(A^{41}-K^{41}),$$
$$(Ca^{40}-A^{40})=2.54+0.47-2.74\text{ mMU}=0.27\pm0.21\text{ mMU},$$

where the r.m.s. error has been taken. These data indicate that Ca^{40} is slightly heavier than A^{40}.

$Ca^{40}-A^{40}$ can also be obtained from the energy of radioactive decay of K^{40} by β^--emission[9] and K-capture:[10]

$$(Ca^{40}-A^{40})=(K^{40}-A^{40})-(K^{40}-Ca^{40}),$$
$$(Ca^{40}-A^{40})=1.67-1.45=0.22\pm0.11\text{ mMU (Table III)}.$$

There is excellent agreement between the two methods of calculating this mass difference.

If the 1.55-Mev γ-ray observed by Hirzel[10] is due to K-capture, then $K^{40}-A^{40}=1.67$ mMU. This agrees closely to the threshold energy for $A^{40}(p,n)K^{40}$ found by Richards,[11] which gives $K^{40}-A^{40}=1.7$ mMU. It appears that this threshold corresponds to the production of K^{40} in the ground state rather than in an excited state as was postulated.[11] The assumption that the threshold is for an excited state of K^{40} would make the agreement of these various mass differences worse. This disagreement would be large if the excited state of K^{40} lay several tenths of a Mev above the ground state. (The first excited state of K^{40} found from the reaction $K^{39}(d,p)K^{40}$ was 0.84 Mev above the ground state.[12])

V. ACKNOWLEDGMENT

The author would like to express his appreciation to Professor E. C. Pollard who assisted with many helpful discussions.

[9] Dželepow, Kopjova, and Vorobjov, Phys. Rev. **69**, 538 (1946).
[10] O. Hirzel and H. Wäffler, Helv. Phys. Acta **19**, 216 (1946).
[11] H. T. Richards and R. V. Smith, Phys. Rev. **74**, 1870 (1948).
[12] Vance L. Sailor, unpublished work.