methods and solving the wave equation directly in the manner of Chase, Wilets, and Edmonds.[2] We feel, however, that for any such program to provide definitive results the calculation must be based on a spin-dependent optical potential such as that of BF which is known to be applicable to many elements over a wide range of energies.

ACKNOWLEDGMENTS

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Reaction $A^{40}(p,n)K^{40}$ and the Decay of K^{40}†

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The energy difference involved in the decay of K^{40} to A^{40} by electron capture was measured in two ways. First, a time-of-flight technique was used to observe the neutron spectra from $A^{40}(p,n)K^{40}$ and the corresponding Q's were computed. Second, the thresholds for production of certain gamma rays from this reaction were measured; these thresholds provided another set of values for the Q's. When these Q values were combined with our measurements of the gamma-ray energies, we obtained a mass difference equivalent to 1.522 ± 0.006 Mev between A^{40} and K^{40} and an energy release of 60 ± 8 kev in the decay of K^{40} to A^{40}. This appears to conflict with other information on this branch of the decay of K^{40}.

I. INTRODUCTION

THE decay scheme of K^{40} has been the subject of many papers since it is of interest not only as a nuclear phenomenon, but also as a geophysical tool. Even so, its decay scheme is not completely understood. In this paper we describe a measurement of the neutron spectra resulting from transitions to states in K^{40} through the reaction $A^{40}(p,n)K^{40}$. From these and other measurements we deduce the energy available for the decay of K^{40} to A^{40} by electron capture.

The threshold of the reaction $A^{40}(p,n)K^{40}$ was first investigated by Richards and Smith,[1] who obtained an upper limit of 2.4 Mev for it. The energies of excitation of the levels of K^{40} were obtained by Buechner *et al.*[2] using the $K^{39}(d,p)K^{40}$ reaction. The low-lying levels of K^{40} appear to arise from j-j coupling of an $f_{7/2}$ neutron with a $d_{3/2}$ proton hole leading to spin states of 2, 3, 4, and 5. The ground-state spin is known[3] to be 4; with other states assigned as in Fig. 1, Pandya[4] and Goldstein and Talmi[5] successfully computed the positions of the corresponding levels in Cl^{38}. These assignments have been confirmed to some extent by recent measurements[6] of the angular distribution of $K^{39}(d,p)K^{40}$. Endt and Braams[7] have recently reviewed data on K^{40}.

From this information one can conclude that we should observe transitions only to the second and third excited states of K^{40}, as indeed we do. In the absence of a (p,n) measurement, Way *et al.*[8] had taken an average of mass-spectroscopic data and other reaction data to obtain a value of 1.51 ± 0.02 Mev for the mass difference between A^{40} and K^{40}. From our work, we obtain a value 1.522 ± 0.006 Mev for this mass difference.

II. EXPERIMENTAL EQUIPMENT

The spectra of neutrons from the reaction $A^{40}(p,n)K^{40}$ were obtained by measuring the neutron time-of-flight in conjunction with an externally pulsed beam from the 4-Mv electrostatic accelerator at Argonne National Laboratory. A block diagram of the equipment is

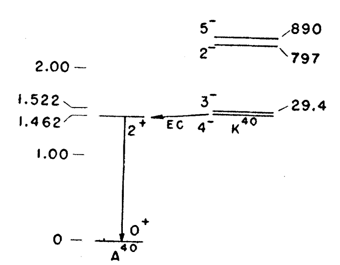

FIG. 1. The energy levels of A^{40} and K^{40}.

† Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] H. T. Richards and R. V. Smith, Phys. Rev. **74**, 1870 (1948).
[2] Buechner, Sperduto, Browne, and Bockelman, Phys. Rev. **91**, 1502 (1953).
[3] Davis, Nagle, and Zacharias, Phys. Rev. **76**, 1068 (1949).
[4] S. P. Pandya, Phys. Rev. **103**, 956 (1956).
[5] S. Goldstein and I. Talmi, Phys. Rev. **102**, 589 (1956).
[6] I. B. Teplov and B. A. Yurev, Zhur. Eksptl. i Teoret. Fiz. U.S.S.R. **33**, 1313 (1957) [translation: Soviet Phys. JETP **6**, 1011 (1958)].
[7] P. M. Endt and C. M. Braams, Revs. Modern Phys. **29**, 683 (1957).
[8] *Nuclear Level Schemes, A=40—A=92*, comp led by Way, King, McGinnis, and van Lieshout, U. S. Atomic Energy Commission Report TID-5300 (U. S. Government Printing Office, Washington, D. C., 1955).

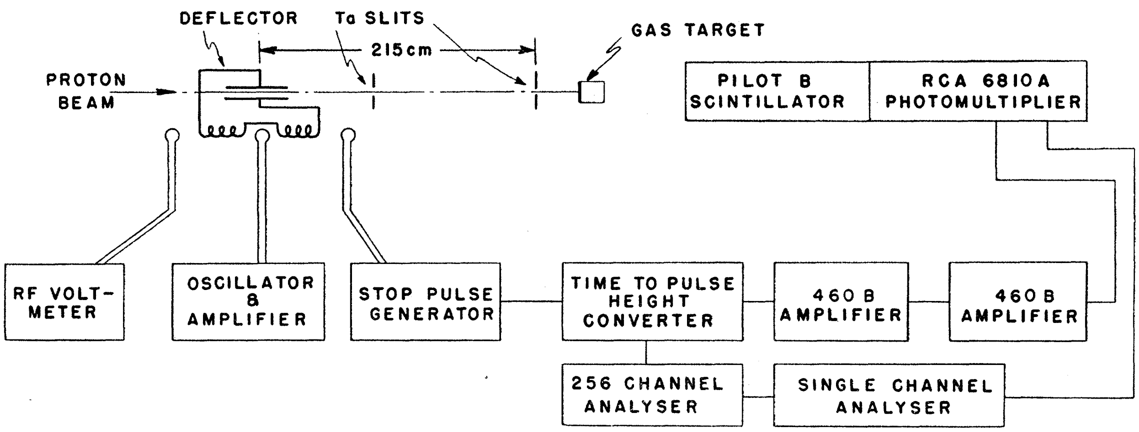

FIG. 2. Block diagram of electronic equipment.

shown in Fig. 2. Short bursts of protons were produced at the target by deflecting the external beam at a high rate across a slit ahead of the target. Gamma rays and neutrons produced in the target by the pulses of protons were detected by a plastic scintillator at a measured distance. Scintillations in the detector produced electrical pulses in the photomultiplier tube which were amplified and sent to a time-to-pulse-height converter similar to that described by Weber, Johnstone, and Cranberg.[9] The converter differed from that of Weber *et al.* by the addition of a diode restoring circuit[10] which reduced pile-up effects in the output of the converter. This converter produced an output pulse whose amplitude was proportional to the difference in time between the pulse from the detector and a timing pulse obtained from the beam deflecting voltage. The pulse amplitudes were then analyzed with a 256-channel analyzer.

In order to minimize the effect of the amplitude of the detected pulse on the time measurement, pulses from the converter were recorded only if they were produced by detector pulses whose amplitude fell in a certain range. This was accomplished by taking from a dynode of the phototube a signal which was sent to a slow amplifier, a single-channel analyzer, and then to the gating circuit of the 256-channel analyzer. Since the position of this "slow" channel determined the efficiency of the counter, the window position was compared daily with the Compton edge for Be^7 gamma rays. The efficiency of neutron detection was measured as a function of neutron energy relative to a long counter using the $Li^7(p,n)Be^7$ reaction with results similar to those given by Cranberg and Levin.[11] The threshold for neutron detection was 250 kev with one bias setting and 350 kev at another.

In Sec. III of this paper are shown data which were obtained with this system. Because there were two bursts of protons but only one timing pulse per cycle of deflecting voltage, there is a double display of the data. Time increases linearly from right to left. The time of arrival of the proton burst at the target was obtained from the position of the gamma-ray peak and the transit time of the gamma rays.

Figure 3 shows the arrangement of beam deflector, target, and detector. The beam deflector consisted of two parallel plates 1 inch wide and 12 inches long, separated by $\frac{1}{4}$ inch. To reduce background, gold, tantalum, or lead surfaces were provided wherever the deflected beam could hit. With this precaution we had no difficulty with a large time-dependent background. The deflector was operated with a 3.5-Mc/sec sinusoidal voltage with a peak value of 6 kv. This produced a beam pulse with full-width at half-maximum of about 2 mμsec, estimated from the reduction in beam current when the deflector voltage was applied.

The neutron detector was mounted in a shield which could be pivoted about the target and moved radially with respect to the target. The detector consisted of a piece of Pilot B scintillator,[12] 0.50 inch thick and 1.75 inches in diameter, placed on an RCA 6810-A photomultiplier tube. Most of the data were taken with a 0.25-inch lead filter between target and detector.

Although the converter was quite linear, we made a small correction (less than 1 mμsec) for nonlinearity. Peaks falling at either end of the spectrum, where such a correction would have been large, were not used for energy measurements.

We took advantage of the duplicate display presented by this system to calibrate the converter in the following manner. First, we noted the spacing between the two gamma-ray peaks which represented approximately one-half of the rf period; and second, we measured the spacing of a pair of neutron peaks which were delayed enough so that they represented the other half of the cycle. Although these two measurements usually

[9] Weber, Johnstone, and Cranberg, Rev. Sci. Instr. **27**, 166 (1956).
[10] F. J. Lynch, Argonne National Laboratory Summary Report ANL-5818, 1957 (unpublished), p. 11.
[11] L. Cranberg and J. S. Levin, Phys. Rev. **103**, 343 (1956).
[12] Pilot Chemicals, Inc., Waltham, Massachusetts.

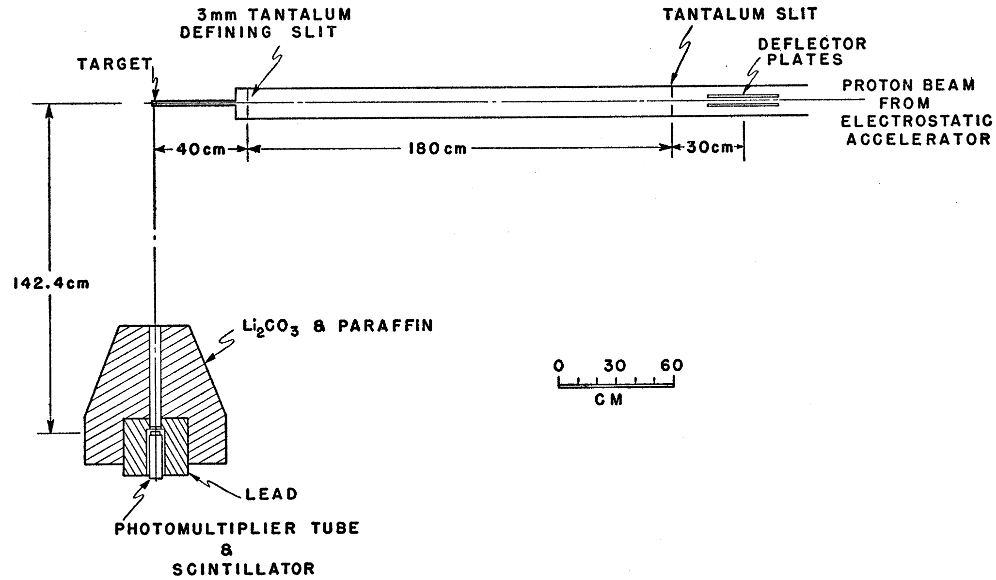

FIG. 3. Schematic diagram of the deflector, target, and detector.

differed by a few millimicroseconds because of inaccuracies in alignment, the sum was equal to the period of the rf deflector voltage. We then calculated the energy of the neutrons which had produced a certain peak from the peak's time delay relative to the corresponding gamma rays from the target. Observations made in this way on the neutrons from $Li^7(p,n)Be^7$ showed an accuracy corresponding to a timing error of about 0.5 mμsec.

The gas target used for the neutron work was similar to that described by Johnson and Banta.[13] An early version of the gas cell had brass walls and a gold end

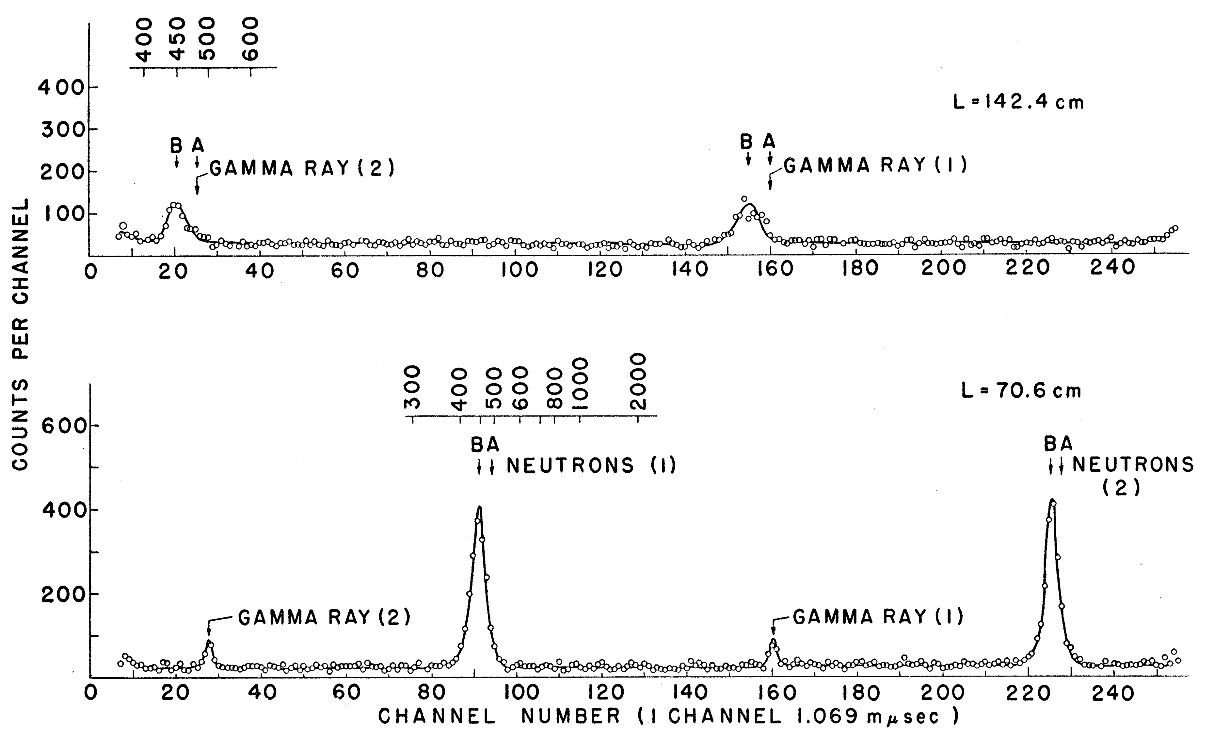

FIG. 4. Neutron time-of-flight spectrum from $A^{40}(p,n)K^{40}$. The upper curve was taken with a detector distance of 142.4 cm, the lower curve with detector distance 70.6 cm. In both cases the proton energy was 2.878 Mev, the angle of observation 93°.

[13] C. H. Johnson and H. E. Banta, Rev. Sci. Instr. **27**, 132 (1956).

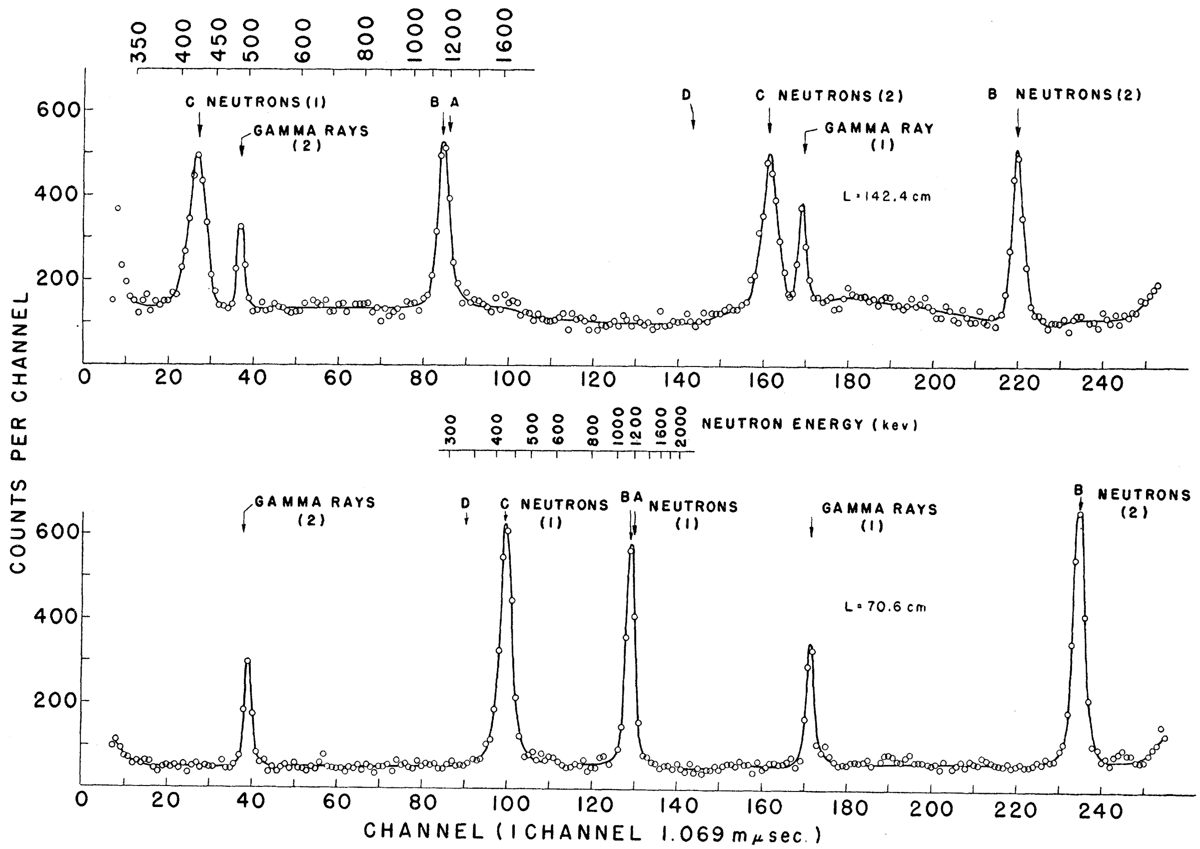

FIG. 5. Neutron time-of-flight spectrum from $A^{40}(p,n)K^{40}$. The upper curve was taken with a detector distance of 142.4 cm, the lower curve with detector distance 70.6 cm. In both cases the proton energy was 3.360 Mev, the angle of observation 93°.

plate, but later a cell was used which had $\frac{1}{32}$-inch aluminum walls lined with 0.008-inch polyethlyene in order to observe the low-energy gamma rays. The data were taken with two kinds of nickel entrance foil; the first was 0.00125 mm thick, and the second 0.0005 mm thick. The threshold of the $Li^7(p,n)Be^7$ reaction was used to measure the minimum energy loss and the energy spread produced by the foil. For the thicker foils, the minimum energy loss was 90 kev with an energy spread of 20 kev; for the thinner foils, the minimum energy loss was 30 kev and the energy spread

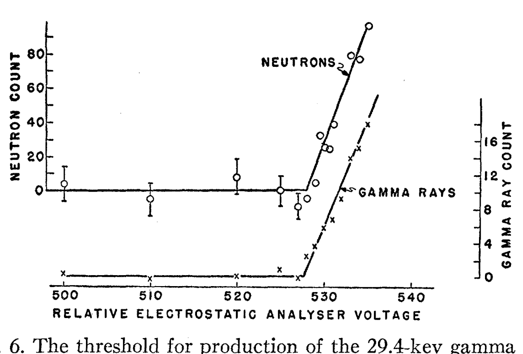

FIG. 6. The threshold for production of the 29.4-kev gamma ray. Also shown is the neutron threshold observed with a long counter.

10 kev. The calculations of Aron *et al.*[14] were used to compute the energy loss at other proton energies.

The energy of the proton beam was measured and controlled by sending the molecular beam through a 25° electrostatic analyzer.[15] This system has an accuracy of about 2 kev.

III. RESULTS

(a) Neutron Spectra

Figure 4 shows a typical measurement of the neutron spectrum from the reaction $A^{40}(p,n)K^{40}$. These data were taken with a proton energy of 2.878 Mev, for which only transitions to the two lower states of K^{40} are energetically possible. The two curves differ only in the distance L to the detector. Assuming a Q value consistent with the other data discussed below, the expected position of the ground state group and first excited state group are labeled A and B, respectively. It is clear that if the transition to the ground state occurs, it is much weaker than the transition to the first excited state.

Figure 5 shows the result of similar measurements at

[14] Aron, Hoffman, and Williams, U. S. Atomic Energy Commission Report AECU-663, 1949 (unpublished).

[15] Hibdon, Langsdorf, and Holland, Phys. Rev. **85**, 595 (1952).

a proton energy of 3.635 Mev. Here transitions to the four lower states of K^{40} are possible. Transitions A and B are not resolved, but it is apparent that the transition C to the second excited state is present and the transition D to the third excited state is not. A number of measurements of neutron spectra were made at 30° and 150° as well as at 90° with a variety of bombarding energies; all of these measurements showed only the transitions seen in Figs. 4 and 5.*

(b) Gamma-Ray Thresholds

In order to verify the conclusions drawn above, we made measurements of the appearance thresholds for the 29.4-kev gamma ray, resulting from excitation of the first excited state, and for the 768-kev gamma ray, resulting from the second excited state. A typical threshold measurement for the 29.4-kev gamma ray is shown in Fig. 6, which also shows the neutron count taken at the same time in a long counter. The threshold obtained in this way was 2.390±0.010 Mev. The neutron counting rate immediately below the threshold was within 10% of the background counting rate, in agreement with the time-of-flight data.

Two measurements of the threshold for production of the 768-kev gamma ray gave an average value for this threshold of 3.174 Mev.

(c) Gamma-Ray Energies

We observed three gamma rays arising from proton bombardment of A^{40}: the two discussed above and a third from excitation of the first state of A^{40} by inelastic scattering. A NaI scintillator in a standard arrangement was used with the 256-channel analyzer to measure the energies of these gamma rays.

Most attention was given to the 29.4-kev gamma ray. Figure 7 shows a typical pulse-height spectrum obtained in a $\frac{1}{2}$-inch by $\frac{1}{16}$-inch NaI crystal covered by aluminum foil 0.004 inch thick. The proton energy was 2.5 Mev, just above the threshold for production of this gamma ray. For comparison, the spectrum from the K x-rays arising from proton bombardment of a tin target is also shown. In addition, K x-rays of radioactive cesium and tellurium were measured. Figure 8 summarizes these measurements. The centroids of the gamma peaks were plotted as abscissa. The ordinates were the centroids of the $K_{\alpha1}$, $K_{\alpha2}$, $K_{\beta1}$, $K_{\beta2}$ lines computed from the energies and relative intensities of the lines as given by Williams.[16] In this region of the periodic table, the average energy $\bar{E}$ was given very

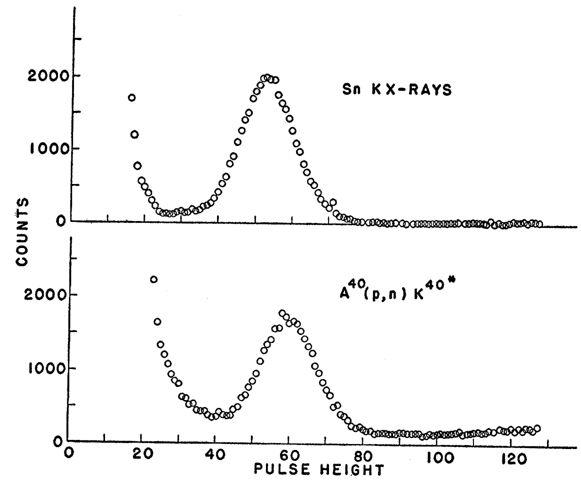

FIG. 7. Pulse-height spectrum in NaI scintillator due to the 29.4-kev gamma ray from $A^{40}(p,n)K^{40*}$. Also shown is the pulse-height spectrum from the K x-rays of tin produced by proton bombardment.

closely by

$$\bar{E}=1.024E_{\alpha1},$$

where $E_{\alpha1}$ is the energy of the $K_{\alpha1}$ line.

Although energies of the components of the K x-ray lines are known with considerable accuracy, it is possible that one component is emphasized over the others either by a difference of absorption in the material between the source and detector or by a difference in the efficiency of the detector. In the worst case, the calculated mean energy of the K x-rays of tin was changed by 0.3% by $\frac{1}{32}$ inch of aluminum absorber. For the cesium and tellurium sources, the absorption of the intervening material was even smaller. No attempt was made to evaluate the variation in detector efficiency; since all of these x-rays have energies below the K-absorption edge of iodine, we believe the effect is small. The energy of the gamma ray as deduced from this work is 29.4±1.0 kev.

A similar measurement of the 768-kev gamma ray, using calibration gamma rays from Be^7, Cs^{137}, and Co^{60},

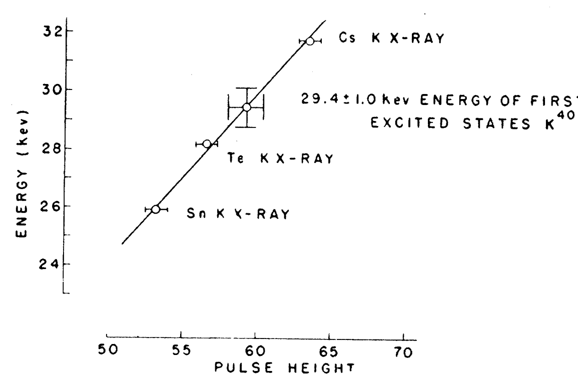

FIG. 8. Summary of the measurements of energy of the 29.4-kev gamma ray and the calibrating gamma rays.

* *Note added in proof.*—J. P. Schiffer of this laboratory has pointed out to us that one should expect on the basis of the penetrabilities that transitions to the ground state of K^{40} should be almost as probable as transitions to excited states of K^{40}. The explanation for the weakness of transitions to the ground state must therefore lie elsewhere.

[16] J. H. Williams, Phys. Rev. 44, 146 (1933).

TABLE I. Summary of measurements of Q (in kev) for $A^{40}(p,n)K^{40}$.

Measurement	Q for $A^{40}(p,n)K^{40*}$	Excitation energy	Ground state Q $A^{40}(p,n)K^{40}$
Neutron group B	-2336 ± 10	29.4 ± 1.0	-2307 ± 10
Threshold 30-kev gamma ray	-2332 ± 10	29.4 ± 1.0	-2303 ± 10
Neutron group C	-3104 ± 15	$797\ \pm5$	-2307 ± 16
Threshold 768-kev gamma ray	-3096 ± 10	$797\ \pm5$	-2299 ± 12
		Weighted average=	-2304 ± 6

gave an energy of 771 ± 10 kev. We have averaged this result with the determination by Day[17] of 767 ± 7 kev and by Buechner *et al.*[2] of 768 ± 10 kev to obtain the value of 768 ± 5 kev for use in Table I. The gamma ray produced by inelastic scattering of protons on A^{40} was measured in the same manner to have an energy of 1442 ± 15 kev.

IV. DISCUSSION

Table I summarizes the results of these measurements. The first column indicates the type of measurement, the second column the Q value for the particular excited state from $A^{40}(p,n)K^{40*}$, the third column the excitation energy of the state, and the fourth column the corresponding Q value for transitions to the ground state of K^{40}. The internal consistency of the data confirms the reaction schemes we have assumed.

We believe that the threshold observed by Richards and Smith[1] was due to transitions to the first excited state of K^{40}. Our value for the threshold of this transition is 2.390 ± 0.010 Mev, in agreement with their value of 2.40 Mev. As shown in Table I, the average of all measurements gives a Q value of -2.304 ± 0.006 Mev for the transition to the ground state. This corresponds to an A^{40}-K^{40} energy difference of 1.522 ± 0.006 Mev, in good agreement with the value 1.51 ± 0.02 Mev which Way *et al.*[8] obtained by averaging other reaction data and mass spectroscopic data. For the position of the first excited state in A^{40}, we prefer the value 1.462 ± 0.005 Mev adopted by Endt and Braams because it is more accurate than our own measurement. This then gives a value 60 ± 8 kev for the energy available in decay of K^{40} to A^{40}.

The manner in which this conflicts with other data is as follows. It is generally assumed that the first excited state of A^{40} is 2^+, so the decay of K^{40} by electron capture is expected to be a unique first-forbidden transition ($\Delta J=2$, yes).[8,18] For such transitions, the calculations of Brysk and Rose[19,8] permit the evaluation of the ratio of L capture to K capture. The ratio varies rapidly with energy and for 60 kev is approximately 0.3. However, Heintze[20] has measured the ratio of L capture to K capture to be 1.37. This would then require a decay energy of 25 kev.

A possible explanation for this apparent discrepancy is that the spin of this first excited state of A^{40} is not 2^+, and that the decay is therefore not a unique first-forbidden transition. This could also explain the large log f^1t of about 11, whereas transitions of this type usually have log $f^1t\approx9$. There is some direct evidence, obtained by electron scattering,[21] that the gamma-ray transition in A^{40} is not an electric quadrupole, and thus that the first excited state of A^{40} does not have spin 2^+. Before a decision on this point can be made, more direct evidence on the nature of this state of A^{40} is necessary.

ACKNOWLEDGMENTS

We are indebted to Dr. Kineo Tsukada for assistance in early stages of the work, to A. Vandergust for building much of the electronic equipment, and to J. Wallace and the Van de Graaff group for assistance in operating the accelerator.

[17] R. B. Day, Phys. Rev. **102**, 767 (1956).

[18] P. Morrison, Phys. Rev. **82**, 209 (1951).

[19] H. Brysk and M. E. Rose, Oak Ridge National Laboratory Report ORNL-1830, 1955 (unpublished).

[20] J. Heintze, Z. Naturforsch. **9A**, 469 (1954).

[21] R. H. Helm, Phys. Rev. **104**, 1466 (1956).