Nuclear Energy Levels in Isotopes of Potassium

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Targets made from the separated isotopes K^{39} and K^{41} were bombarded by 3.90-Mev deuterons, and protons from the nuclear reactions $K^{39}(d,p)K^{40}$ and $K^{41}(d,p)K^{42}$ were observed. The energy distribution of the protons emitted in each reaction was obtained by measuring the proton yield as a function of range. The ground state Q-value for $K^{39}(d,p)K^{40}$ was found to be 5.48 ± 0.08 Mev, giving the mass difference $K^{40}-K^{39}=1.00070\pm0.00007$ mass units. Excited states of K^{40} were found at 0.81, 2.01, 2.56, 3.3, 3.7, 4.2, and 4.8 Mev. The ground state Q-value for $K^{41}(d,p)K^{42}$ was 5.12 ± 0.10 Mev, giving the mass difference $K^{42}-K^{41}=1.00109\pm0.00010$ mass units. Excited states of K^{42} were found at 0.62, 1.18, 1.97, and 2.29 Mev.

INTRODUCTION

NUCLEAR energy level schemes for K^{40} and K^{42} can be obtained by measuring the Q-values of the reactions $K^{39}(d,p)K^{40}$ and $K^{41}(d,p)K^{42}$. In 1940, Pollard[1] bombarded natural potassium with deuterons and observed three groups of protons giving Q-values of 5.6, 4.5, and 3.4 Mev. All three of these were attributed to the reaction $K^{39}(d,p)K^{40}$, because K^{39} is the most abundant of the potassium isotopes.

Natural potassium contains three isotopes in the following abundances:[2] $K^{39}=93.3$ percent, $K^{40}=0.01$ percent, and $K^{41}=6.7$ percent. It would be expected that d,p type reactions would result from each of the three isotopes in the target, because d,p reactions are generally exoergic and have reasonably large cross sections. It is possible to prove that a nuclear reaction occurs by observing the half-life of the activity produced in the target provided that the product nucleus is radioactive. In this manner the reaction $K^{41}(d,p)K^{42}$ has been identified[3] and measurements have been made of the total yield of K^{42} from deuteron bombardment of thick targets of natural potassium.[4,5] No such proof of the occurrence of $K^{39}(d,p)K^{40}$ can be obtained because the increased target activity due to the production of K^{40} is negligible. Likewise, $K^{40}(d,p)K^{41}$ cannot be detected by this method because K^{41} is stable.

Another method which has many advantages for detecting the occurrence of d,p reactions consists of studying the proton yield from targets enriched in the isotope in question. Comparison of the proton yield from the enriched target with the yield from a natural target usually shows at once whether or not the reaction occurs with appreciable cross section. The use of an enriched target also permits the assignment of the various observed Q-values to the proper isotope.

This paper is a report on the reactions $K^{39}(d,p)K^{40}$ and $K^{41}(d,p)K^{42}$ which were studied with the assistance of enriched targets.

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[1] E. C. Pollard, Phys. Rev. **57**, 1086 (1940).
[2] W. Paul and M. Pahl, Naturwiss. **32**, 228 (1944).
[3] D. G. Hurst and H. Walke, Phys. Rev. **51**, 1033 (1937).
[4] E. C. Barker, MDDC-7, May, 1946.
[5] Clarke and Irvine, Phys. Rev. **70**, 893 (1946).

APPARATUS AND PROCEDURE

Various targets of potassium were bombarded by the 3.90-Mev deuteron beam of the Yale cyclotron and the protons emerging from the target were observed with a proportional counter. The counter was placed at 90° from the direction of the deuteron beam. Protons from the target passed through several calibrated aluminum absorbers, a short air gap, then entered the counter. The aluminum absorbers could be changed by remote control so that the total absorption in the proton path was variable.

The energy of the deuteron beam was determined by measuring its range in an air absorption cell and converting the range into energy by means of the Cornell 1937 range-energy curves. The apparatus for observing the protons and measuring the beam range has been described previously.[6]

Curves of proton yield as a function of total absorption were obtained by varying the aluminum absorption in steps of 1-cm air-equivalent and observing the number of protons at each absorption. The cyclotron beam current was collected by the target and integrated. The counting interval was chosen to be the time required to accumulate a standard amount of beam current. Two types of yield curves were obtained: (A) "Integral Curves" obtained by counting all protons entering the counter (i.e., all pulses above noise); and (B) "Peaked Curves" obtained by counting only those protons giving the largest pulses (i.e., those protons which were very near the end of their range).

TABLE I. Isotopic abundance of natural potassium and enriched samples in percent.

	Natural potassium	Sample #346(a)†	Sample #348(a)†
K^{39}	93.3	96.5 ± 2.0	13.3 ± 0.5
K^{40}	0.01	$0.6^{+0.1}_{-0.6}$	$0.2^{+0.1}_{-0.2}$
K^{41}	6.7	3.0 ± 0.5	86.6 ± 1.0

† Sample number as designated by the Carbide and Carbon Chemicals Corporation.

[6] V. L. Sailor, Phys. Rev. **75**, 1836 (1949).

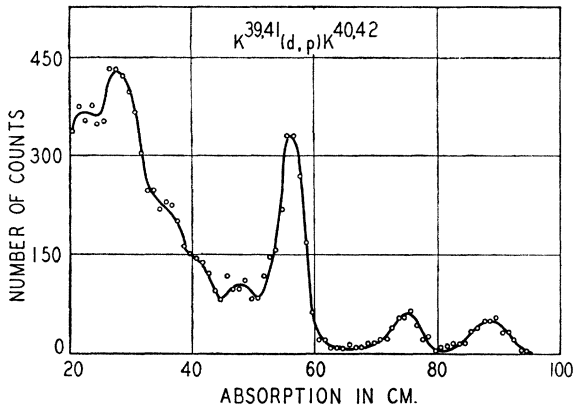

FIG. 1. The proton yield from a target of natural potassium bombarded by 3.90-Mev deuterons. Counting statistics are given approximately by the square root of the ordinate. The absorption is in cm air-equivalent.

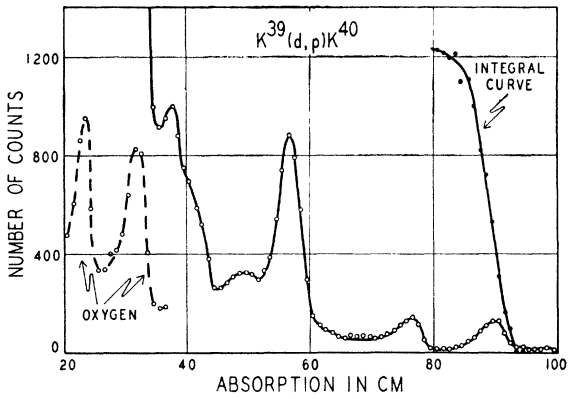

FIG. 2. The proton yield from a target enriched to 96.5 percent in K^{39}. The integral curve was used to calculate Q_0 for $K^{39}(d,p)K^{40}$. The dashed curve is due to oxygen contamination and has been reduced by a factor of ten relative to the solid curve.

Integral curves (type A) were used to determine the Q-value of the longest range group of each reaction, and therefore to calculate the mass difference between the target and residual nucleus. Peaked curves (type B) were used for determining the group structure of the shorter range protons, and hence to obtain the energy level schemes.

The extrapolated range of each proton group was determined graphically and this range was used to compute the Q-value according to the procedure outlined by Livingston and Bethe.[7] The computations take into account the variation in the stopping power of aluminum with energy, proton straggling, and the effect of observing over a finite solid angle for the case of "good geometry." In addition a small correction was applied for the effect of the proton range of the inhomogeneity of the deuteron beam, according to the method developed recently by H. T. Motz and R. F. Humphreys.[8]

PREPARATION OF TARGETS

The quality of the target is a primary factor in determining the results of the study of a nuclear reaction. The target should be uniform and thin so as to permit maximum resolution, but must be thick enough to give usable counting rates. It is important of course to keep the target free of contaminations. For these studies the targets were prepared by depositing thin layers of potassium metal or potassium iodide on gold foil by evaporation in high vacuum.

Three types of potassium were used: Natural potassium, potassium enriched in K^{39}, and potassium enriched in K^{41}. The relative concentrations of the isotopes in these three types are listed in Table I.

The targets of natural potassium were prepared from several different samples of the metal, the iodide and the chloride. The use of a variety of samples from independent sources reduced the possibility of the presence of some unsuspected impurity which might give large proton yields. The proton yield curves from all the targets of natural potassium were identical with the exception of those made from the metal, which always contained large amounts of oxygen. Target thicknesses varied from 0.5 to 2.0 mg/cm^2.

Two samples of enriched isotopes were supplied by the Carbide and Carbon Chemicals Corporation and obtained on allocation from the Stable Isotopes Division, AEC. The mass spectroscopic analysis furnished with the samples is given in Table I. Both of the enriched samples were in the form of KCl, which is not suitable for use as a target because of the copious yield of protons from chlorine. A method was devised for preparing targets from the KCl which eliminated the chlorine and in the same step gave thin uniform deposits of potassium or potassium iodide. The KCl was mixed in stoichiometrical proportions with calcium metal filings and placed in a small glass oven in a vacuum chamber. A nichrome filament was sealed in the walls of the oven to permit the contents to be heated without allowing contaminations from the filament to reach the target. When the mixture in the oven was heated to about 400°C in high vacuum, potassium vapor was released through a $\frac{1}{4}$-inch opening at the top of the oven and condensed on the gold target foil placed about 2 cm above. The gold foil was cooled from behind by a brass block through which water circulated. A baffle system surrounded the oven and target to trap any of the valuable potassium sample which failed to condense on the target. After the potassium had condensed on the target a small amount of iodine vapor was admitted to the chamber and served to convert the thin potassium deposit on the target to potassium iodide. The potassium iodide targets could be exposed to air without damage while transferring the target from the evapora-

[7] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 245 (1937).

[8] H. T. Motz and R. F. Humphreys (to be published).

tion apparatus to the cyclotron target chamber. Targets produced in this manner contained no detectable chlorine or calcium contamination.

The gold foil used for making the targets was of the highest purity available commercially. 3.90-Mev deuterons produce no appreciable yield of protons from gold. Experimental studies were made to determine what proton yield could be expected from the surface contaminations of the gold which was processed in the same way as the targets. It was found that at 90° observation the proton yield was negligible. At 0° observation, however, two long range groups were present but with very low yield. These were found to be due to nitrogen contamination on the front and back surfaces of the gold foil. Also at 0° small yields from the $O^{16}(d,p)O^{17}$, $C^{12}(d,p)C^{13}$, and $D^2(d,p)T^3$ reactions were located.

The yield from a PbI_2 target was observed and found to be negligible indicating that iodine contributed nothing to the proton yield from KI targets.

PROTON YIELD FROM NATURAL POTASSIUM

A typical proton yield curve taken at 90° with a target of natural potassium iodide is shown in Fig. 1. Several unsuccessful attempts were made to obtain better resolution of the group structure at ranges less than 40 cm by using thinner targets and a more homogeneous beam. It appears that many groups from both K^{39} and K^{41} isotopes lie in this region with small spacing and much better resolution will be necessary to separate them.

Several factors limit the resolution in range measurements; the most important being the straggling of the protons, the inhomogeneity of the deuteron beam and the thickness of the targets. These factors cause a proton group to have a half-width of about 3 cm at 30 cm range increasing to about 4 cm at 100 cm range. The half-width is the group width at one-half the maximum. If the resolution is defined as being the half-width in cm air-equivalent divided by the range, then the resolution is about 4 percent at 100 cm and 10 percent at 30 cm.

Several runs were taken at 0° observation and the relative intensities of some of the shorter range groups were sufficiently different from the relative intensities at 90° to assist in the location of the groups. Targets of several different specimens of potassium metal and potassium iodide were used for these observations and the same group structure was consistently obtained. The groups with peaks at 88, 75, and 56 cm are those previously reported by Pollard.[1]

Some early data taken at 0° observation indicated the presence of two long range groups having Q-values of 8.2 and 7.6 Mev. These values were incorrectly reported in a previous abstract[9] as belonging to one of the potassium d,p reactions. Subsequent data showed however that these two groups are due to the nitrogen contamination on the front and back surfaces of the gold foil as mentioned above and are not due to potassium.

TABLE II. Q-values from $K^{39}(d,p)K^{40}$ and energy levels in K^{40}. The proton yield relative to the longest range group is given in the last column. The assignment of Q_6 to this reaction is uncertain.

	Q	Energy levels in K^{40}	Relative proton yield
Q_0	5.48±0.08 Mev	0 Mev	1.0
Q_1	4.67±0.09	0.81±0.03	1.1
Q_2	3.47±0.09	2.01±0.03	6.7
Q_3	2.92±0.10	2.56±0.05	2.4
Q_4	2.2 ±0.1	3.3 ±0.1	2.4
Q_5	1.8 ±0.1	3.7 ±0.1	3.8
Q_6	*1.3 ±0.1*	*4.2 ±0.1*	*7.4*
Q_7	0.7 ±0.1	4.8 ±0.1	6.5

PROTON YIELD FROM K^{39}

The proton yield from the $K^{39}(d,p)K^{40}$ reaction is shown in Fig. 2. The target for this curve was prepared from sample #346(a) (Table I) enriched to 96.5 percent in K^{39}. Comparison with Fig. 1 shows that the three most prominent long range groups belong to $K^{39}(d,p)K^{40}$ as previously assigned by Pollard.[1] An extensive search was made at longer ranges for additional groups but none were found, so the group with a peak at 88 cm is apparently due to the formation of K^{40} in the ground state. The Q-value corresponding to this group was calculated from the integral curve in Fig. 2. From this Q-value the mass difference between K^{40} and K^{39} may be calculated giving: $K^{40}-K^{39}=1.00070\pm0.00007$ mass units.

Excited states in the K^{40} nucleus were obtained from the several groups in the peaked curve (Fig. 2, solid curve), because the groups at ranges shorter than 88 cm correspond to the formation of K^{40} in excited states. The excitation energy and the Q-values of each level are listed in Table II.

In Fig. 2 the group structure at ranges less than 40 cm is badly distorted by the presence of oxygen. The potassium target used for this curve was allowed to oxidize. The two peaks due to $O^{16}(d,p)O^{17}$ are shown in Fig. 2 as the dashed curve and have been reduced by a

TABLE III. Q-values of $O^{16}(d,p)O^{17}$ obtained from oxidized K^{39} target. Q_1 is probably too high because Q_7 of $K^{39}(d,p)K^{40}$ falls at approximately the same range and was not resolved.

	Q	Energy levels in O^{17}	Relative proton yield
	This report		
Q_0	1.94±0.08 Mev	0 Mev	1.0
Q_1	1.13±0.10	0.81	1.14
	Heydenburg *et al.*[10]		
Q_0	1.90 Mev	0 Mev	
Q_1	0.99	0.90	

[9] V. L. Sailor, Phys. Rev. **75**, 1292 (1949).

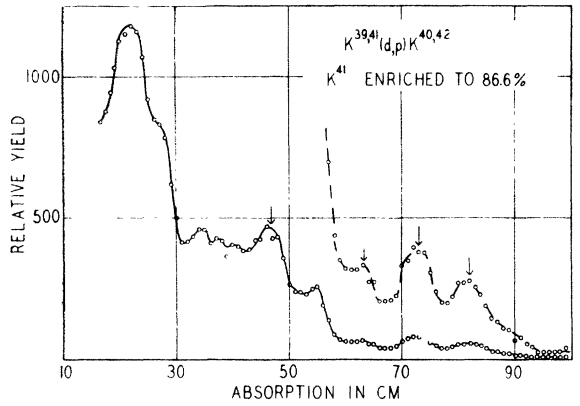

FIG. 3. The proton yield from a target enriched in K^{41} to 86.6 percent but containing also 13.3 percent of K^{39}. The arrows indicate the peaks of proton groups attributed to $K^{41}(d,p)K^{42}$. The dashed curve has been magnified by a factor of four.

factor of ten relative to the rest of the curve. The shorter range oxygen peak almost coincides with the potassium group Q_7 and is therefore somewhat distorted toward longer ranges. The $O^{16}(d,p)O^{17}$ reaction can be used as a reference reaction because it has been observed in many different experiments at many laboratories. Table III lists the Q-values calculated for the oxygen reaction from Fig. 2 and compares them with the results of Heydenburg *et al.*,[10] which are probably the most reliable values at present.

The energy level spacing in K^{40} is similar to the spacing found for other nuclei of odd Z and even A. For example Al^{28} obtained from $Al^{27}(d,p)Al^{28}$, and Cl^{38} from $Cl^{37}(d,p)Cl^{38}$ show spacings of approximately 1 Mev between the lowest levels with the spacing between levels decreasing rapidly with increasing excitation.[11,12]

The most striking feature of the proton yield curve is the relative intensity of the four longest range groups. The ratios of the proton yields for the groups are: Q_0 (88 cm):Q_1(75 cm):Q_2 (56 cm):Q_3 (48 cm)=1:1.1:6.7:2.4. If the requirements for the conservation of angular momentum are considered for the *ground* state it is seen that the incident deuterons or the emerging protons (or both) must have large orbital angular momentum, because the spin of K^{39} is $\frac{3}{2}$ and the spin of K^{40} ground state is 4. Thus the cross section for the production of K^{40} in the ground state is reduced. This suggests that the level Q_2 has a spin such that the conservation of angular momentum is most easily satisfied; i.e., a spin of 2, which would permit an s-deuteron to produce an s-proton. Similar reasoning indicates that the spin of the level Q_1 is 3, and of Q_3 is 1.

PROTON YIELD FROM $K^{40}(d,p)K^{41}$

The mass difference between K^{40} and K^{41} computed from several related nuclear reactions[6] is about 0.9981 mass units, indicating that the most energetic protons from the $K^{40}(d,p)K^{41}$ reaction would have a range between 120 and 150 cm for bombarding deuterons of 3.9 Mev. Because of the absence of other protons at such a long range the presence of the $K^{40}(d,p)K^{41}$ protons could be detected with this apparatus if as much as 0.1 percent of K^{40} were in the target (assuming that the cross section for the reaction is of the same order of magnitude as for the $K^{39}(d,p)K^{40}$ reaction). A careful search for the long range protons was made using a target prepared from sample #346(a) which contained $0.6\ ^{+0.2}_{-0.6}$ percent K^{40}. No protons were found. It appears that a target with greater enrichment of K^{40} will be necessary to verify the reaction.

PROTON YIELD FROM $K^{41}(d,p)K^{42}$

The occurrence of the $K^{41}(d,p)K^{42}$ reaction has been verified many times by the presence of the radioactivity of K^{42} in the irradiated target. Q-values from this reaction have not been obtained previously because of the low abundance of K^{41} in targets of natural potassium. Sample #348(a) enriched in K^{41} to 86.6 percent was used as a target to obtain the Q-values. The proton yield resulting from this target is shown in Fig. 3. Because the target contained 13.3 percent of K^{39} it was necessary to subtract out the yield due to this isotope. This operation was performed by normalizing Fig. 2 to fit the 56-cm peak in Fig. 3 and then subtracting.

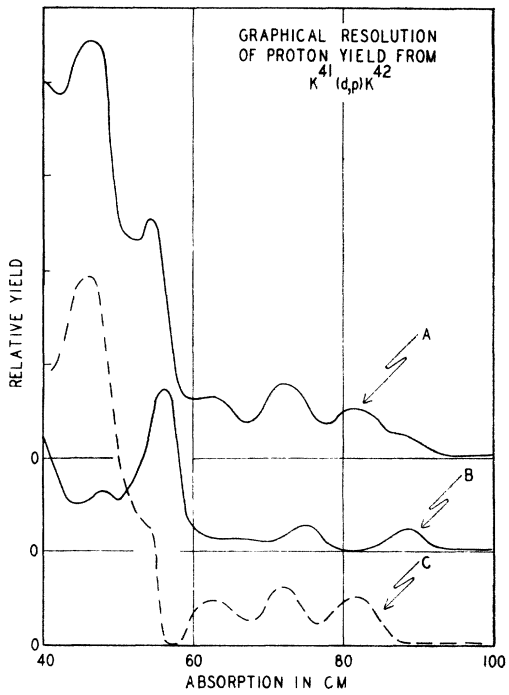

FIG. 4. Graphical resolution to about $K^{41}(d,p)K^{42}$ proton yield. Curve B (from Fig. 2) was subtracted from curve A (from Fig. 3) to obtain curve C, which is the proton yield of $K^{41}(d,p)K^{42}$. Curve B was normalized to A at the peak occurring at 56 cm.

[10] Heydenburg, Inglis, Whitehead, and Hafner, Phys. Rev. **75**, 1147 (1949).
[11] Pollard, Sailor, and Wyly, Phys. Rev. **75**, 725 (1949).
[12] E. F. Schrader and E. C. Pollard, Phys. Rev. **59**, 277 (1941).

The resultant curve is shown in Fig. 4 (curve C) and is the proton yield attributed to $K^{41}(d,p)K^{42}$. The Q-values calculated from this curve are less accurate because of the graphical subtraction. An additional curve of the $K^{41}(d,p)K^{42}$ spectrum of protons was obtained by comparing the yield from a target of natural KCl with the yield from a KCl target enriched in K^{41}. This curve verified the results shown in Fig. 4, curve C.

The Q-values from $K^{41}(d,p)K^{42}$ are listed in Table IV. The mass difference between K^{42} and K^{41} computed from Q_0 is $K^{42}-K^{41}=1.00109\pm0.00010$ mass units.

The spacings between the levels in K^{42} are similar to those in K^{40} and the relative yields of the proton groups show similar variations. Many more levels in K^{42} exist above Q_3 but the proton spectrum was so complicated that they could not be accurately located with the available resolution.

TABLE IV. Q-values from $K^{41}(d,p)K^{42}$ and energy levels in K^{42}.

	Q	Excitation of K^{42}	Relative proton yield
Q_0	5.12±0.10 Mev	0 Mev	1
Q_1	4.50±0.12	0.62±0.07	1.2
Q_2	3.94±0.12	1.18±0.07	0.9
Q_3	3.15±0.18	1.97±0.15	0.9
Q_4	2.83±0.12	2.29±0.07	7.5

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Low Energy Beta-Ray Spectra: Pm^{147} S^{35} *

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The beta-spectra of S^{35} and $_{61}Pm^{147}$ have been measured in order to study further the nature of any low energy deviation from the Fermi theory of beta-decay. Measurements were made with thin, relatively uniform sources in both the 40-cm radius of curvature spectrometer and also in a small 180 degree focusing Helmholtz coil spectrometer designed specifically for low energy spectra. The thinnest sources were less than 10 micrograms/cm². Using Zapon counter windows ranging from 15 to 3 micrograms/cm² and also a windowless counter technique, Fermi plots were obtained which showed how the measured distribution of particles at low energy depends on both source and counter window thickness.

Favorable experimental conditions yielded a straight line Fermi plot for Pm^{147} above 8 kev. Less favorable conditions resulted in a straight line plot for S^{35} down to at least 50 kev. Thus, S^{35}, which is allowed, and Pm^{147}, which is probably once forbidden, are found to have spectra of the allowed shape. It is concluded that under very favorable experimental conditions there is probably no real disagreement between the observed momentum distribution and that predicted for an allowed transition by the Fermi theory. On the basis of an improved calibration, the following end points are obtained: Pm^{147}, 223.2±0.5 kev and S^{35}, 167.0±0.5 kev.

I. INTRODUCTION

RECENT experimental investigations,[1-4] particularly of the beta-ray spectra of Cu^{64}, Cu^{61}, N^{13}, and S^{35}, have suggested possible deviations from the Fermi theory in the low energy region. Some experiments[3,5-7] indicated that this excess of low energy particles might be a function of source thickness. Other experiments showed no observable increase in the number of low energy particles as the thickness of the source was varied.[2] Still other investigations[8-10] resulted in straight line Fermi plots extending to quite low energies even when extremely thick sources were employed.

Further studies in the low energy region were undertaken in order to clarify this question and in order to try to determine the extent to which instrumentation may distort the shape of a spectrum. Some instrumental effects which may influence the shape of a spectrum at low energies are: source thickness and uniformity, source backing, scattering from the residual gas and walls of the spectrometer chamber, distortion of the analyzing field by saturation or remanence, counter window thickness, and counter response as a function of particle energy. In the present investigation, thin and relatively uniform sources deposited on extremely thin backings were employed, and the experiments were designed so as to make the other possible distortion factors negligible. Detailed measurements were made on the spectra of the allowed S^{35} transition (87 day) and the empirically once forbidden Pm^{147} transition (3.7 year) under favorable experimental conditions in both the 40-cm radius of curvature spectrometer[11] and in a small Helmholtz coil spectrometer designed specifically for low energy measurements.

* Assisted by the Joint Program of ONR and AEC.
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