Decay of the 185-μsec Isomer in Ho^{166}

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(Received 2 July 1965)

The 185-μsec isomer in Ho^{166} has been produced by the Ho^{165} (d,p) reaction and the delayed radiation studied with γ scintillation spectrometers and a magnetic β spectrometer. The results have been combined with high-resolution measurements of the γ rays from thermal-neutron capture in Ho^{165}, using a curved-crystal spectrometer. A $K^\pi=3^+$ level at 190.90 keV decays by two K-forbidden $E1$ transitions of 19 and 136.66 keV to the 3^- and 2^- members, respectively, of the $K^\pi=0^-$ ground-state rotational band of Ho^{166}.

INTRODUCTION

TWO β-emitting species of Ho^{166} are known.[1] A 27-h activity of $K^\pi=0^-$ with the Nilsson assignment[2] $(Nn_z\Lambda)\Omega^\pi$, $p(523)\frac{7}{2}^- - n(633)\frac{7}{2}^+$, and a 1200-yr activity[3] with the assignment $K^\pi=7^-$ resulting from the coupling $p(523)\frac{7}{2}^- + n(633)\frac{7}{2}^+$. In addition, Alexander and Bredel[4] have found that an isomer with a half-life of ~ 200 μsec is abundantly populated by thermal neutron capture in Ho^{165} which has spin $\frac{7}{2}$. The spin of the isomer is thus likely to lie between 0 and 7, with 3 or 4 as the most probable values. Struble *et al.*[5] have interpreted their high-resolution (d,p) measurements on Ho^{165} targets in terms of a level diagram for Ho^{166}, which exhibits an irregular rotational band built on the 0^- ground state, a band built on the 7^- state at 12 keV, and a 3^+ $p(523)\frac{7}{2}^- - n(521)\frac{1}{2}^-$ band, starting at 190 keV, plus higher lying bands. The structure of the 0^- band is established by several authors[6,7] who have studied the β decay of Dy^{166}.

In this report we present measurements of γ rays and conversion electrons emitted in the decay of the isomeric state, which is produced by the (d,p) reaction on Ho^{165}. These measurements are compared with γ-ray spectra from thermal neutron capture in Ho^{165}, recorded with a curved-crystal spectrometer. It is concluded that a large proportion of the capture events leads to the isomer, and that this is a $K^\pi=3^+$ level at 190.90 keV. The resulting assignment of three of the prominent low-energy γ rays from the $Ho^{165}(n,\gamma)$ spectrum to low-lying levels in Ho^{166} strengthens the base on which a more detailed interpretation of the (n,γ) and (d,p) spectra can be carried out. (See Motz *et al.*[8]).

EXPERIMENTAL

The isomer was produced by irradiation of a 1-mg/cm² metallic foil of holmium (99.9%, monoisotopic) with pulsed beams of 6–12-MeV deuterons from the tandem Van de Graaff accelerator of The Niels Bohr Institute. Each irradiation period of 200 μsec was followed by a 200–2000-μsec intermission, during which the decaying radiation and the long-lived background could be recorded, one after the other. The γ rays were detected with a 3.7×3.7-cm NaI crystal and a smaller Be-window NaI crystal; the conversion electrons were recorded in a point-by-point manner with a six-gap β spectrometer[9] installed on the beam line. The electronic equipment comprised electrostatic beam deflectors, two oscilloscope time units, a slow time-to-amplitude converter[10] and a 512-channel pulse-height analyzer, with its memory divided into two halves, corresponding to decaying and background radiation, respectively. (A somewhat more detailed description is given elsewhere.[11])

The neutron-capture γ rays of Ho^{166} have been measured with the curved-crystal spectrometer[12] of the DR-3 reactor at Risø. The spectrum emitted from a holmium source ($\sim$60 mg Ho_2O_3, purity 99.8%) was detected in the energy range from 23 to 860 keV. The intense lines have been measured point by point, in order to obtain accurate energy values.[13] More than 350 transitions have been found with energies from 38 to 735 keV. The observed line width was 11 seconds of arc, corresponding to a resolution of $\Delta E/E \simeq 2.1\times E$ (keV)$\times 10^{-5}/n$ (n=order of reflexion). The 137-, 117-, 82-, and 54-keV lines have been measured in the respective fifth, fifth, second and second order of reflexion at resolutions of 0.06, 0.05, 0.09, and 0.06%.

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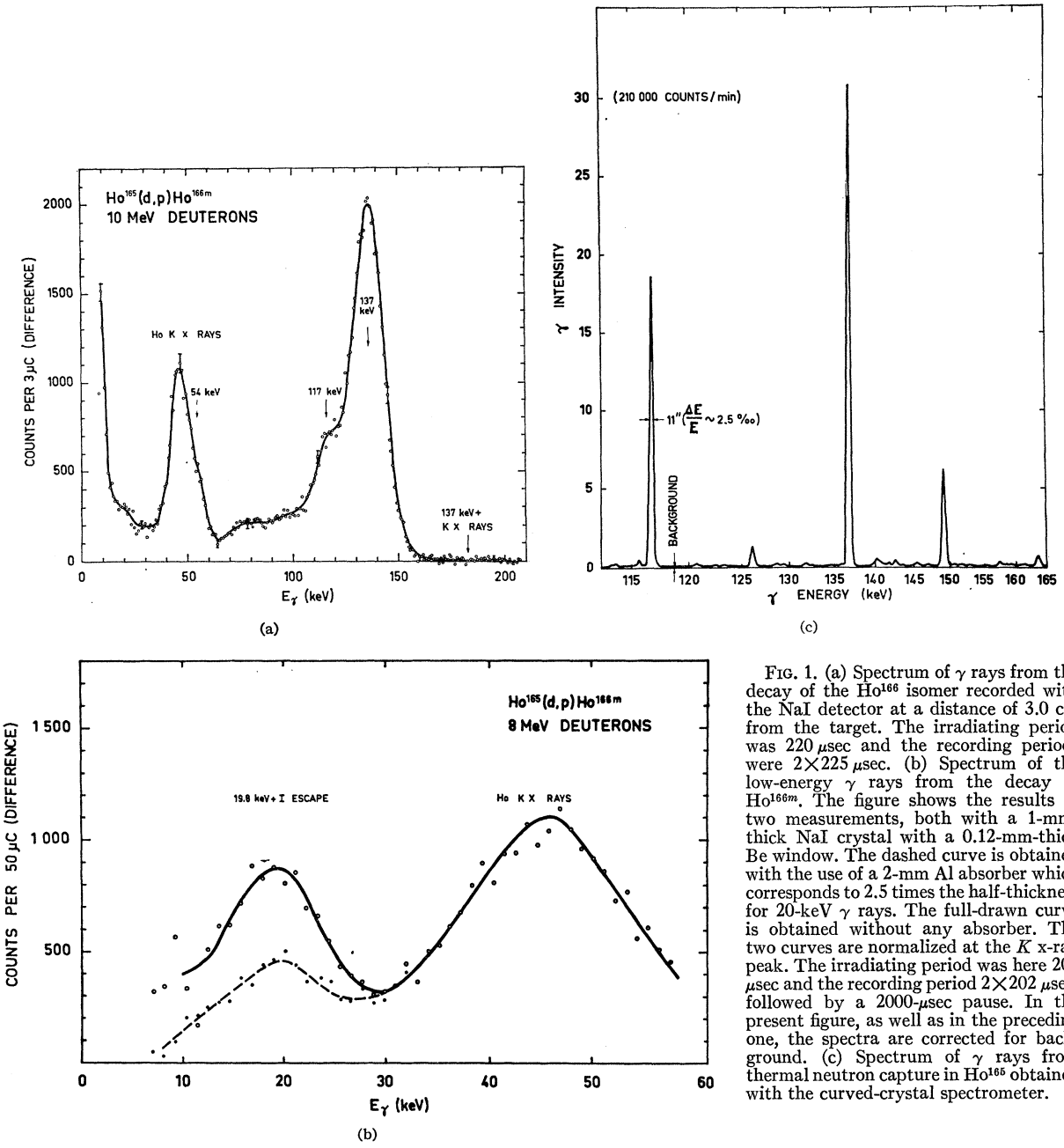

FIG. 1. (a) Spectrum of γ rays from the decay of the Ho^{166} isomer recorded with the NaI detector at a distance of 3.0 cm from the target. The irradiating period was 220 μsec and the recording periods were 2×225 μsec. (b) Spectrum of the low-energy γ rays from the decay of Ho^{166m}. The figure shows the results of two measurements, both with a 1-mm-thick NaI crystal with a 0.12-mm-thick Be window. The dashed curve is obtained with the use of a 2-mm Al absorber which corresponds to 2.5 times the half-thickness for 20-keV γ rays. The full-drawn curve is obtained without any absorber. The two curves are normalized at the K x-ray peak. The irradiating period was here 200 μsec and the recording period 2×202 μsec, followed by a 2000-μsec pause. In the present figure, as well as in the preceding one, the spectra are corrected for background. (c) Spectrum of γ rays from thermal neutron capture in Ho^{165} obtained with the curved-crystal spectrometer.

RESULTS

The NaI scintillation spectrum recorded in the 3.7×3.7 cm crystal is shown in Fig. 1(a). The peak to the right is clearly composed of two γ rays of energies about 117 and 137 keV. Beyond this double peak the count rate drops to zero. With the photopeak efficiency and solid angle used, the absence of sum peaks excludes that the two γ rays are coincident with each other or with K x rays.

The energy difference between the two γ rays is about 20 keV. Measurements with a Be-window crystal demonstrate the existence of a third γ ray of this energy [Fig. 1(b)]. A section of the neutron-capture γ-ray spectrum, containing two of the most intense lines observed, is shown in Fig. 1(c). The correspondence in energy of the lines in Fig. 1(a) and 1(c), together with the observation[14] that the isomer is produced in about one-half of the capture events, permits identification of the lines and establishes the energies within an uncertainty of a few eV.

[14] H. F. Brinckmann, Zentralinstitut für Kernphysik, Rossendorf bei Dresden, Report No. ZfK-RN16, 1962 (unpublished).

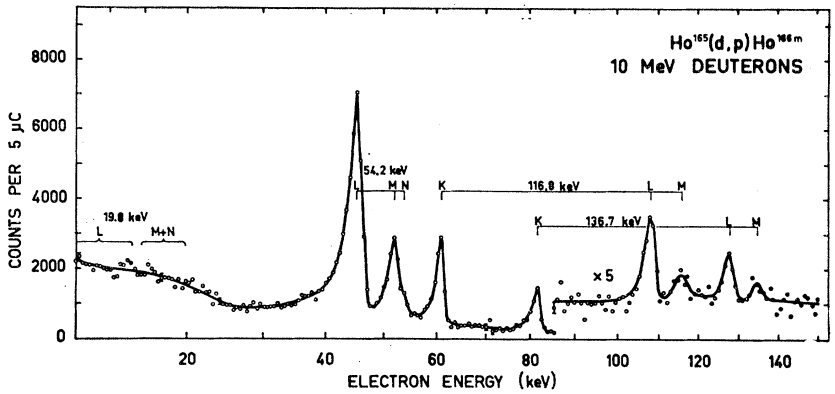

FIG. 2. Spectrum of conversion electrons from the Ho^{166} isomer.

The conversion electron spectrum of the isomer is shown in Fig. 2. Besides the 117- and 137-keV transitions a strong 54 keV transition is established. It is identified as the 54.22-keV $E2$ transition observed by Geiger *et al.*[6] in the decay of Dy^{166}, and as the 54.239-keV γ ray seen in the (n,γ) spectrum. The quantitative results on the isomeric decay are summarized in Table I. From these results it is possible to derive the multipolarities and the total intensities of all the transitions, with the exception of the well-known 54.2-keV $E2$ transition.

The decay period of the 117+137-keV γ-ray peak and of the 117-keV K-conversion line was measured, Fig. 3. The mean value is 185 ± 15 μsec.

The partial (d,p) cross section for the population of the isomer is about 15 mb at 10 MeV deuteron energy.

The low-energy lines from the (n,γ) reaction, observed with the bent-crystal spectrometer and thought to be relevant to the present investigation, are listed in Table II. The relative intensities are given in column 3. The determination of the absolute intensities, column 5, is based on the following considerations:

Absolute γ intensities of the 117- and 137-keV transitions have been determined previously by Orecher.[15] He also quotes a rough number for the intensity of the weak 82-keV line.

We obtain directly the absolute intensities of this 82-keV transition and the 54-keV line by comparing our relative values $I_{\gamma\text{rel}}$ with Orecher's data. Orecher used a cross section of 64 b$\pm$5% given by Pomerance,[16] who based his measurements on a cross section of 95 b for gold. The determination of the neutron flux during Orecher's experiment was performed[17] on the basis of a value of 98.7 ± 0.35 b for the cross section of gold.[18] Therefore, Orecher's absolute intensities must be multiplied by 0.96. Consequently, our relative numbers should be divided by $f=3.4\pm0.4$ to give absolute intensities $I_\gamma/100n$, the number of γ quanta per 100 captured neutrons.

The observation of the 80.5-keV $E2$ ground-state transition in Er^{166}, which is excited in the β decay of the 27-h ground state of Ho^{166}, permits an independent method for the calculation of the absolute intensity. The relative intensity of the 80.5-keV line was measured to be 22.6 ± 2.3. This number was obtained during a three-week continuous irradiation of the Ho^{165} source with neutrons, about one week after the start of the reactor.

The partial cross section for the formation of the Ho^{166} ground state has been reported to be 59.6 b $\pm$20%.[19] The corrected value for the total absorption cross section (66.5 b$\pm$5%) includes the excitation of the long-lived isomer[20] in Ho^{166}. The contribution in intensity of the 80.5-keV line from the decay of the long-lived isomer can be neglected because of its long half-life[3] and its partial cross section being small compared with that for the population of the Ho^{166} ground state.

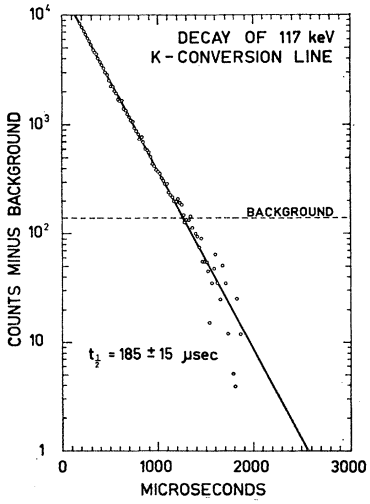

FIG. 3. Decay curve obtained with the aid of the time-to-amplitude converter. The background has been subtracted.

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TABLE I. Summary of results on the isomeric decay in Ho^{166}.

E_γ (keV)	I_K (%)	I_L (%)	I_γ (%)	αK expt.	αK theory	αL expt.	αL theory	Multipole order	I_{tot} (%)
19.8		$\ll 130$	7±3			$\ll 22$	3.6	$E1$	40±18[a]
K x rays			21±4[b]						
54.2		73±15	3±0.5[c]			...	22	$E2$	100
116.8	16±3	3±0.6	13±5	1.2	1.45	0.23	0.20	$M1$	33±8
136.7	7±2	1.1±0.2	50±10	0.14	0.12	0.022	0.017	$E1$	59±12

[a] From I_γ, assuming $E1$.
[b] The γ spectrum is normalized against the conversion-electron spectrum by the assumption of $I_{Kx}+I_\gamma(54.2)=0.93\times\Sigma\, I_K+I_\gamma(54.2)$.
[c] Calculated from the intensity of the L line using the theoretical α_L for an $E2$ transition.

Graham *et al.*[21] report 48.4% for the total intensity of the 80.5-keV line in Er^{166}. The measured intensity of the K- and L-conversion electron lines of this transition are: $I_K(80.5)=10.1\%$ and $I_L(80.5)=25.3\%$.[22] The calculated L-conversion coefficient of the 80.5-keV $E2$-transition is $\alpha_L=3.93$, if we average between the values 3.95 according to Sliv[23] and the number 3.90 taken from Rose.[24] The theoretical K-conversion coefficient $\alpha_K=1.59$ is a little less than the average $\alpha_K=1.82\pm0.15$ of several experimental numbers.[25–27] Therefore, we put $\alpha_K=1.70\pm0.17$ and calculate from Graham's conversion-electron intensity I_K the γ intensity of the 80.5-keV transition to be $I_\gamma(80.5)=6.0\%$. Similarly, we get $I_L/\alpha L=I_\gamma(80.5)\simeq 6.4\%$. Thus the γ intensity of the 80.5-keV line is estimated to be $(6.2\pm0.8)\%$ with respect to the decay rate of the 27-h ground state. The probability for the population of the Ho^{166} ground state is $p=(59.6\text{ b}\pm20\%)/(66.5\text{ b}\pm5\%)=0.90_{-0.20}^{+0.10}$. Therefore, this second method yields a factor $f=22.6/[p\times I_\gamma(80.5)\times100]\simeq 4.0_{+1.0}^{-0.4}$. We adopt the mean of the two factors: $\bar{f}=3.7\pm0.5$.

The absolute intensities given in column 5 and the errors in column 6 of Table II are then calculated from the relative intensities according to the equation $I_\gamma/100n=I_{\gamma\text{rel}}/\bar{f}$.

TABLE II. Gamma transitions in Ho^{166} observed during the irradiation of Ho^{165} with thermal neutrons.

E_γ (keV)	dE_γ (eV)	$I_{\gamma\text{rel}}$	$dI_{\gamma\text{rel}}$	$I_\gamma/100n$	$dI_\gamma/100n$
54.239	2	8.1	1.5	2.2	0.5
82.469	3	3.4	0.4	0.9	0.15
108.432	...	<0.05	...	<0.014	...
116.835	3	60	5	16	2.5
136.662	4	100	6	27	4

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DISCUSSION

The decay scheme of the isomer is shown in Fig. 4. The 54-keV $E2$ transition is placed between the 2^- level and the 0^- ground state of Ho^{166} (cf. Refs. 6 and 7). Since the 117-keV $M1$ plus 20-keV $E1$ transitions have equal intensity and add to the same energy as the 137-keV $E1$ transition, the three transitions are placed as cascade and cross-over transitions populating the 2^- level. The in-out intensity balance for the 2^- state is consistent with this. A spin and parity of 1^+, 2^+, or 3^+ is possible with the observed multipolarities, but only a 3^+ assignment can explain the absence of any 108.432-keV ($E1$) transition to the well-known 1^- state at 82.45 keV. The 171.074-keV state is regarded as the 3^- member of the irregular 0^- rotational band.

The decay scheme is fully consistent with the band diagram for Ho^{166} proposed by Struble *et al.*[5] on the basis of (d,p) measurements with a high-resolution heavy-particle spectrograph.

The 20- and 137-keV $E1$-transitions depopulating the isomeric level are hindered 1.1×10^8 times and 5×10^9 times, respectively, relative to the Weisskopf

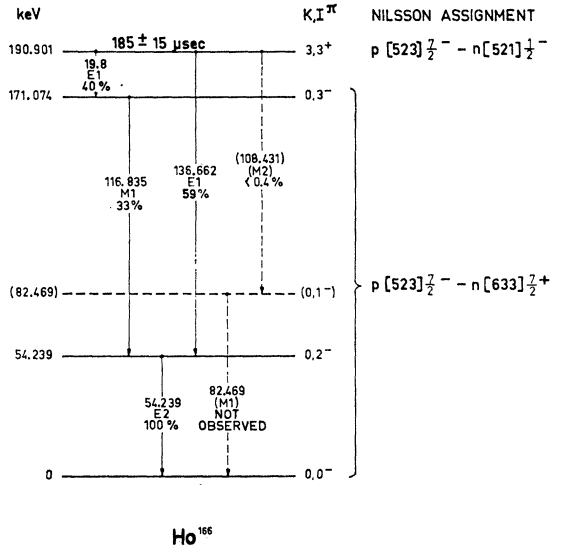

FIG. 4. Decay scheme of the Ho^{166} isomer. The Nilsson assignments given to the right are based on general systematics and on the stripping measurements of Struble *et al.* (Ref. 5).

single-particle estimate.[28] These hindrance factors seem rather high, although not unreasonably high, for twice K-forbidden $E1$ transitions. No $M2$ transition from the 3^+ to the 1^- level has been observed. The lowest limit can be derived from the capture γ-ray spectrum, Table II. The intensity of the 108.432 $M2$ γ ray is less than 0.014%, from which a partial half-life longer than 0.9 sec is derived. The hindrance factor[28] is consequently greater than 1.2×10^4 for this once K-forbidden $M2$ transition.

[28] A. H. Wapstra, G. J. Nijgh, and R. van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1959).

From a comparison of the intensities in Tables I and II, one obtains

$$\sigma_1=(0.58\pm0.08)\sigma_T,$$

where σ_1 is the partial cross section for the formation of the isomer in the (n,γ) reaction and σ_T is the total capture cross section. The agreement with Brinckmann's[14] value 0.48 is satisfactory.

ACKNOWLEDGMENTS

The authors wish to thank Civilingeniør Mogens Olesen and Civilingeniør Per Høy-Christensen for their support in providing the experimental facilities at the Tandem Van de Graaff Laboratory.

PHYSICAL REVIEW VOLUME 140, NUMBER 4B 22 NOVEMBER 1965

Nuclear Spin and Magnetic Moment of Ar^{37}†

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(Received 12 April 1965)

The hyperfine structure of the $3p^54s$-$3p^54p$ lines of Ar^{37} I, studied in an electrodeless discharge, has been used to determine the nuclear spin $I(Ar^{37})=\frac{3}{2}$, and the nuclear magnetic moment $\mu(Ar^{37})=(+0.95\pm0.20)$ nm. The Ar^{37}-Ar^{40} isotope shift, which has been completely resolved for only one line, tends generally to confirm earlier work.

EXPERIMENTAL

THE absence of any electronic magnetic moment in the atomic ground state and the small amount of material available make high-resolution optical spectroscopy the most practical means for studying the nuclear moments of Ar^{37}.

The Ar^{37} was produced by neutron irradiation of optical-quality crystals of CaF_2. One sample was irradiated in the Brookhaven graphite reactor and one in the Oak Ridge high-flux reactor; the latter yielded the greater concentration of Ar^{37}.

The reaction producing the Ar^{37} was $Ca^{40}+n\rightarrow Ar^{37}+\alpha$. The fluorine underwent the reaction $F^{19}+n\rightarrow Ne^{20}+\beta^-$, which has a much higher cross section than the (n,α) reaction. Differential cleanup of Ar in the presence of large quantities of the other gases made it desirable to separate the Ar from the He and the Ne^{20}. The gas purification involved the following steps: heating of the irradiated CaF_2 in high vacuum to release the trapped gases, adsorption of the Ar^{37} on charcoal cooled with liquid nitrogen, pumping off the He and Ne while the Ar^{37} remained trapped on the charcoal, compressing the Ar^{37} into the quartz electrodeless discharge tube to a pressure of about 3 mm Hg with a modified Toepler pump, and freezing out the Hg vapor with liquid nitrogen while sealing off the discharge tube. We are indebted to Dr. Raymond Davis for essential suggestions and advice in the preparation of the Ar^{37}.

The gas-handling system is shown schematically in Fig. 1(a) and the fused-silica electrodeless discharge tube in Fig. 1(b). The tube had a capacity of roughly 0.5 cm^3 and contained about one-half of the total Ar^{37} produced. About one-half of the total gas in the tube at first was Ar^{40}, whose origin was not determined but which probably came from the atmosphere through the silica while it was hot; the fraction of one per cent of other isotopes would have escaped notice.

The tube was operated submerged in a Dewar with a clear side window. It was excited by a Raytheon 2450-Mc/sec diathermy unit. The high-frequency exci-

† Supported in part by the Research Committee of the Graduate School from funds supplied by the Wisconsin Alumini Research Foundation, by a grant from the National Science Foundation, by the Office of Ordinance Research, and by the U. S. Atomic Energy Commission. This paper substantially comprises the principal part of the 1960 Wisconsin Ph.D. thesis of M. M. Robertson. Microfilm copies of the thesis may be obtained from University Microfilms, 313 North First Street, Ann Arbor, Michigan.

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