vibration corrective term, which would seem to be a reasonable extension of the model, would move the 4^+ state in the right direction to agree with experiment.[47]

In the simplest approximation the models of Scharff-Goldhaber and Weneser and of Wilets and Jean predict that the quantity R should be 2. The fact that the observed values for R are mostly somewhat less than 2 is probably best interpreted as an indication that the models oversimplify the actual situation.

The model of Davydov and Filippov makes quantitative predictions for both R and the ratio of the cross-over to cascade $E2$ decay of the second 2^+ state. Van Patter[48] has collected all available information of $E2$ transition rates in nuclei and has made comparisons with the predictions of the Davydov-Filippov model. Fairly good over-all agreement is found. Preliminary values from the measurements reported here were included in this survey. In Table VI we have listed our final values and compared these to the predictions of the Davydov-Filippov model. There is generally good agreement.

It is concluded that although the available information on the type of nuclei under discussion supports a collective model interpretation, it is, at present, difficult to draw conclusions concerning the shape of the nuclear potential energy surface governing this collective motion.

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Nuclear Spins of Thulium-166 and 167†

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The spins of 7.7 hour thulium-166 and 9.6 day thulium-167 have been measured by the atomic-beam magnetic resonance method. Spin values are Tm^{166}, $I=2$; Tm^{167}, $I=\frac{1}{2}$.

INTRODUCTION

Measurements of ground-state properties of nuclei in the region $150<A<190$ are especially interesting because of relatively large nuclear deformations with consequent collective nuclear effects. These spin measurements are the beginning of a program of investigation at this laboratory of spins and hyperfine structure in this region.

EXPERIMENTAL PROCEDURE

Thulium-166 and 167 were produced both by $(\alpha,3n)$ and $(\alpha,2n)$ reactions on 100% holmium-165 and by (p,n) reactions on 33% erbium-166 and 23% erbium-167. The bombardments of holmium were made on the Brookhaven cyclotron and the erbium bombardments were made on the Princeton cyclotron. The alpha bombardments were more successful from the standpoint of the amount of activity produced. An alpha bombardment of 13 microampere-hours at 40 Mev produces activity sufficient for thirty five-minute exposures, each with beam counting rates of about 2000 to 3000 counts per minute.

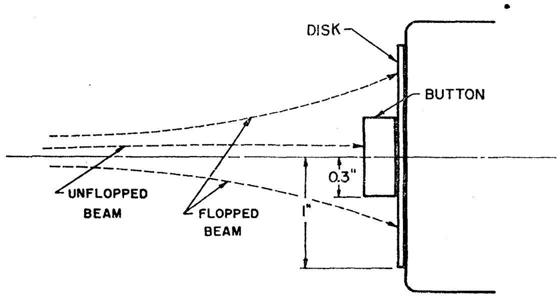

Fig. 1. Button and disk arrangement for collection of thulium atoms. Beam trajectories are schematic.

The radioactive material, either foil or metal filings, was placed in small cylindrical molybdenum ovens which were vacuum loaded and heated by electron bombardment. Beams were produced by evaporating the more volatile thulium from holmium at a brightness temperature of about 1075°C.

The atomic beam machine used was the focusing six-pole magnet apparatus described elsewhere.[1] A type of flop-in detection was used which automatically compensates for variations in beam strength. This method utilizes collection simultaneously on a copper button of 0.6-inch diameter and a copper disk of 2.0-inch diameter arranged as in Fig. 1. The atoms which have undergone appropriate $\Delta F=0$ transitions are collected on the disk, and the main beam on the center button. Designating counts per minute (total counts minus counter background) on the disk as O and counts

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per minute on the button as I, one may form the ratio O/I. For nonresonance conditions with thulium-166 this ratio normally had the approximate value 0.050, and at resonance rose to values from 0.10 to 0.20. These values of the ratio were insensitive to any but the largest fluctuations in the main beam.

Carefully cleaned copper at room temperature was found to collect the thulium atoms reproducibly. Other materials tried, including cooled copper and flamed platinum, gave essentially similar results. Buttons and disks were separately counted in standard thin-crystal NaI scintillation counter systems.

RESULTS

The approximately 8-hour activity produced by alpha bombardment of holmium has been quite definitely assigned to Tm^{166}.[2] We have observed this isotope to have a spin of 2 as indicated by Table I. Table I records, in the case of $I=2$, the observed O/I (background not subtracted) for the peak of a resonance curve based on several experimental points. For thulium, with the known atomic J of 7/2,[3] and a given value of I, resonances are expected for several different F's at each value of the static field. The values of frequency indicated in Table I are the values to be expected on the basis of the g_J for thulium as measured by Lindgren *et al.*[4] As indicated in Table I, at $\mu_0 H/2h$ $=0.35$ to 0.37, Mc/sec, resonances were found at all four of the distinct frequencies associated with $I=2$. At this value of $\mu_0 H/2h$ a search at a selection of frequencies corresponding to other values of I yielded O/I values equal, within statistics, to the no-resonance level for the run involved. At both $\mu_0 H/2h=0.550$ and 1.007, $I=2$ resonances were looked for, and observed, at three separate frequencies corresponding to different F levels.

Figure 2 shows a typical resonance pattern for $\mu_0 H/2h$ $=0.550$ Mc/sec. It is seen that the line width is ~ 30 kc/sec; there is no ambiguity in the assignment of spin 2 to these resonances. Figure 3 shows a decay curve of a spin 2 resonance point with nonresonant background subtracted. The association of spin 2 with the 7.7-hour activity is clear.

TABLE I. Summary of resonance data for Tm^{166}.

$\mu_0 H/2h$ (Mc/sec)	I	F	ν (Mc/sec)	O/I
0.374	2	11/2	0.545	0.165 ± 0.007
0.374	2	9/2	0.595	0.114 ± 0.006
0.348	2	7/2	0.640	0.125 ± 0.007
0.348	2	5/2	0.836	0.113 ± 0.007
0.374	3	5/2	0.612	0.052 ± 0.004
0.374	3	11/2	0.476	0.060 ± 0.004
0.348	4	11/2	0.348	0.065 ± 0.004
0.348	5	11/2	0.232	0.060 ± 0.004
0.348	1	7/2	0.740	0.046 ± 0.003
0.550	2	11/2	0.800	0.140 ± 0.003
0.550	2	9/2	0.877	0.119 ± 0.005
0.550	2	7/2	1.018	0.123 ± 0.002
1.007	2	11/2	1.461	0.103 ± 0.003
1.007	2	9/2	1.602	0.101 ± 0.003
1.007	2	7/2	1.860	0.090 ± 0.004

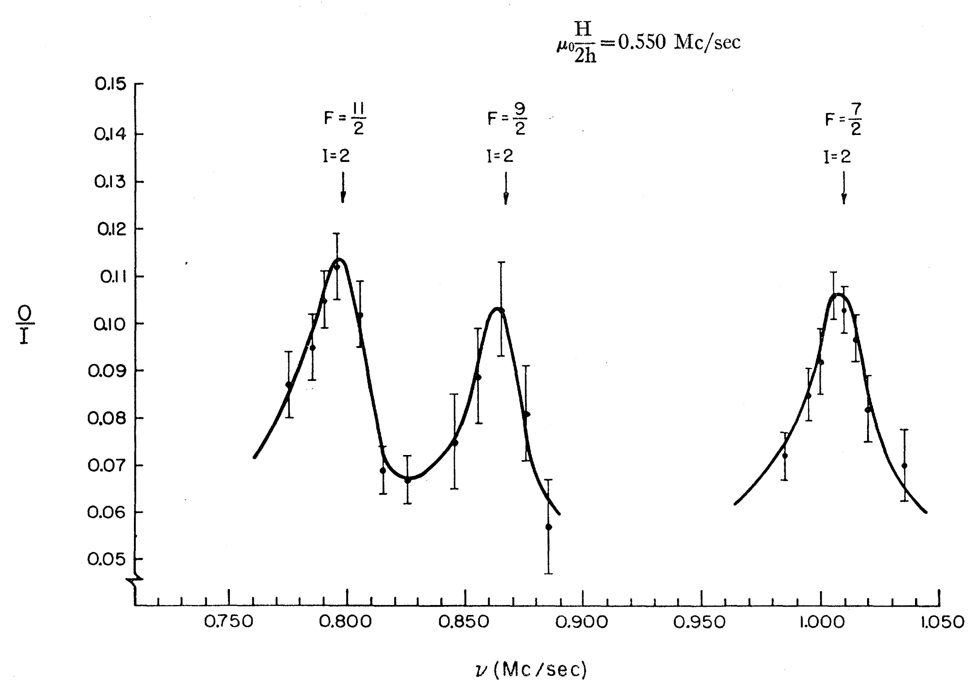

FIG. 2. Typical Tm^{166} resonances in the Zeeman region. Expected resonance positions for $I=2$; $F=11/2$, 9/2, and 7/2 are indicated.

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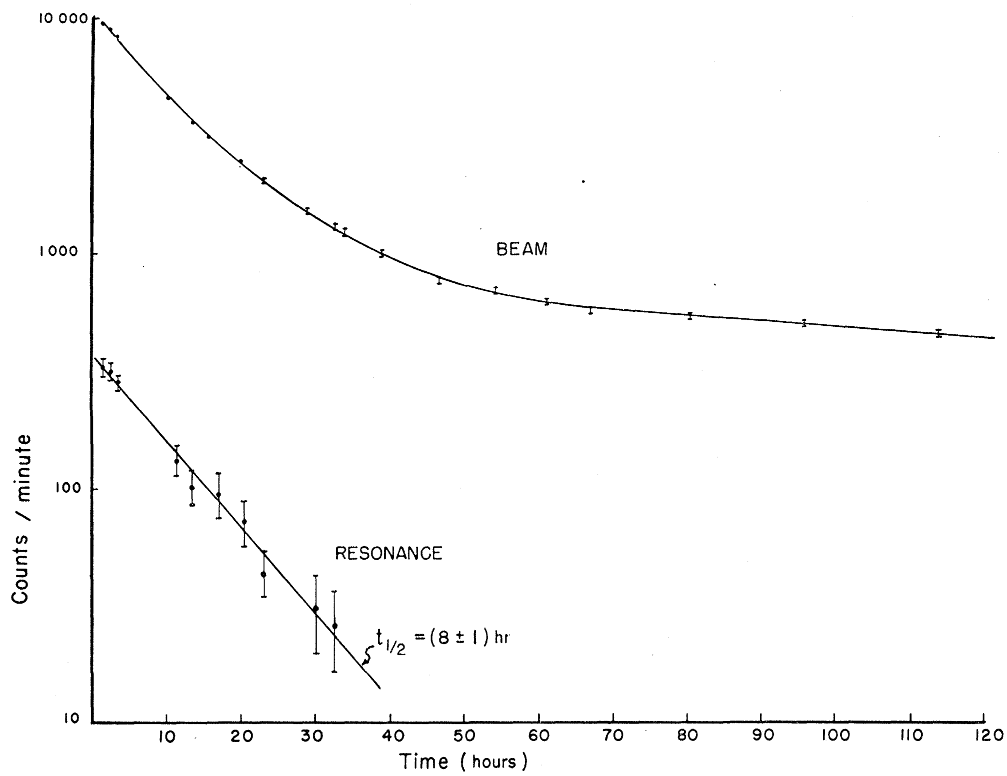

FIG. 3. Decay of beam and resonance activity for $I=2$, $F=11/2$ resonance in Tm^{166}. Errors shown are standard deviation.

Resonances for the longer half-life Tm^{167} were observed by exposing button and disk and then setting them aside for about 36 hours until the 8-hour Tm^{166} had largely decayed away. Resonances not visible immediately after the run were quite prominent when the counting was done at this later time. Table II gives a summary of the data from which we obtained a value of $\frac{1}{2}$ for the ground-state spin of Tm^{167}. The main

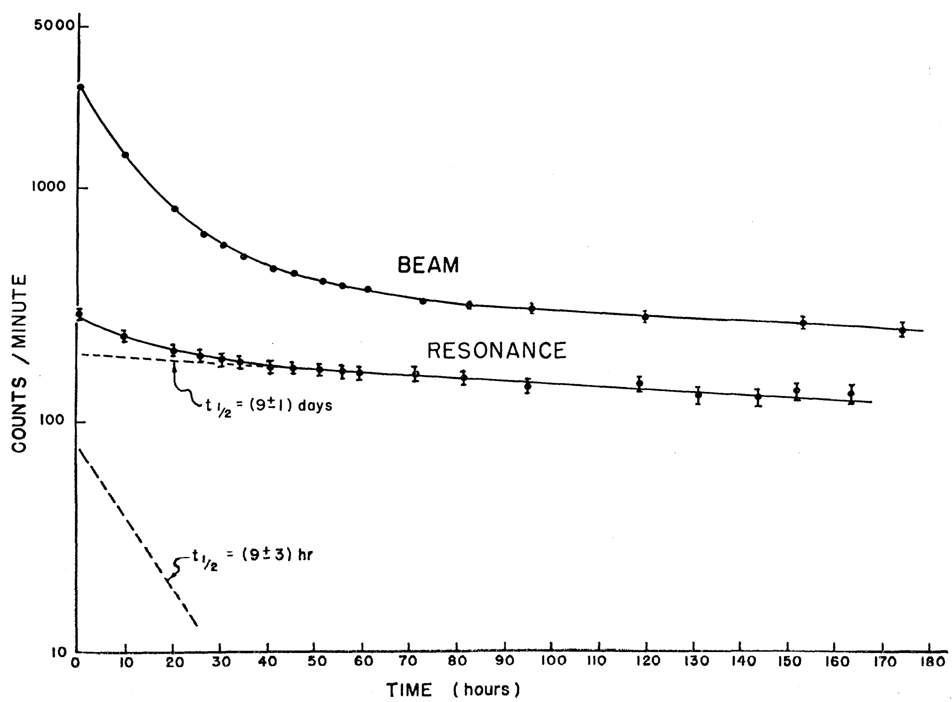

FIG. 4. Decay of beam and resonance activity for $I=1/2$, $F=4$ resonance in Tm^{167}. The solid resonance curve is the sum of the two dashed curves.

beam is found to consist almost entirely of ~8-hour and ~9-day components so that the half-life identification for the spin 1/2 activity is already fairly clear from the way in which the spin 1/2 O/I values "grow" with time. A direct determination of the half-life of the activity associated with spin 1/2 is shown in Fig. 4. It can be noticed that the curve labeled "resonance" shows some ~9-hour activity along with the more abundant 9-day activity. This is probably due to incomplete resolution of the $I=1/2$, $F=4$ peak from the $I=2$, $F=7/2$ peak. The main beam contains 85% 8-hour activity and 15% 9-day activity, while the "flopped" beam shows 29% 8-hour and 71% 9-day activity. We can thus clearly assign the spin $\frac{1}{2}$ to the 9-day activity. This activity has been definitely assigned to Tm^{167}.[5]

There is some indication of 29-hour Tm^{165} both in the beam and in the spin 1/2 resonance, but in both cases the amount of this activity is so small as to make it difficult to get more than a rough estimate of the amount of activity or the half-life. Further work must be done on the production of this activity before conclusive measurements can be made.

DISCUSSION

Interpretation of the observed spin of 2 for Tm^{166} is unsatisfactory using a jj coupling model for the odd neutron and odd proton with appropriate shell model configurations[6] for the proton and neutron. From the work of Mottelson and Nilsson,[7] however, one expects, in the case of large nuclear deformations, a state of $5/2-[523]$ (Mottelson's notation) for the 97th neutron; and a state of $1/2+[411]$ for the 69th proton. If we designate these orbitals as Ω_n and Ω_p, then the work of Bohr and Mottelson[8] shows that an odd-odd nucleus with these odd proton and neutron orbitals should have a ground state of spin of $I=|\Omega_p \pm \Omega_n|$ with the difference favored in the strong-coupling approximation, i.e., assuming strong coupling of each odd nucleon to the nuclear surface relative to its coupling to the other odd particle. This offers a satisfactory interpretation of the observed spin of 2 for Tm^{166}.

TABLE II. Summary of resonance data for Tm^{167}.

$\mu_0 H/2h$ (Mc/sec)	I	F	ν (Mc/sec)	O/I
0.383	1/2	3	0.983	0.215±0.040
0.383	1/2	4	0.760	0.410±0.040
0.682	1/2	3	1.851	0.133±0.020
0.682	1/2	4	1.440	0.150±0.010
1.038	1/2	3	2.665	0.112±0.020
1.038	1/2	4	2.073	0.164±0.020
1.038	3/2	4	1.895	0.058±0.006
1.038	3/2	5	1.658	0.055±0.006
1.038	5/2	6	1.382	0.052±0.006

While the spin 1/2 of Tm^{167} is not necessarily at odds with shell model predictions, it is definitely predicted by Mottelson and Nilsson. The $1/2+[411]$ state is the expected ground-state configuration for the 69th proton in all thulium isotopes.

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[8] A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **27**, No. 16 (1953).