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NUCLEAR SPINS OF NEODYMIUM-147 AND PROMETHIUM-147

A. Cabezas, I. Lindgren, E. Lipworth, R. Marrus
and M. Rubinstein

March 16, 1960
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University of California, Berkeley, California

March 16, 1960

Several investigations of the beta decay of Nd$^{147}$ to the excited states of Pm$^{147}$ have all been characterized by the failure to observe any direct beta transition to the ground state. The most intense beta line is a first-forbidden transition to the first excited state, which then decays to the ground state by an M1 gamma-ray transition. These observations are very difficult to explain, in view of a recent measurement, by paramagnetic resonance, of 5/2 for the ground-state spin of Nd$^{147}$, and the probable assignment of the ground-state of Pm$^{147}$ on the basis of the single-particle shell model. In the hope of improving our knowledge concerning this situation, we have undertaken to measure by the method of atomic beams, the spins of these isotopes. Our results confirm the paramagnetic resonance measurement of $I = 5/2$ for Nd$^{147}$ and yield $I = 7/2$ for Pm$^{147}$.

Prior atomic-beam measurements on stable neodymium have established the existence of a low-lying electronic state characterized by $J = 4$ and $g_J = 0.6$. Such an electronic state is coupled by the hyperfine-structure interaction to a nuclear spin of $I = 5/2$ to result in six nondegenerate levels of the total angular momentum ($F$) with Landé splitting factors given by

$$g_F = 0.603 \frac{F(F+1) + 55/4}{2F(F+1)},$$

where a term in the nuclear moment has been neglected.
In an atomic-beam apparatus with flop-in magnet geometry and with ordering of the $F$ states, transitions in the highest four $F$ states are observable. We have observed transitions in the $F = 13/2, 11/2, \text{ and } 9/2$ states at two magnetic fields. The $g_F$ values corresponding to the observed resonant frequencies are given in Table I along with the values predicted from Eq. (1). The discrepancy between the calculated and experimental $g_F$ values are probably due to quadratic shift resulting from a small hyperfine structure. The failure to observe the transition in the $F = 7/2$ state is probably due to the inability of the apparatus to refocus transitions for which $\Delta m_J = \pm 1$ for such low $g_J$ values.

The Nd$^{147}$ used in these runs was produced by neutron irradiation of commercially obtained material which was spectroscopically verified to be > 99% neodymium by weight. The method of production, together with the 11.5-day half-life established for the decay of a foil exposed to the neodymium beam at resonance and the $g_J$ value, uniquely determines the material to be Nd$^{147}$.

The Pm$^{147}$ used in these experiments was obtained in a weak HCl solution from Oak Ridge National Laboratory, and is guaranteed by the supplier to be > 99% pure. It is found that a satisfactory procedure for obtaining a beam of atomic promethium is to convert the material to the nitrate and mix the nitrate salt with an excess of lanthanum metal in the atomic-beam oven. The oven is then heated slowly up to operating temperature (about 1000°C), at which temperature a beam of atomic promethium is formed. The mechanism for the reaction is believed to be the initial decomposition (at low temperatures) of promethium nitrate to promethium oxide, then the reduction by the lanthanum (at some higher temperature) to the metal.
Since no prior information concerning the electronic ground state of promethium existed, a systematic search was initiated at low magnetic fields to observe resonances within the range of \( g \geq 0 \leq 2.0 \). Three resonances were observed, each of which was followed up in field to a maximum field of 38.2 gauss. Table II gives the \( g_F \) values corresponding to the observed resonant frequencies.

Interpretation of these data is based on the assumption that the ground-state configuration of promethium is \((4f)^5\). This hypothesis is supported by the fact that the ground-state configuration of \( ^{60}\text{Nd} \) and \( ^{62}\text{Sm} \) are known to be \((4f)^4\) and \((4f)^6\), respectively. A calculation of the electrostatic energies indicates that the Hund's Rule term \( 6\hbar \) is expected to be the ground state.

The spin-orbit interaction will split this term into six \( J \) states, with the \( J = 5/2 \) state lying lowest. An estimate of the separations can be obtained from the fine-structure splitting constant, measured in the optical spectrum of samarium to be about \( a_{4f} \approx 1.00 \text{ cm}^{-1} \). This indicates that the \( J = 5/2, 7/2, \) and \( 9/2 \) states should all be present in measurable amounts in the beam. The \( J = 7/2 \) and \( J = 9/2 \) states are easily refocused, and the \( L-S \) coupled \( g_J \) values are given in Table II and compared with the values inferred from the experimental data on the assumption \( I = 7/2 \). The state \( J = 5/2 \) is not observed, for the \( g_J \) value of atoms in this state is too low to allow refocusing in our apparatus.

In analogy with the other rare earth elements, the only possible ground state configuration besides \((4f)^5\) could be \((4f)^4\) \((5d)\). An attempt to exclude the possibility of a data fit for the configuration \((4f)^4\) \((5d)\) can be made on the following basis. Judd has calculated the electrostatic energies for \( f^4d \) and has shown that for this configuration the Hund's Rule term should lie lowest.
This term will give rise to states with all half-integral J values from
J = 11/2 through J = 21/2, of which several would be present in the beam. An
attempt has been made to fit the observed data in a g_J-independent way, i.e.,
by trying to fit ratios of the observed frequencies to ratios of the cosine factors
\[ \frac{F(F+1)+J(J+1)-I(I+1)}{2F(F+1)} \]
that arise from all possible F's corresponding to a given I and J. All values of I from 3/2 to 13/2 and all values of J from 3/2 to
21/2 were tried. No fit was obtained to all of the data for a single I and J.
We are also able to exclude the case of two resonances occurring in one electronic state,
and the third resonance occurring in another, except for the assigned I and
J's. Hence we conclude that the spin of Prm^{147} is 7/2, that (4f)^5 in the ground-
state configuration, and that L-S coupling to the Hund's Rule ground state
gives an excellent approximation to the observed g values. It is of interest
to note that the ground-state configuration of neptunium, the actinide homologue
of promethium, is (5f)^4 (6d)^1.8

The most plausible shell-model interpretation of the observed spin of
Prm^{147} is to assign the 61st proton to the level 1g 7/2. This implies that the
2d 5/2 level lies lower than the 1g 7/2 level. The measured spins of 59Pr^{147}
and 63Eu^{151,153} are all 5/2,9,10 which indicates that for these nuclei the
converse is true. The configuration (d5/2)^3 coupling to J = 7/2 is forbidden
by the Pauli principle.

The measured spins of the ground states of Nd^{147} and Prm^{147}, taken
along with the beta decay information, indicate that the spin of the first excited
state of Prm^{147} is either 5/2 or 7/2. It is difficult to understand the failure
to observe the direct beta decay between the ground states of Nd^{147} and Prm^{147}
on the basis of the now known spins, and the ordinary selection rules governing
beta decay. It is possible that in this particular case some unusual effect re-
sults in a modification of the selection rules.
Table I

Observed resonances in Nd$^{147}$. The calculated g_f values are based on the previously measured g_J values.

<table>
<thead>
<tr>
<th>$\mu_0 H/h$ (Mc)</th>
<th>Transition</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>I = 5/2, J = 4</td>
<td>I = 5/2, J = 4</td>
<td>I = 5/2, J = 4</td>
<td></td>
</tr>
<tr>
<td>$F = 13/2$</td>
<td>$F = 11/2$</td>
<td>$F = 9/2$</td>
<td></td>
</tr>
<tr>
<td>5.880</td>
<td>0.371 ±0.018</td>
<td>0.394±0.020</td>
<td>0.438±0.021</td>
</tr>
<tr>
<td>9.679</td>
<td>0.3755±0.0021</td>
<td>0.4008±0.0026</td>
<td>0.4452±0.0025</td>
</tr>
<tr>
<td>mean experimental g_f</td>
<td>0.3755±0.0021</td>
<td>0.4008±0.0026</td>
<td>0.4452±0.0025</td>
</tr>
<tr>
<td>calculated g_f</td>
<td>0.3710</td>
<td>0.3943</td>
<td>0.4385</td>
</tr>
</tbody>
</table>

Table II

Observed resonances in Pm$^{147}$. The calculated g_f values are based on the assumption of pure L-S coupling among the electrons of the configuration f^5 to the Hund's Rule term $g_H$.

<table>
<thead>
<tr>
<th>$\mu_0 H/h$ (Mc)</th>
<th>Transition</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>I = 7/2, J = 7/2</td>
<td>I = 7/2, J = 9/2</td>
<td>I = 7/2, J = 9/2</td>
<td></td>
</tr>
<tr>
<td>All F</td>
<td>F = 8</td>
<td>F = 7</td>
<td></td>
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<tr>
<td>15.208</td>
<td>0.416±0.002</td>
<td>0.600±0.003</td>
<td>0.620±0.003</td>
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<tr>
<td>29.050</td>
<td>0.602±0.002</td>
<td>0.623±0.002</td>
<td></td>
</tr>
<tr>
<td>53.528</td>
<td>0.416±0.0010</td>
<td>0.604±0.0015</td>
<td>0.623±0.0015</td>
</tr>
<tr>
<td>mean experimental g_f</td>
<td>0.416±0.0010</td>
<td>0.603±0.0015</td>
<td>0.623±0.0015</td>
</tr>
<tr>
<td>calculated g_f</td>
<td>0.4127</td>
<td>0.6023</td>
<td>0.6214</td>
</tr>
</tbody>
</table>
References

1. W. C. Rutledge, J. M. Cork, and S. B. Burson, Phys. Rev. 86, 775 (1952);
   P. R. Evans, Phil. Mag. 3, 1061 (1958);


7. Bryan Judd, (Lawrence Radiation Laboratory), private communication.


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