Title
THE NUCLEAR SPIN OF NEODYMIUM-141

Authors
Alpert, Seymour S.
Budick, Burton
Lipworth, Edgar
et al.

Publication Date
1961-07-03

UCRL-9774

UNIVERSITY OF CALIFORNIA

Ernest O. Lawrence Radiation Laboratory

BERKELEY, CALIFORNIA

DISCLAIMER

UCRL-9774

UNIVERSITY OF CALIFORNIA

Lawrence Radiation Laboratory
Berkeley, California

Contract No. W-7405-eng-48

THE NUCLEAR SPIN OF NEODYMIUM-141

Seymour S. Alpert, Burton Budick, Edgar Lipworth, and Richard Marrus

July 3, 1961

THE NUCLEAR SPIN OF NEODYMIUM-141

Seymour S. Alpert, Burton Budick, Edgar Lipworth, and Richard Marrus

Lawrence Radiation Laboratory
University of California
Berkeley, California

July 3, 1961

ABSTRACT

The spin of neodymium-141 was measured by the method of atomic beams and found to be 3/2. A lower limit placed on the hyperfine separation of the states with total angular momentum $F = 11/2$ and $F = 9/2$, $\Delta\nu$ (11/2, 9/2) by second-order perturbation theory shows $\Delta\nu\,(11/2, 9/2) \gtrsim 1630$ Mc/sec.

THE NUCLEAR SPIN OF NEODYMIUM-141*

Seymour S. Alpert, Burton Budick, Edgar Lipworth,† and Richard Marrus

Lawrence Radiation Laboratory
University of California
Berkeley, California

July 3, 1961

INTRODUCTION

Neodymium-141 is an even-odd nucleus with 60 protons and 81 neutrons. Since the neutron number is one less than the magic number 82, the properties of the nucleus should be well described by the single-particle shell model, which predicts that the state of the eighty-second neutron is $d_{3/2}$. Hence the spin of Nd^{141} should be 3/2 and the ground state should have even parity.

Evidence concerning the spin comes from the measurements by Polak et al.,[1] who have investigated the positron decay of Nd^{141} and the associated gamma rays. The resulting spectrum is consistent with the assignment of 3/2 for the spin of Nd^{141}.

A prerequisite for the determination of the nuclear spin from hyperfine-structure measurements is the knowledge of the electronic structure. The ground-state configuration of neodymium is known to be $(4f)^4$, from the optical spectroscopic investigations by Schuurmans.[2] The atomic beam work of Smith and Spalding[3] has further established the ground state to be characterized by $^5I_4$ with $g_J = -0.6031$. This value is used throughout this work.

METHOD

The method used is the "flop-in" atomic-beam resonance method first proposed by Zacharias.[4,5] The apparatus is of conventional design,

utilizing an oven arrangement particularly convenient for handling materials with high radiation levels. Both the apparatus and oven have been discussed elsewhere.[6,7] Beam was collected on freshly flamed platinum for neodymium is at least 25%, and very probably 100%. This is comparable to what has been observed with other elements in the lanthanide and actinide series. After collection, the deposited neodymium is counted in methane counters.

For an odd-A isotope such as Nd^{141} in an electronic state with $J = 4$, at least two transitions are observable in a "flop-in" apparatus. These transitions will be between levels characterized by the quantum number

$$(F = I + 4,\ m_F = -I + 1 \leftrightarrow F = I + 4,\ m_F = -I - 1)$$

and

$$(F = I + 3,\ m_F = -I + 2 \leftrightarrow F = I + 3,\ m_F = -I),$$

where F is the total angular momentum of the atom, m_F is the projection along the axis of quantization, and I is the nuclear spin. Resonances arising from transitions in the state $F = I + 4$ will be denoted as α resonances, and those in the state $F = I + 3$ will be denoted as β resonances. Both of the above transitions are of a double-quantum nature, i.e., $\Delta m_F = \pm 2$. This is a consequence of an integral J value and can best be seen from the schematic energy level diagram, Fig. 1. Such transitions were first observed in Pu^{239},[6,7] and have been observed since in many isotopes.[8]

In the Zeeman region, i.e., in the weak-magnetic-field region, the frequency ν of an observable transition is given by

$$\nu = g_F \mu_0 H/h, \qquad (1)$$

where g_F is the splitting factor for the particular F level in which the

transition is observed, μ_0 is the Bohr magneton, H is the magnetic field, and h is Planck's constant. The splitting factor g_F is related to the electronic splitting factor g_J by the relation

$$g_F \approx g_J \frac{F(F+1) + J(J+1) - I(I+1)}{2F(F+1)} , \qquad (2)$$

where a term in the nuclear moment has been neglected. Using $g_J = -0.6031$ for the $J = 4$ state of Nd, one determines the transition frequencies for α and β type resonances to be

$$\nu \approx \frac{2.4124}{I + 4} \frac{\mu_0 H}{h} \qquad (\alpha \text{ type}) \qquad (3)$$

and

$$\mu \approx \frac{0.30155\,(3I + 16)}{(I + 4)(I + 3)} \frac{\mu_0 H}{h} \qquad (\beta \text{ type})$$

Equations (3) determine the nuclear spin from the resonant frequencies observed in weak magnetic fields.

The experimental procedure consisted of searching for a signal from the isotope of unknown spin at the discrete frequencies given by Eq. (3). This procedure was repeated at several magnetic fields.

The magnetic field was determined from the resonant frequency of K^{39} ($F = 2$, $m_F = -1 \longleftrightarrow F = 2$, $m_F = -2$).

SAMPLE PREPARATION

The radioactive sample was produced in the Berkeley 60-inch cyclotron by the reaction $Pr^{141}(p,n)Nd^{141}$. The target material, praseodymium, was machined into discs 0.025 in. thick and bombarded with 12-Mev protons for from 5 to 8 hours. The total integrated flux was generally about 175 μa-hr.

At the completion of a scheduled bombardment, the target material was immediately unloaded and placed in a sharp-lipped tantalum crucible contained in a tantalum oven and introduced into the atomic beam machine. Optical line-up was effected and oven outgassing was carried out. Usually less than 2 hours elapsed between the completion of the cyclotron bombardment and the production of a stable beam. The duration of a run was ordinarily about 4 hours.

RESULTS

An initial search made at a low magnetic field at frequencies determined from Eq. (3) for all likely half-integral spin values yielded the results shown in Fig. 2. It is seen that $I = 3/2$ is strongly indicated. The transitions observed were seen at several higher fields, and the linear relation of transition frequency and field established. Two resolved resonances are shown in Figs. 3 and 4, and the observations are summarized in Table I.

In the last two columns of this table, the experimentally observed frequency and its compounded uncertainty are given. The compounded uncertainty, Δf_i, is defined by

$$(\Delta f_i) = \left[(\Delta \nu_i)^2 + \left(\frac{\partial \nu_i}{\partial H_i} \right)^2 (\Delta H_i)^2 \right]^{1/2},$$

where $\Delta \nu_i$ is the uncertainty associated with the finite line width of the neodymium resonance, $\frac{\partial \nu_i}{\partial H_i}$ is the rate of change of the resonant frequency with field, and ΔH_i is the uncertainty in the magnetic field.

Identification of the observed material as Nd^{141} is assured in several ways. The target material is known to be greater than 99% Pr^{141} by weight, from spectroscopic analysis. The method of production, the

observed g_J value, the half-integral spin, and a half-life of 2.5 hours observed in the decay of several resonance foils serve to establish unambiguously that the observed material is Nd^{141}.

CONCLUSIONS

The measured spin of 3/2 is in agreement with the shell-model prediction and the work of Polak et al.[1] as noted in the introduction.

The observed data make possible the setting of a lower limit to the zero-field hyperfine-structure separation between the F = 11/2 and F = 9/2 states, $\Delta\nu(11/2, 9/2)$. From second-order perturbation theory the deviation of an α resonance from the Zeeman frequency, δ_α, should be related to $\Delta\nu(11/2, 9/2)$ according to

$$\delta_\alpha = 0.1190 \left(g_J \frac{\mu_0}{h} H\right)^2 / \Delta\nu(11/2, 9/2). \quad (4)$$

Assuming the value of δ_α to be equal to or less than the compounded uncertainty at the highest observed field, we obtain

$$\Delta\nu(11/2, 9/2) \geq 1630 \text{ Mc/sec} \quad (5)$$

as a lower limit to the hyperfine separation.

ACKNOWLEDGMENTS

The authors wish to thank the members of the University of California Crocker Laboratory cyclotron group and the Lawrence Radiation Laboratory Health Chemistry Department for the efficient production, transportation, and handling of the active samples. Especial thanks are intended for Mr. Kaye Voice

of the Health Chemistry Department for his assistance.

FOOTNOTES AND REFERENCES

*This work was done under the auspices of the U. S. Atomic Energy Commission.

†Now at Brandeis University, Waltham, Massachusetts.

1. H. L. Polak, W. Schoo, B. L. Scram, R. K. Girgis, and R. Vanlieshout, Nuclear Phys. 5, 271 (1958).
2. Ph Schuurmans, Physica 11, 419 (1946).
3. K. F. Smith and Spalding (Cavendish Laboratories, Cambridge, England), private communication.
4. J. R. Zacharias, Phys. Rev. 61, 270 (1942).
5. L. Davis, D. E. Nagel, and J. R. Zacharias, Phys. Rev. 76, 1068 (1949).
6. Gilbert O. Brink, Nuclear Spins of Thallium-197, Thallium-198 M, and Thallium-199, and Thallium-204, (Thesis), University of California Radiation Laboratory Report UCRL-3642, June 1957. (unpublished).
7. J. C. Hubbs, R. Marrus, W. A. Nierenberg, and J. L. Worcester, Phys. Rev. 109, 390 (1958).
8. S. S. Alpert, E. Lipworth, M. B. White, and K. F. Smith, Hyperfine Structure and Nuclear Moments of Ra E (Bi^{210}), submitted to Phys. Rev.

Table I. Resolved resonances in Nd^{141}. The Zeeman frequency is calculated on the assumption $I = 3/2$, $J = 4$, and $g_J = -0.6031$.

No.	Resonance type	Field (gauss)	Calculated Zeeman frequency (Mc/sec)	Observed frequency (Mc/sec)	Compound uncertainty
1	α	12.264	7.529	7.545	0.045
2	α	19.566	12.012	12.025	0.052
3	α	36.198	22.223	22.215	0.068
4	β	6.915	4.835	4.838	0.057
5	β	19.566	13.680	13.665	0.062
6	β	36.198	25.310	25.325	0.113

FIGURE LEGENDS

Fig. 1. Schematic energy-level diagram; $I = 3/2$.

Fig. 2. Low field spin search. Arrows along abscissa give predicted values of resonant frequencies for appropriate spin assignments.

Fig. 3. A resolved α-resonance.

Fig. 4. A resolved β-resonance.

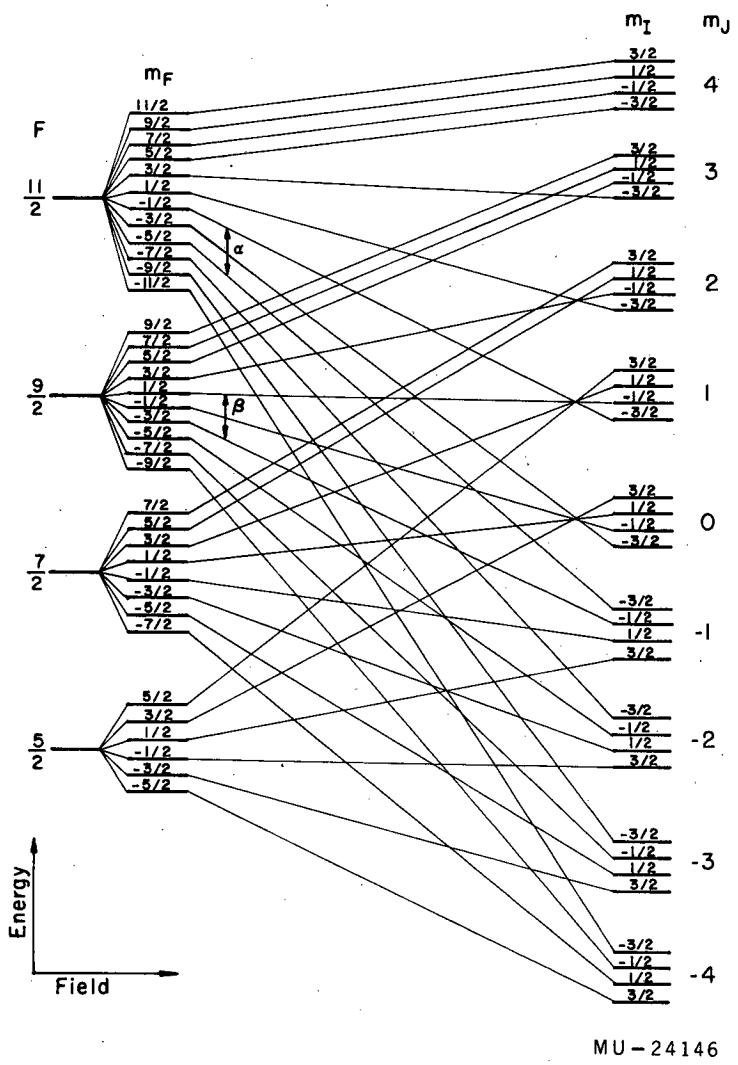
m_I
m_J
m_F
F
11/2
9/2
7/2
5/2
3/2
1/2
-1/2
-3/2
-5/2
-7/2
-9/2
-11/2
α
β
4
3
2
1
0
-1
-2
-3
-4
Energy
Field
MU-24146

Fig. 1

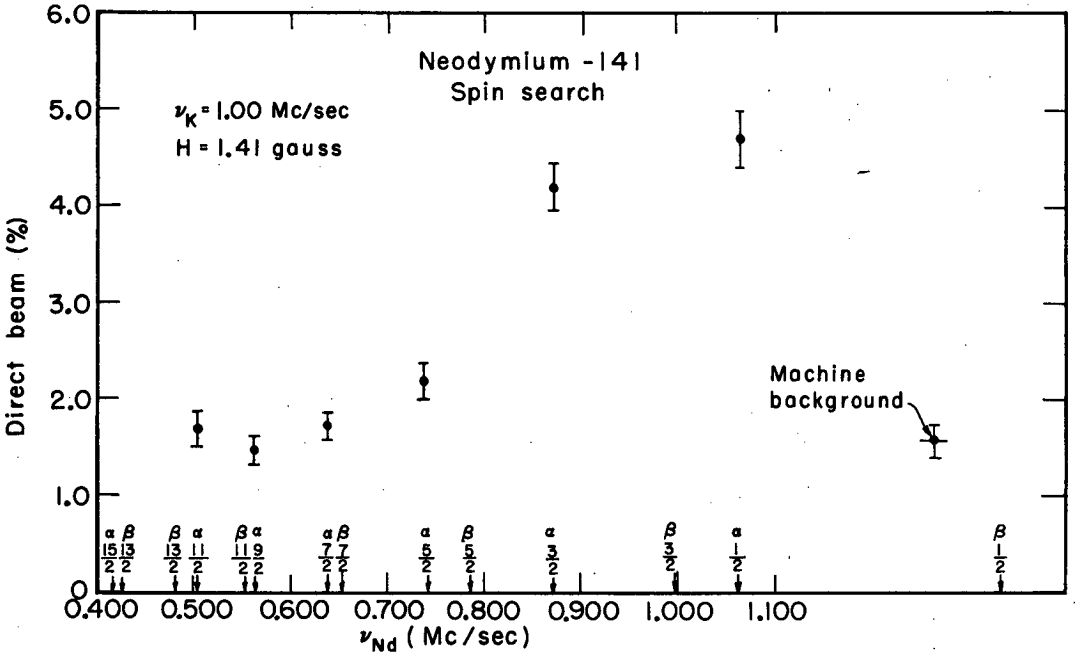
Neodymium -141
Spin search
ν_K = 1.00 Mc/sec
H = 1.41 gauss
Machine background
Direct beam (%)
6.0
5.0
4.0
3.0
2.0
1.0
0
0.400
0.500
0.600
0.700
0.800
0.900
1.000
1.100
ν_{Nd} (Mc/sec)
α 15/2 β 13/2
β 13/2 α 11/2
β 11/2 α 9/2
α 7/2 β 7/2
α 5/2
β 5/2
α 3/2
β 3/2
α 1/2
β 1/2
MU-24143

Fig. 2

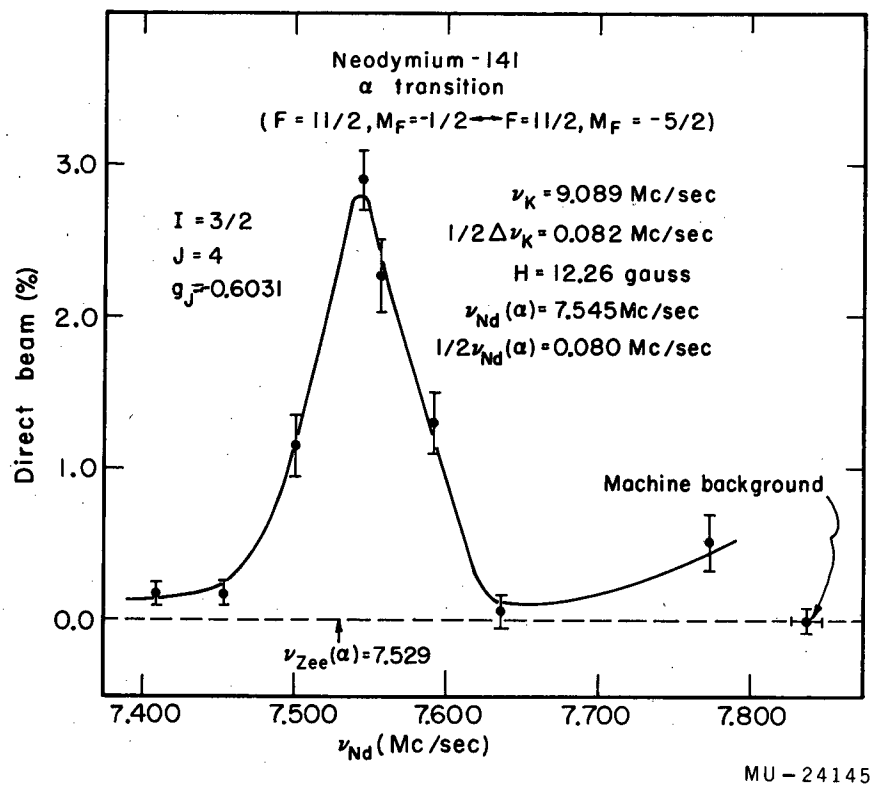
Neodymium-141
α transition
(F = 11/2, M_F = -1/2 ⟷ F = 11/2, M_F = -5/2)
I = 3/2
J = 4
g_J = 0.6031
ν_K = 9.089 Mc/sec
1/2 Δν_K = 0.082 Mc/sec
H = 12.26 gauss
ν_Nd(α) = 7.545 Mc/sec
1/2 ν_Nd(α) = 0.080 Mc/sec
Machine background
ν_Zee(α) = 7.529
Direct beam (%)
3.0
2.0
1.0
0.0
7.400
7.500
7.600
7.700
7.800
ν_Nd (Mc/sec)
MU-24145

Fig. 3

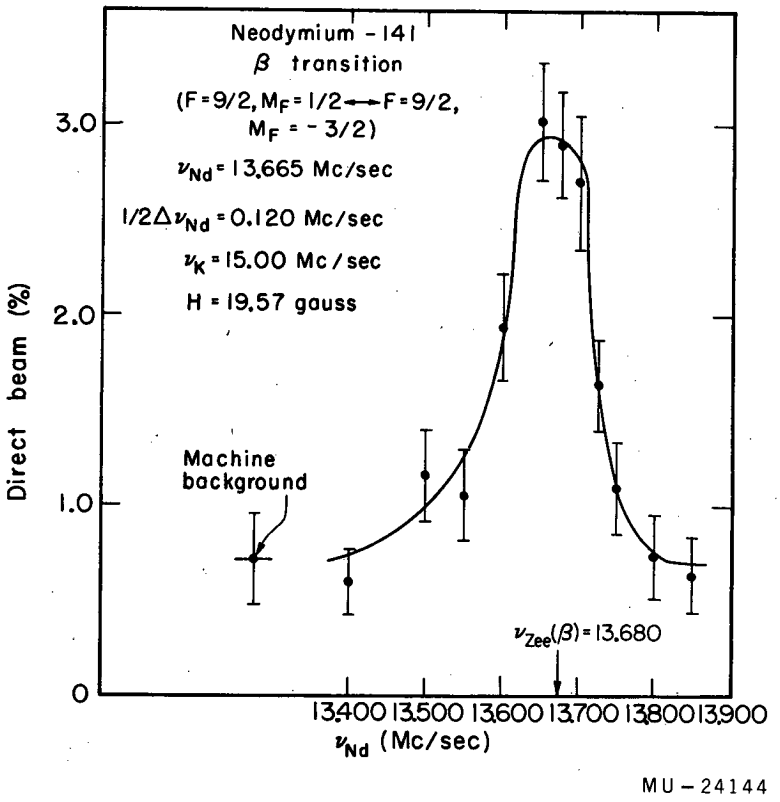
Neodymium - 141
β transition
(F=9/2, M_F=1/2 ⟷ F=9/2, M_F = -3/2)
ν_Nd = 13.665 Mc/sec
1/2Δν_Nd = 0.120 Mc/sec
ν_K = 15.00 Mc/sec
H = 19.57 gauss
Machine background
ν_Zee(β) = 13.680
Direct beam (%)
3.0
2.0
1.0
0
13.400 13.500 13.600 13.700 13.800 13.900
ν_Nd (Mc/sec)
MU-24144

Fig. 4