$$S_{3c}=-4Eq^3/3K_1,$$
$$S_{3d}=-E(K_-^3-p^3+2q^3-3K_-^2p+3K_-p^2-3K_-q^2+3pq^2)/3K_1,$$
$$S_{3e}=-8K_2pE,$$
$$S_{3f}=0,$$
$$S_{3g}=E[K_+^3+p^3+2q^3-3(K_+^2-2K_-^2)p+3K_+p^2-3K_+q^2-3pq^2]/3K_1,$$
$$S_{3h}=E(K_+^3-p^3-2q^3-3K_+^2p+3K_+p^2-3K_+q^2+3pq^2)/3K_1,$$
$$S_{3i}=\tfrac{2}{3}E(K_1^2+3K_2^2+3p^2-3q^2-6K_2p),$$
$$S_{3j}=0,$$
$$S_{3k}=E(K_-^3+p^3-2q^3+3K_-^2p+3K_-p^2-3K_-q^2-3pq^2)/3K_1,$$
$$S_{3l}=2EK_2(K_2^2+3K_1^2+3p^2-3q^2-6K_1p)/3K_1. \quad \text{(A13)}$$
$$S_4=(4\pi^3)^{-1}pq\int(\mathbf{p}\cdot\mathbf{q})\delta(\mathbf{p}\cdot\mathbf{k}_2+\mathbf{q}\cdot\mathbf{k}_2+K_1\mathbf{k}_1\cdot\mathbf{k}_2+K_2)\times d\Omega_e d\Omega_\nu d\Omega_{\gamma 1},$$
$$S_{4a}=0,$$
$$S_{4b}=4K_-p^3/3K_1,$$
$$S_{4c}=4K_-q^3/3K_1,$$
$$S_{4d}=(K_-^4-3p^4-3q^4+8K_-q^3+8K_-p^3+6p^2q^2-6K_-^2p^2-6K_-^2q^2)/12K_1,$$
$$S_{4e}=-(8/3)p^3,$$
$$S_{4f}=-(8/3)q^3,$$
$$S_{4g}=-[K_+^4-3p^4-3q^4+8(K_+-2K_-)p^3+8K_+q^3-6K_+^2p^2-6K_+^2q^2+6p^2q^2]/12K_1,$$
$$S_{4h}=-[K_+^4-3p^4-3q^4+8K_+p^3+8(K_+-2K_-)q^3-6K_+^2p^2-6K_+^2q^2+6p^2q^2]/12K_1,$$
$$S_{4i}=-(\tfrac{2}{3})(K_1^2K_2+K_2^3+2p^3+2q^3-3K_2p^2-3K_2q^2),$$
$$S_{4j}=0,$$
$$S_{4k}=(-K_-^4+3p^4+3q^4+8K_-p^3+8K_-q^3+6K_-^2p^2+6K_-^2q^2-6p^2q^2)/12K_1,$$
$$S_{4l}=-[K_1^4+K_2^4-3p^4-3q^4+8K_1p^3+8K_1q^3-6(K_1^2+K_2^2)p^2-6(K_1^2+K_2^2)q^2+6K_1^2K_2^2+6p^2q^2]/6K_1. \quad \text{(A14)}$$

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# Spin of Neptunium-238†

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The atomic-beam magnetic-resonance method has been used to investigate 2.10-day $Np^{238}$ in the low-field or Zeeman region of hyperfine structure. The spin of this nuclide is found to be 2.

## INTRODUCTION

THE research reported here is part of a continuing program leading to nuclear spins and moments, and to the properties of low-lying electronic states in the heavy-element region. The spin of this nuclide is particularly interesting, for $Np^{238}$ is an odd-odd isotope for which the states of the last proton and neutron are presumably known from $Np^{239}$ and $Pu^{239}$ respectively.[1] Therefore the observed spin is expected to yield information regarding the coupling of neutrons and protons in deformed nuclei.

Previous research[2] on $Np^{239}$ has disclosed an electronic energy level with $J=11/2$, $g_J=0.6551\pm0.0006$ apparently arising from the configuration $(5f)^4(6d)^1$; the measurements reported here are made on this level.

## TARGET PREPARATION, MATERIAL PRODUCTION, AND BEAM DETECTION

The sample is made by neutron activation of a mixture of 3 mg of $Np^{237}$ and 10 mg of $U^{238}$ oxides for 72 hr at a flux of $2\times10^{13}$ neutrons/cm² sec. The target is prepared by coprecipitation of neptunium and uranium hydroxides and subsequent decomposition to the oxides by heating. The $U^{238}$ is added for carrier purposes only; the thermal-activation cross sections[3] of $U^{238}$ and $Np^{239}$ are such that the product activity is about 95% 2.1-day $Np^{238}$ and 5% 2.36-day $Np^{239}$.

The neptunium is detected by allowing the atomic beam to fall on small flamed platinum foils which are then counted in flow proportional counters with high detection efficiency for beta particles above 25 kev. Counter background is typically 6 counts per minute.

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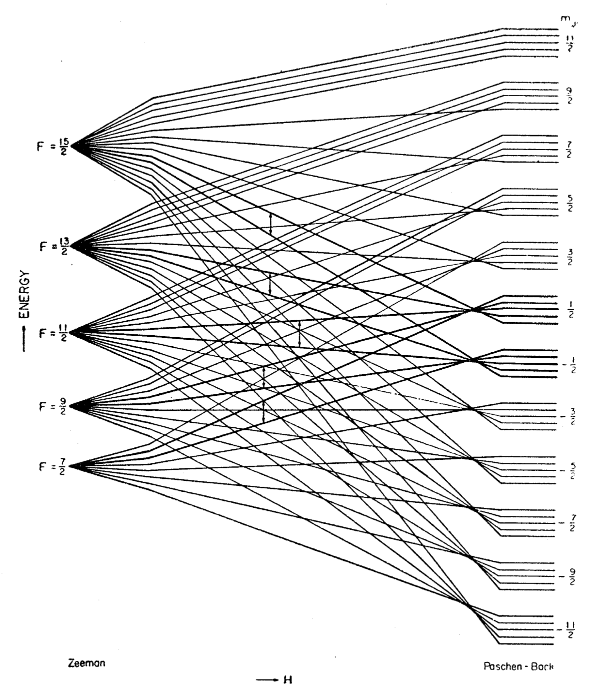


FIG. 1. Energy-level diagram for the system. $J=11/2$, $I=2$ assuming normal hfs obeying the interval rule. (Not to scale.) Flop-in transitions are indicated by arrows.

## METHOD

The spin, $I$, of a nucleus interacting with an electronic system of known $\mathbf{J}$ and $\mathbf{g}_J$, can be established in the low-field or Zeeman region of hfs providing that the $g$ values, $g_F$, of the various states of total angular momentum, $\mathbf{F}=\mathbf{I}+\mathbf{J}$, can be measured to sufficient precision. In the low-field limit $F$ is a good quantum number and, if contributions from the nuclear magnetic moment are ignored, these $g$ values are given by the product of the electronic $g$ value, $g_J$, and the relative projection of the electronic angular momentum on the direction of total angular momentum,

$$g_F=g_J\frac{\mathbf{J}\cdot\mathbf{F}}{\mathbf{F}^2}=g_J\frac{F(F+1)+J(J+1)-I(I+1)}{2F(F+1)}. \quad (1)$$

Thus the observed transition frequencies, $g_{F0}\mu H$, will be a function of but one unknown, $I$.

Departures from this simple scheme arise from mixing by the external magnetic field of states of different $F$ but the same projection $M_F$ on the field direction. The term quadratic in the field which is, in general, the first to appear is in this case about $0.01(g_J\mu_0H)^2/A$, where $A$ is the dipole hfs constant defined by $\mathcal{H}=A\mathbf{I}\cdot\mathbf{J}$. The $J$ and $g_J$ observed in neptunium suggest that the electronic energy level under consideration arises from the configuration $(5f)^4(6d)^1$, with the $5f$ and $6d$ electrons independently coupling to the several Hund's rule ground states $^5I_4$ and $^2D_{\frac{3}{2}}$; such a situation would be the consequence of a mutual electrostatic interaction smaller than either fine-structure interaction. On the assumption that this is the case, a calculation has been made of $A$ by using a simple extension of methods previously enumerated,[4] and $5f$ and $6d$ electron-wave functions obtained from a Hartree relativistic calculation for uranium.[5] The result for the $(^5I_4-{}^2D_{\frac{3}{2}})_{11/2}$ state is $A=470g_I$ Mc/sec. Therefore with an apparatus resolution of 20 kc/sec one expects the Zeeman region of hfs to extend to at least 30 gauss ($g_I\geq 0.1$).

## EXPERIMENTAL PROCEDURE

The atomic-beam apparatus, which has been described elsewhere,[6] uses the Zacharias[7] or flop-in resonance system, requiring for a refocused beam a transition between magnetic substates having equal and opposite high-field magnetic moments, i.e., a transition between magnetic substates characterized by the high-field quantum numbers $m_J$ and $-m_J$; all such transitions for which $\Delta F$ is 0 are allowed in the Zeeman limit.[8] On the other hand the deflection in the magnet system is proportional to $m_J$, and the neptunium beam temperature and $g_J$ value give rather smaller deflections than those for which the apparatus was designed. Therefore transition intensities generally decrease as the maximum value of $\Delta m_J$ decreases, or in this case as $F$ decreases (Fig. 1).

A beam of neptunium atoms is made by the same process as is used for $Np^{239}$; the neptunium and uranium oxides are mixed with a large excess of graphite powder, placed in a small tantalum oven, and heated in the apparatus. The oxides are first reduced to carbides at a temperature of about 1300°C and then the oven temperature is raised to about 2000°C, at which temperature a beam of neptunium is made by decomposition of the carbides.

An initial search was made at a field of 0.70 gauss at

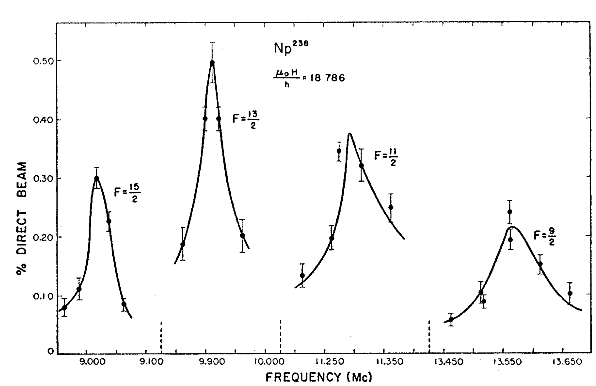


FIG. 2. Observed transitions in $Np^{238}$ at 13.4 gauss.

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TABLE I. Summary of observations. Frequencies in Mc/sec.

| State | $F=15/2$ | $F=13/2$ | $F=11/2$ | $F=9/2$ | $F=7/2$ |
|---|---|---|---|---|---|
| Observed frequency | 9.020±0.025 | 9.912±0.025 | 11.290±0.035 | 13.562±0.025 | (17.790±0.050) |
| Predicted frequency | 9.025 | 9.908 | 11.274 | 13.550 | 17.776 |

discrete frequencies given by Eq. (1); it indicated that the spin of $Np^{238}$ is 2. This assignment has been verified by the observation of at least four of the five $F$ states at a field of 13.4 gauss (Fig. 2), where the resolution in $g_F$ is about 0.2%. Each state of total angular momentum has been observed at this higher field a minimum of three times. The resonance effect for the $F=\frac{7}{2}$ state is no more than 0.1%. Observed and predicted resonance frequencies are given in Table I.

The beam material is identified as essentially pure $Np^{238}$ by half-life analysis. The half-life of the gross sample (direct beam) is found to be 2.16±0.15 days and that of the $F=15/2$ state is found to be 2.1±0.4 days.

## DISCUSSION

The measured spin of $Np^{238}$ is in agreement with all beta and gamma spectroscopic studies[9–12] that favor spins 2 or 3.

The last odd nucleons in $Np^{238}$ would most reasonably be expected to be in the states $(642+)\frac{5}{2}+$ for the proton[1] as in $Np^{239}$ and $(631-)\frac{1}{2}+$ for the neutron[1] as in $Pu^{239}$. [The states are labeled, following Nilsson, as $(Nn_z\Lambda\pm)\Omega\pi$, the symbols being defined in reference 1, and the $\pm$ appearing inside the parentheses according as $\Omega=\Lambda\pm\frac{1}{2}$.] Moszkowski's[13] extension of the Nordheim[14] rules would then predict 2+ for the ground state of $Np^{238}$. There are, however, alternative assignments for both the neutron and the proton states which are not unreasonable, namely the proton state $(523-)\frac{5}{2}-$ which appears[15] only 60 kev above the ground state in $Np^{237}$, and the neutron state $(501-)\frac{1}{2}-$, observed[16] as the ground state of $U^{237}$. There is, then, considerable uncertainty as to the parity of $Np^{238}$; in addition, the reasonable 2+ assignment is in conflict with one beta-spectroscopic study.[11] A measurement of the magnetic moment would be of little assistance in regard to the parity, for in the limit of large deformation, which is a reasonable approximation in the neighborhood of $Np^{238}$, either neutron state in combination with a given proton state gives the same magnetic moment.

By use of the observed resonance frequencies in $Np^{238}$ a recomputation of the $g_J$ values of the observed levels can be made, yielding $g_J=0.6553\pm0.0010$, in good agreement with the value obtained from the $Np^{239}$ research. No change in the best value of $g_J$ is indicated.

## ACKNOWLEDGMENT

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