University of California

Ernest O. Lawrence Radiation Laboratory

SPINS OF GADOLINIUM-153, DYSPROSIUM-159,
AND PROMETHIUM-148

Berkeley, California

DISCLAIMER

Submitted to Nuclear Physics

UCRL-11837

UNIVERSITY OF CALIFORNIA

Lawrence Radiation Laboratory
Berkeley, California

AEC Contract No. W-7405-eng-48

SPINS OF GADOLINIUM-153, DYSPROSIUM-159, AND PROMETHIUM-148

Dolores Ali

January 7, 1965

SPINS OF GADOLINIUM-153, DYSPROSIUM-159, AND PROMETHIUM-148†

Dolores Ali

Lawrence Radiation Laboratory
University of California
Berkeley, California

January 7, 1965

ABSTRACT

Ground-state nuclear spins of 236-d Gd^{153}, 134-d Dy^{159}, and 5.3-d Pm^{148} have been measured by the atomic-beam magnetic-resonance method. They are found to be $I(Gd^{153}) = 3/2$, $I(Dy^{159}) = 3/2$, and $I(Pm^{148}) = 1$.

The spins of Gd^{153} and Dy^{159} are found to be consistent with collective-model state assignments for the odd neutrons, 3/2+[651] and 3/2-[521] respectively. The spin of Pm^{148} is found to be consistent with shell-model state assignments $g_{7/2}$ for the odd proton and $(f_{7/2})^{-3}_{5/2}$ for the odd neutrons.

1. Introduction

The rare earths ($57 \leq Z \leq 71$) occur in a transition region between spherical and highly deformed nuclear cores. Measurements of the nuclear spins of neutron-enriched isotopes of the rare earths are useful in the determination of the neutron numbers N for which collective effects become important in these elements. The spins further serve as a test of nuclear-model predictions -- shell model or collective model; and the spins of deformed nuclei may serve as a test of the deformations calculated by Nilsson.

It is necessary for one to know the electronic angular momentum (J) and the electronic splitting factor (g_J) to infer the nuclear spin (I) from the measured Zeeman splitting of the hyperfine structure levels; i. e., the quantity measured by the atomic-beam magnetic-resonance method is

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

where a term in the nuclear g_I has been neglected. Values of J and g_J are available for the ground states of almost all the rare earths[1]).

2. Experimental Method and Results

The radioactive materials used in this research were produced in the Materials Testing Reactor at ARCO, Idaho, where the maximum flux is 5×10^{14} neutrons/cm^2/sec. Generally, following irradiation, the sample is placed in a sharp-lipped tantalum crucible and then sealed in a tantalum oven; the oven is then inserted into the beams machine and heated by electron bombardment to produce a beam of atoms. The beams machine is a conventional flop-in design; details of the apparatus are given in references 1 and 2. The atoms are detected by deposition on freshly flamed platinum foils, which after exposure are placed in methane beta counters to determine the collected activity. Platinum has a relatively high and reproducible collection efficiency for the rare earths.

Transitions may be observed between energy levels of the Hamiltonian

$$\mathcal{H} = A\,\underset{\approx}{I} \cdot \underset{\approx}{J} + B\,\frac{3(\underset{\approx}{I} \cdot \underset{\approx}{J})^2 + 3/2(\underset{\approx}{I} \cdot \underset{\approx}{J}) - I(I+1)J(J+1)}{2IJ(2I-1)(2J-1)} - g_J\,\mu_0(\underset{\approx}{J} \cdot \underset{\approx}{H}) - g_I\mu_0(\underset{\approx}{I} \cdot \underset{\approx}{H})$$

by means of the atomic-beam magnetic-resonance method. Occurrence of a flop-in transition ($m_J \rightarrow -m_J$) is indicated by an increase in intensity at the detector.

Experiments in which nuclear spins are measured usually are conducted at low magnetic fields where I and J couple strongly to a total angular momentum F, and the transition frequency between magnetic substates of the same hyperfine structure level is $\nu = g_F\,\mu_0 H/h$. By exposing the beam to discrete Zeeman frequencies, which are calculated by assuming reasonable values for the nuclear spin, and noting the particular frequencies for which resonance occurs, we can determine the correct value of the spin. The magnetic field is measured by observation of resonances in a calibrating isotope, K^{39}.

2.1 GADOLINIUM-153

Optical spectroscopic results indicate a ground electronic configuration of $4f^7 5d^1$ for gadolinium[3]). The Russell-Saunders g_J values for a ^9D ground term agree with those measured in an atomic-beam experiment on stable Gd^{158} and confirmed by Cabezas for the J = 2, 3, 4, 5 levels[4]).

Gadolinium-153 was produced by neutron irradiation of the natural metal (0.2% abundant in Gd^{152}). Two-hundred-milligram quantities of the metal were irradiated for 6 weeks, after which samples were allowed to decay for 3 weeks in order that the short-lived isotopes, 18-h Gd^{161} and 7-d Tb^{161}, would be eliminated.

At beam temperatures of approximately 2000°K, the J = 2, 3, 4, 5 levels were sufficiently populated to allow a satisfactory spin search for each level. The data taken at H = 2.81 G and H = 5.56 G indicate a spin I = 3/2 for Gd^{153}. (See Figs. 1 and 2.) Decay of an I = 3/2 resonance exposure indicated that the isotope was 236-d Gd^{153} (Ref. 5).

2.2 DYSPROSIUM-159

Cabezas inferred a ground electronic configuration of $4f^{10}6s^2$ for dysprosium and determined that the electrons are Russell-Saunders coupled to a $^5I_8$ ground state[4,6]. For the $^5I_8$ state, he measured g_J = -1.24166(7).

Dysprosium-159 was produced by neutron irradiation of 40 mg of dysprosium oxide (7 to 14% enriched in Dy^{158}) for 6 weeks. (The oxide was used in preference to the natural dysprosium metal because the metal contains <0.1% Dy^{158}.) Each 40-mg sample was allowed to decay for 6 weeks in order that the short-lived isotopes -- Dy^{165}(23-h), Dy^{166}(80-h), and Ho^{166}(27.2-h) -- would be eliminated. A reducing agent, misch metal -- primarily a mixture of lanthanum and cerium -- was added to the oven in order to obtain a beam of atoms from the oxide.

The first few experiments were complicated by the presence of Tb in the beam. In a spin search at H = 2.81 G, many resonances were observed, which gave the appearance of a broad (2-Mc-wide) resonance curve; most of these were attributed to Tb upon discovery that the 3%-enriched oxide contained >1% Tb (and ≈ 2% Ho). The results of a repeat spin search at H = 2.81 G, with the 14%-enriched oxide (0.05% Tb; 0.1% Ho) used, are shown in Fig. 3. These results indicate the spin to be I = 1/2 or 3/2. However, at this field the I = 1/2 and I = 3/2 resonance frequencies are within a line width of each other. To remove the ambiguity it was necessary to go to higher fields, where these frequencies are separated by more than 200 kc/sec. Data from the spin searches at H = 5.56 G and H = 10.86 G indicate the spin I = 3/2 for Dy^{159} (Figs. 4 and 5).) Decay of an I = 3/2 resonance exposure identified the isotope as 134-d Dy^{159} (Ref. 7).

2.3 PROMETHIUM-148

Promethium has a ground electronic configuration of $4f^5 6s^2$ and a Russell-Saunders ground-state term of ^6H.[6] At beam temperatures (≈1000°C) both the J = 5/2 and J = 7/2 levels are relatively well populated. However, the J = 5/2 level was not observed because its g_J value, 0.293 (Ref. 8), is too low to be deflected around the stopwire of our atomic-beam machine. For the J = 7/2 level, the g_J has been measured and found to be -0.8279(4) (Ref. 9).

Curie amounts of 2.7-y Pm^{147} in chloride solution were obtained from the Union Carbide Nuclear Company at Oak Ridge, Tennessee. An excess of nitric acid was added to the solution to convert it to nitrate. The nitrate solution was then heated to dryness, and approximately 1 mg of the nitrate powder was irradiated for 3 weeks to produce a sample of Pm^{148}. After irradiation the powder was dissolved in a weak solution of nitric acid, transferred to the oven crucible, and heated in air to 700°F to convert the nitrate to oxide. The radiochemistry was performed in a shielded glove box with manipulators. A reducing agent -- misch metal -- was added to the crucible.

Spin searches at H = 2.81 G and H = 5.56 G clearly indicate the spin I = 1 for Pm^{148}. (See Figs. 6 and 7.) The isotope was identified as 5.3-d Pm^{148} (Ref. 10) by decay of the resonance exposures.

On the basis of its beta decay, the ground state of Pm^{148} was assigned spin I = 2- [11]). From the results of low-temperature nuclear-alignment experiments, Grant and Shirley assigned the spin I = 1- [12]). Our result (I = 1) agrees with that of Grant and Shirley.

3. Discussion

The shell-model state assignment for the 89th neutron is $5f_{7/2}$ or $6h_{9/2}$ [13]). The measured spin of Gd^{153} (I = 3/2) disagrees with the shell-model prediction and indicates that the Gd^{153} nucleus is probably deformed. For mass number A = 153 the deformation is expected to be relatively small. The collective-model orbital assigned to the odd neutron by Mottelson and Nilsson[14]) with the provision that δ be small (3/2 + [651]) agrees with the measured spin. In Table I the spin of Gd^{153} is listed with the spin and neutron state assignments of three other gadolinium isotopes. The spin of Gd^{159} only is in disagreement with collective-model orbital assignments.

The measured spin of Dy^{159} (I = 3/2) is consistent with the Nilsson orbital 3/2-[521] for the 93rd neutron. The spins and neutron state assignments of six dysprosium isotopes, including Dy^{159}, are listed in Table II. The empirical energy-level structure of the 89th through 99th neutrons obtained from these results is in good agreement with that calculated by Mottelson and Nilsson[14]). The spin of Dy^{165} suggests that the Nilsson state 7/2 + [633] lies below the 1/2 - [521] state. It is also interesting that the orbital of the 95th neutron of Dy^{161} differs from that of the 95th neutron of Gd^{159}.

The results indicate that Pm^{148} is best described by the shell model. The nucleon configuration is probably $g_{7/2}$ for the odd proton and $(f_{7/2})^{-3}_{5/2}$ for the odd neutrons[15]). These assignments are consistent with the measured spin I = 1.

Table I. Spins, moments, and nucleon-state assignments for some odd-A gadolinium isotopes.

Nuclei	I	Neutron state	Magnetic moment (nm)	Quadrupole moment (barns)
$_{64}Gd^{153}$	3/2	3/2+[651]	---	---
Gd^{155}	3/2	3/2-[521]	0.28(4)[a]	+ 1.1[b]
Gd^{157}	3/2	3/2-[521]	0.38(5)[a]	+ 1.0[b]
Gd^{159}	3/2	3/2-[521]	---	--- [c]

a. B. Bleaney, Nuclear Moments of the Lanthanons, in Proceedings of the International Symposium on Quantum Electronics 3d, Paris, February 1963 (Columbia University Press, New York, 1964).

b. D. Strominger, J. M. Hollander, and G. T. Seaborg, Rev. Mod. Phys. 30, 585 (1958).

c. Reference 6.

Table II. Spins, moments, and nucleon state assignments for some odd-A dysprosium isotopes.

Nuclei	I	Neutron state	Magnetic moment (nm)	Quadrupole moment (barns)
$_{66}Dy^{155}$	3/2	3/2+[651]	(-) 0.21(5)[a]	---
Dy^{157}	3/2	3/2-[521]	(-) 0.32(2)[a]	---
Dy^{159}	3/2	3/2-[521]	---	---
Dy^{161}	5/2	5/2+[642]	- 0.455(10)	+ 1.35(30)[b]
Dy^{163}	5/2	5/2-[523]	+ 0.635(14)	+ 1.62(40)[b]
Dy^{165}	7/2	7/2+[633]	---	---[c]

a. Q. O. Navarro and D. A. Shirley, Phys. Rev. 123, 186 (1961).

b. B. Bleaney, Nuclear Moments of the Lanthanons, in Proceedings of the International Symposium on Quantum Electronics 3d, Paris, February 1963 (Columbia University Press, New York, 1964).

c. Reference 6.

FOOTNOTES AND REFERENCES

† Work performed under the auspices of the U.S. Atomic Energy Commission.

1. For a summary, see Richard Marrus and William A. Nierenberg, in Proceedings of the International School of Physics, Enrico Fermi, Course XVII (Academic Press Inc., New York, 1962), pp. 118-156.
2. William A. Nierenberg, Ann. Rev. Nucl. Sci. 7, 349 (1957).
3. Walter Albertson, Phys. Rev. 47, 370 (1935).
4. Amado Y. Cabezas, Electronic and Nuclear Properties of Some Radioactive Rare Earth Elements (Ph.D. Thesis), Lawrence Radiation Laboratory Report UCRL-9346, Aug. 1960 (unpublished).
5. R. E. Hein and A. F. Voigt, Phys. Rev. 79, 783 (1950).
6. Amado Y. Cabezas, Ingvar Lindgren, and Richard Marrus, Phys Rev. 122, 1796 (1961).
7. F. D. S. Butement, Proc. Phys. Soc. (London) 64A, 428 (1951).
8. B. R. Judd and I. Lindgren, Phys. Rev. 122, 1802 (1961).
9. Burton Budick and Richard Marrus, Phys. Rev. 132, 723 (1963).
10. G. W. Parker, P. M. Lantz, M. G. Inghram, D. C. Hess, Jr., and R. J. Hayden, Phys. Rev. 72, 85 (1947); J. D. Kurbatov and M. L. Pool, Phys. Rev. 63, 463A (1943).
11. C. F. Schwerdtfeger, E. G. Funk, Jr., and J. W. Mihelich, Phys. Rev. 125, 1641 (1962).
12. R. W. Grant and D. A. Shirley, Phys. Rev. 130, 1100 (1963).
13. Maria Goeppert Mayer and J. Hans D. Jensen, Elementary Theory of Nuclear Shell Structure (John Wiley & Sons, Inc., New York, 1955).
14. B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab. Mat. Fys Skrifter 1, No. 8 (1959).
15. Dolores E. Ali, Spins of Gd^{153}, Dy^{159}, and Pm^{148} and Hyperfine Structures of Pm^{148} and Er^{165} (Ph.D. Thesis), Lawrence Radiation Laboratory Report UCRL-11536, June 1964 (unpublished).

FIGURES

Fig. 1. Gd^{153} spin search at H = 2.81 G.

Fig. 2. Gd^{153} spin search at H = 5.56 G.

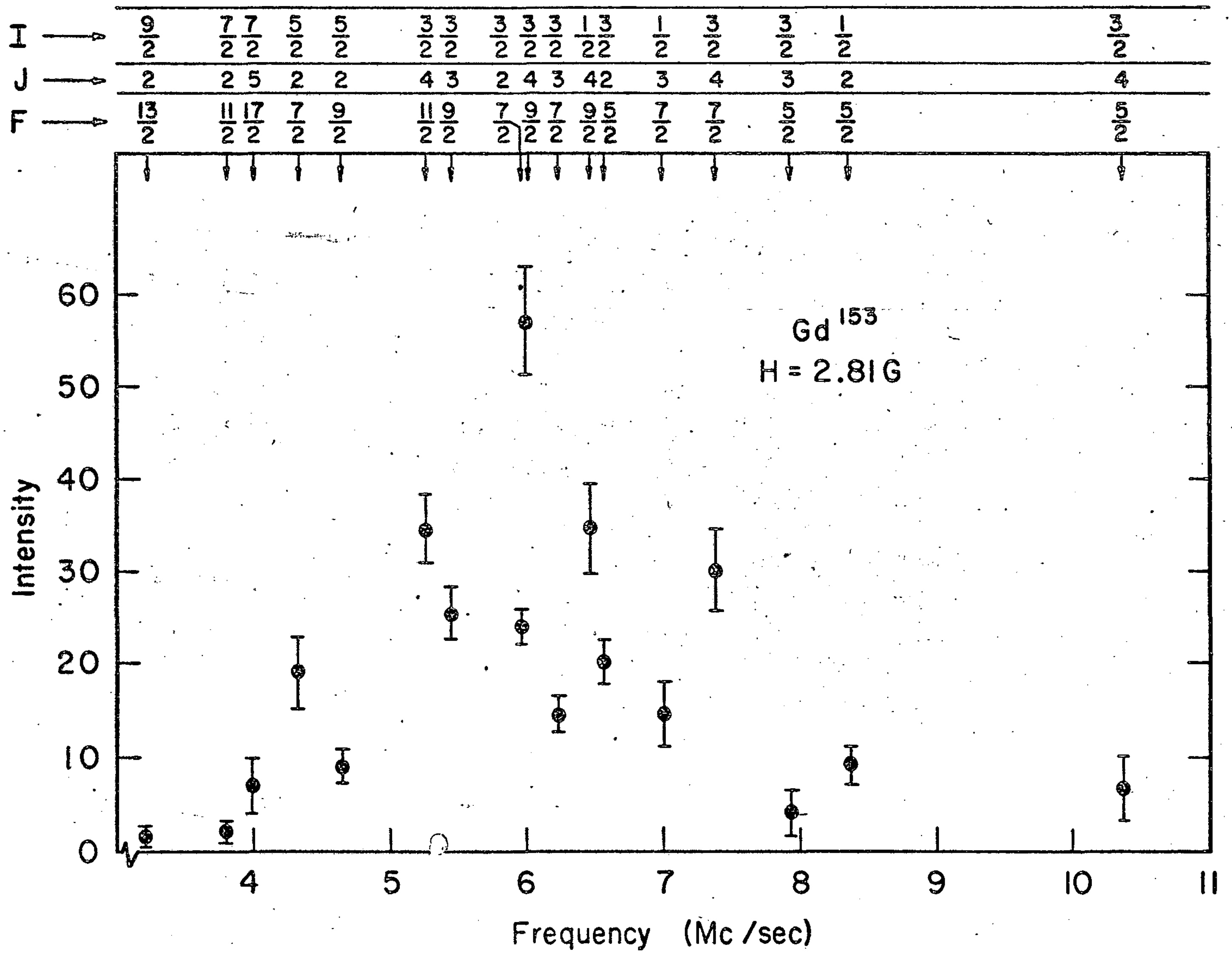
Fig. 3. Dy^{159} spin search at H = 2.81 G.

Fig. 4. Dy^{159} spin search at H = 5.56 G.

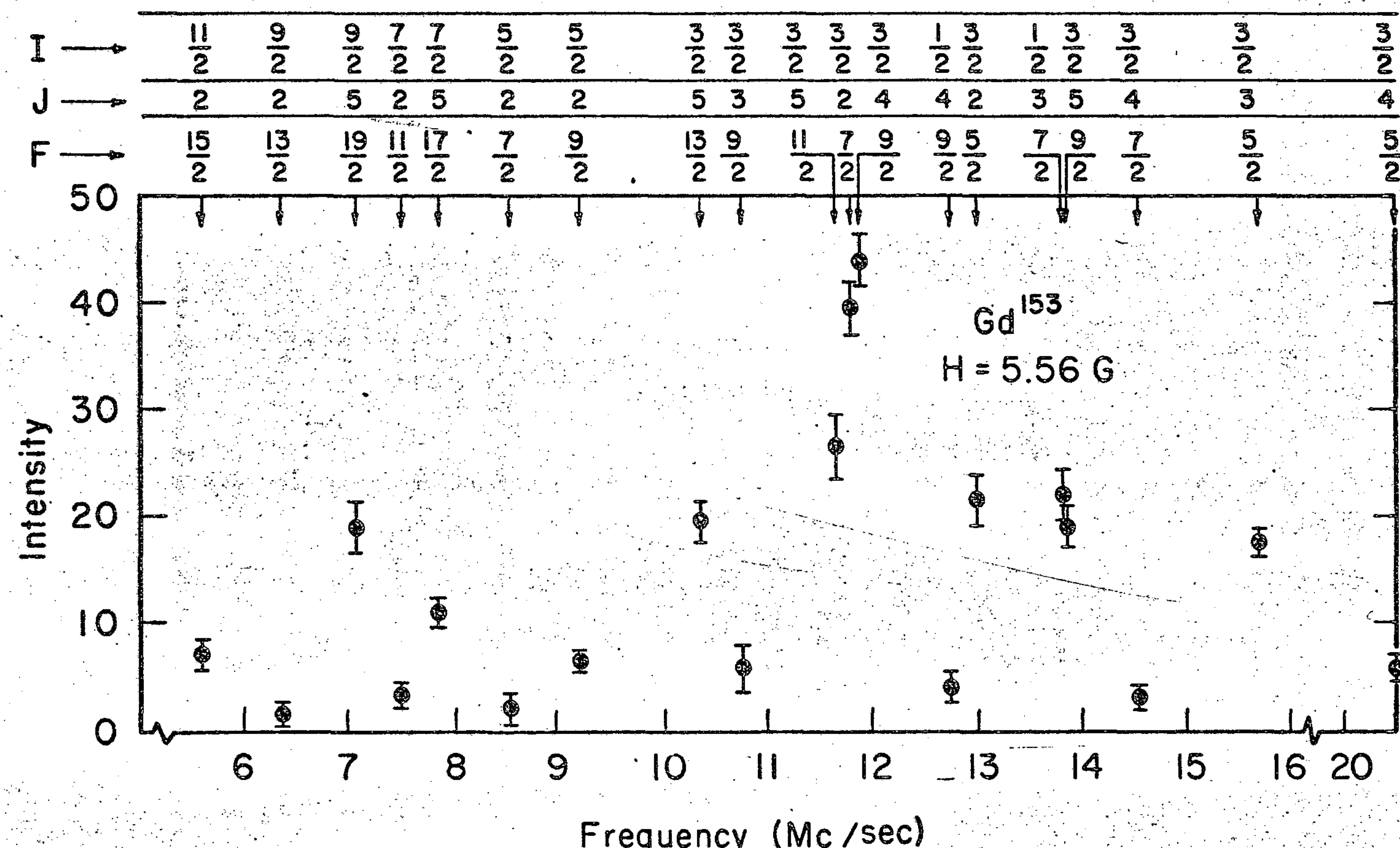
Fig. 5. Dy^{159} spin search at H = 10.86 G.

Fig. 6. Pm^{148} spin search at H = 2.81 G. The high point corresponding to I = 3 and F = 13/2 is attributed to Pm^{147}. The frequency 1.759 Mc/sec lies within a line width of the Pm^{147} (I = 7/2, J = 7/2) Zeeman frequency at this field.

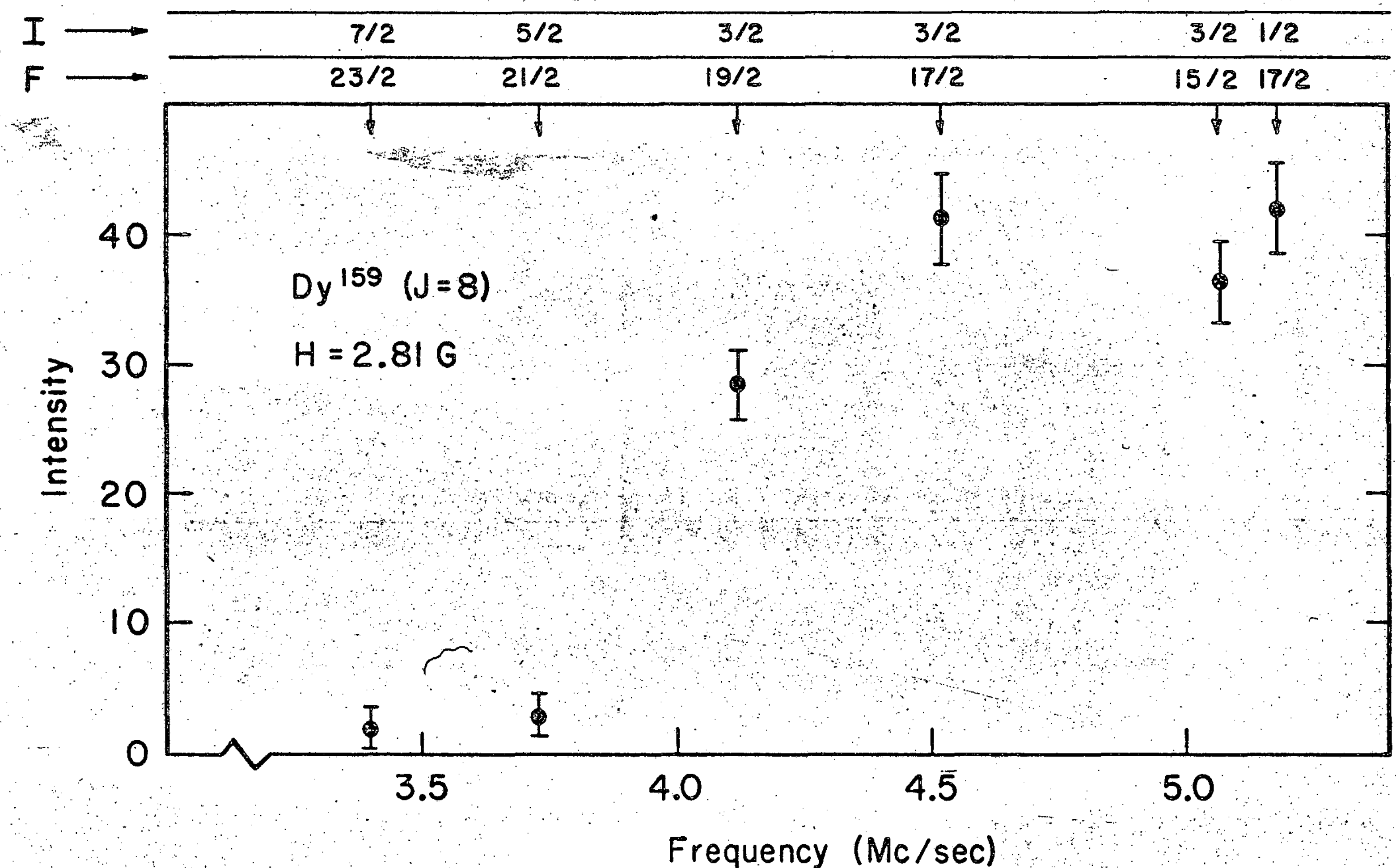
Fig. 7. Pm^{148} spin search at H = 5.56 G.



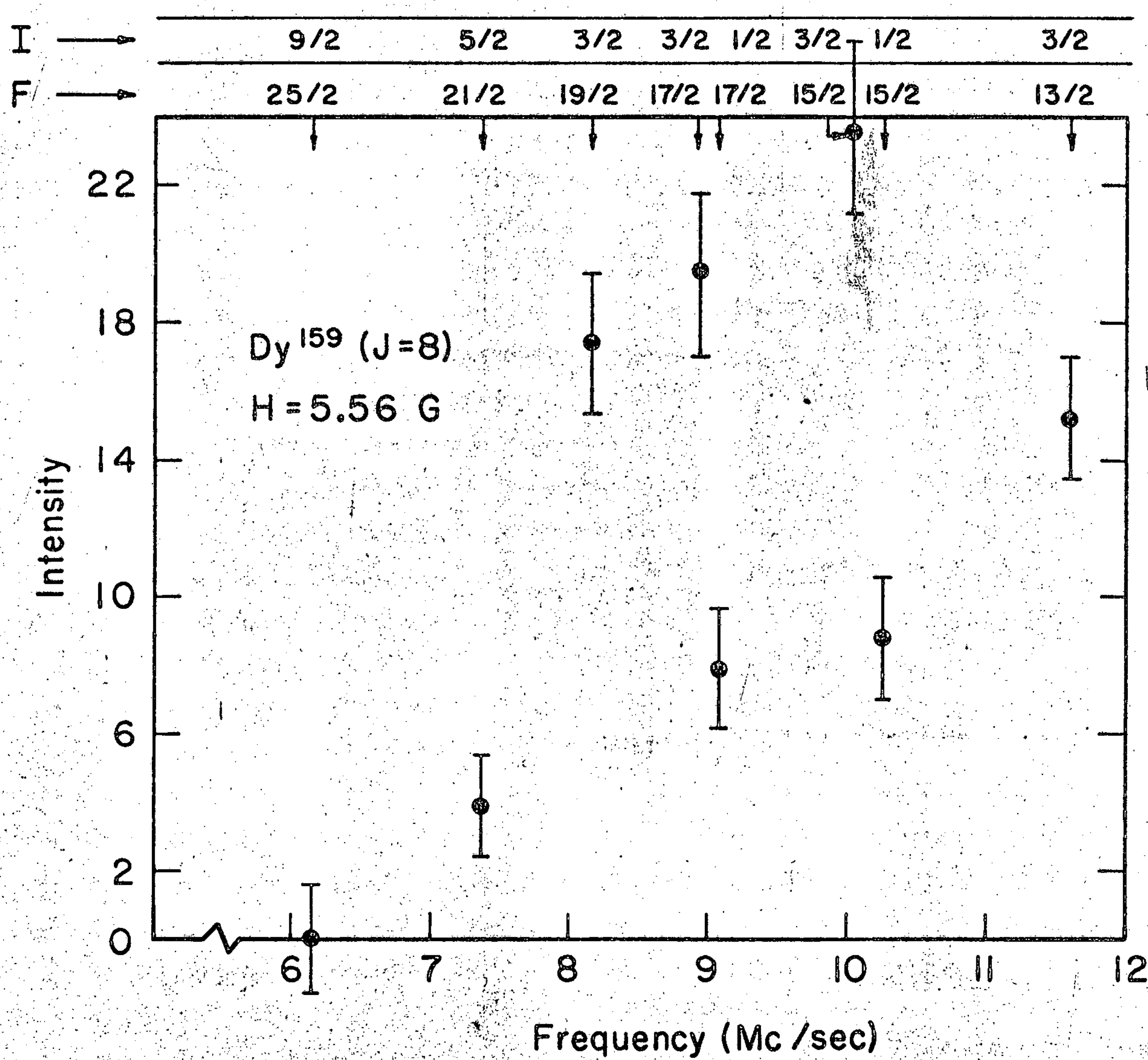
MU-34119



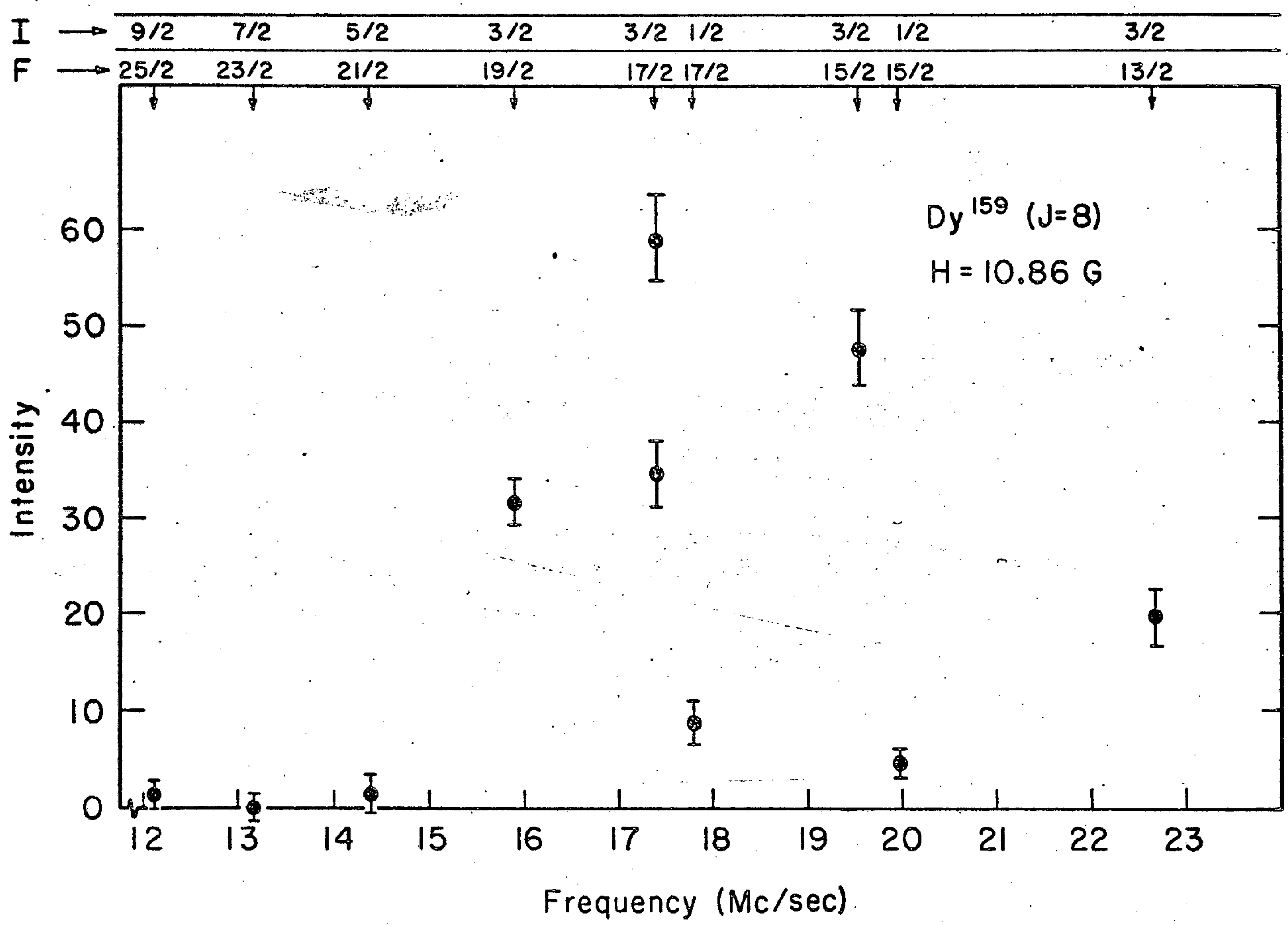
MU-34121


I
F
7/2
23/2
5/2
21/2
3/2
19/2
3/2
17/2
3/2
15/2
1/2
17/2
Dy159 (J=8)
H=2.81 G
Intensity
0
10
20
30
40
3.5
4.0
4.5
5.0
Frequency (Mc/sec)

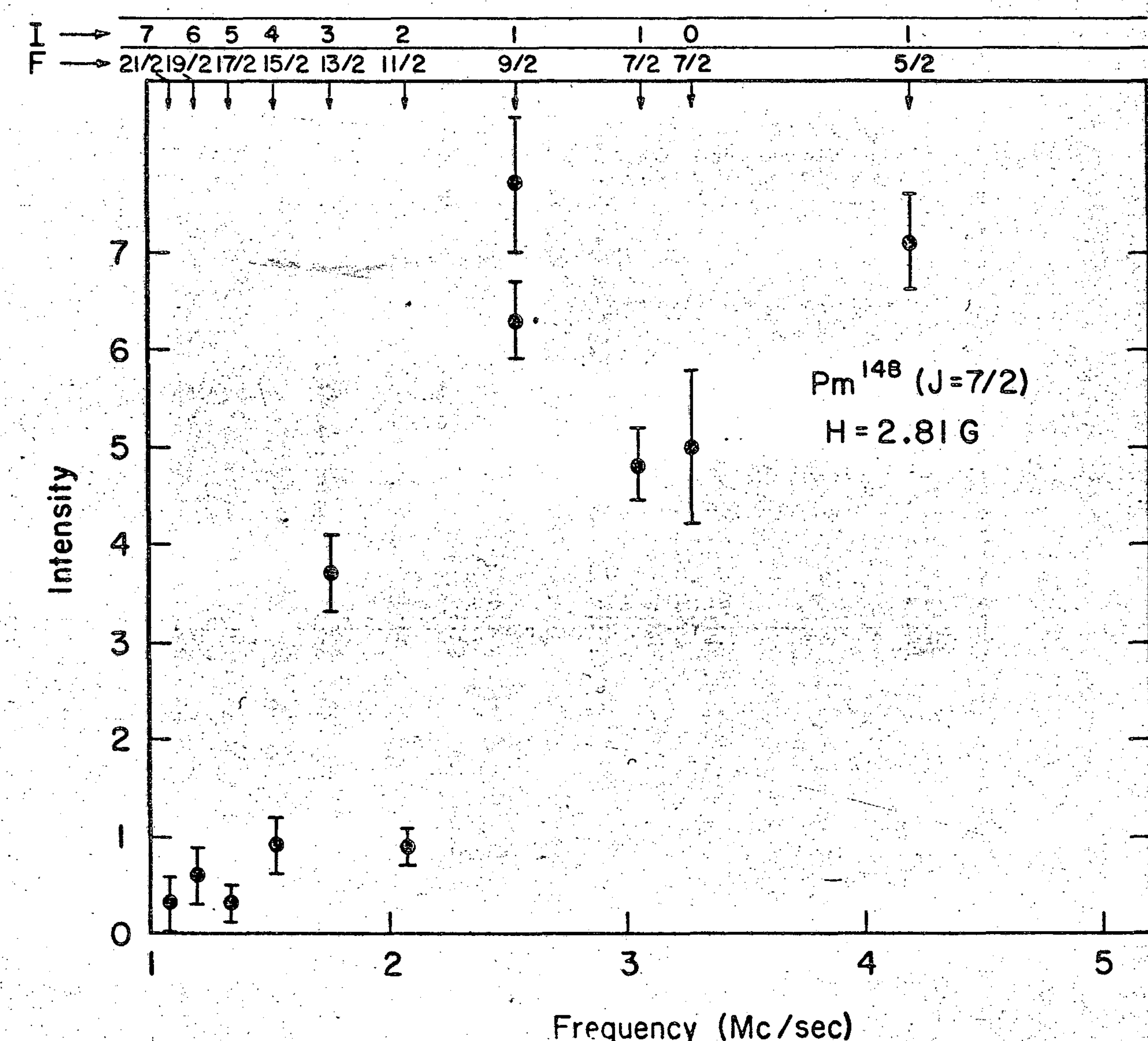
MU-34113


I
F
9/2
5/2
3/2
3/2
1/2
3/2
1/2
3/2
25/2
21/2
19/2
17/2
17/2
15/2
15/2
13/2
Dy159 (J=8)
H=5.56 G
Intensity
0
2
6
10
14
18
22
6
7
8
9
10
11
12
Frequency (Mc/sec)

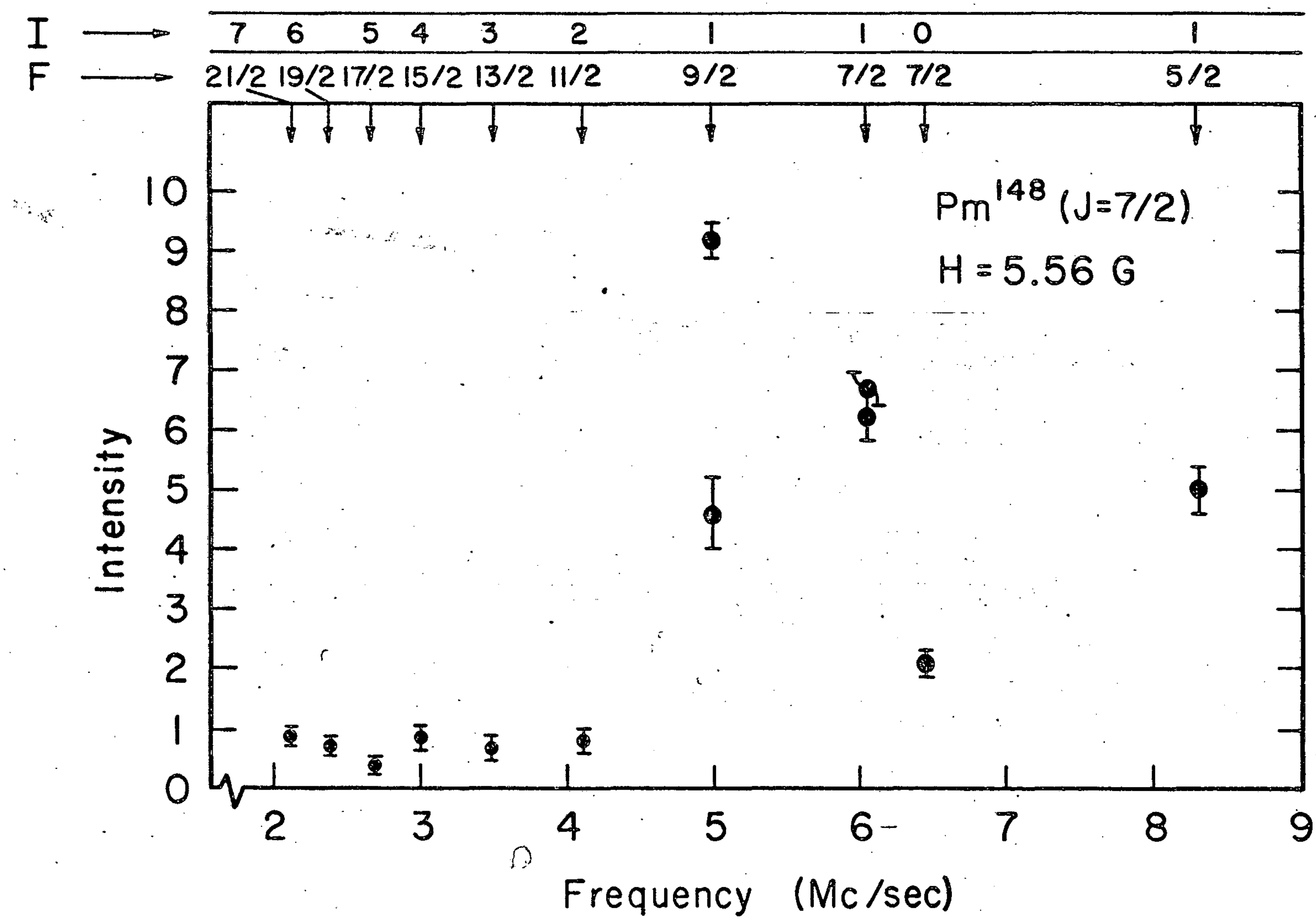
MU-34114


I
F
9/2
7/2
5/2
3/2
3/2
1/2
3/2
1/2
3/2
25/2
23/2
21/2
19/2
17/2
17/2
15/2
15/2
13/2
Dy 159 (J=8)
H = 10.86 G
Intensity
0
10
20
30
40
50
60
12
13
14
15
16
17
18
19
20
21
22
23
Frequency (Mc/sec)

MU-34115


I
F
7 6 5 4 3 2 1 1 0 1
21/2 19/2 17/2 15/2 13/2 11/2 9/2 7/2 7/2 5/2
Pm148 (J=7/2)
H=2.81 G
Intensity
Frequency (Mc/sec)

MU-34116


I
F
7 6 5 4 3 2 1 1 0 1
21/2 19/2 17/2 15/2 13/2 11/2 9/2 7/2 7/2 5/2
Pm148 (J=7/2)
H = 5.56 G
Intensity
0 1 2 3 4 5 6 7 8 9 10
2 3 4 5 6 7 8 9
Frequency (Mc/sec)

MU-34112