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Magnetic Moment and Spin of 6.9-h ^{93}Mo^{m}†

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Nuclei of ^{93}Mo^{m} were oriented in an iron lattice at temperatures down to 7 mK. Anisotropic angular distributions were observed for the 263-, 1477-, and 685-keV γ rays. The form of the angular distributions confirmed the spin-multipolarity sequence $\frac{21}{2}^{+}$ $(M4)$ $\frac{13}{2}^{+}$ $(E2)$ $\frac{9}{2}^{+}$ $(E2)$ $\frac{5}{2}^{+}$ for the isomeric decay. Their temperature dependences yielded the nuclear moment. Magnetic resonance measurements [NMR/ON (NMR with oriented nuclei)] were also performed, yielding a resonance at 170.5(4) MHz with a 1-kOe external polarizing field present. Comparison of the derived g factor with the moment from anisotropy data establishes the spin of ^{93}Mo^{m} as $\frac{21}{2}$. The final value of the magnetic moment is $|\mu| = 9.21(20)\mu_N$, assumed positive, with the error arising almost entirely from the uncertainty in the hyperfine field. Direct-field orientation in a 44-kOe field at 9 mK gave results in rough agreement. The measured moment confirmed the structure of the $\frac{21}{2}^{+}$ state as $[(\pi g_{9/2})_8^2;\ \nu d_{5/2}]_{21/2}$. The derived value of the proton $g_{9/2}$ g factor agrees well with trends in the $Z = 40$–45 region, but not with the g factor of the 8^{+} state in ^{92}Mo.

I. INTRODUCTION

High-spin nuclear isomers provide important tests of the validity of nuclear-structure calculations, because these isomers may be formed by coupling of several particles. Detailed information about the isomeric states can therefore often be interpreted in terms of properties of the single-particle states. This approach is especially valuable near closed shells or in other cases for which the composition of the isomeric state can be restricted *a priori* to a small number of likely configurations. If the magnetic moment is the property under study, the interpretation is most straightforward when proton states with $j = l + \frac{1}{2}$ are involved and the configuration is coupled to yield the maximum allowable spin. When these two criteria are satisfied the magnetic moment will have a larger value than for most other configurations that give the same spin.

The 6.9-h isomeric state[1-3] at 2425 keV in ^{93}Mo meets all the above conditions (Fig. 1). It is thus an ideal candidate for a nuclear moment measurement. With two protons and one neutron outside the closed shells at $Z = 40$ and $N = 50$, this state is generally considered[2] to have the structure $[(\pi_{9/2})_{8^+}{}^2;\ \nu d_{5/2}]_{21/2}$. The $(g_{9/2})_{8^+}{}^2$ proton configuration is further supported by the presence of 8^{+} states, with g factors that can only arise from a dominantly $(g_{9/2})^2$ configuration, at 2761 keV in ^{92}Mo[4] and at 2953 keV in ^{94}Mo.[5] In this paper we report the results of nuclear orientation experiments in which both the spin and the magnetic moment of the 6.9-h isomer of ^{93}Mo were determined. In addition to orientation experiments and NMR/ON (NMR with oriented nuclei) measurements with samples of ^{93}Mo^{m} in a ferromagnetic iron lattice, from which the spin and moment were obtained, we also report successful direct-field, or "brute-force" nuclear orientation on this isomer in a niobium lattice.

II. EXPERIMENTAL

The ^{93}Mo^{m} activity was produced by (p,n) or $(d,2n)$ reactions on niobium foils in the Berkeley 88-in. cyclotron. The target foils were used directly for the direct-field polarization studies. To bond these foils to the copper heat link, a thin layer of copper was first vapor deposited onto them. They were then soldered to the heat link with a Bi-Cd alloy. Foils of Fe(^{60}Co) were soldered nearby to provide a temperature reference.

The Fe(^{93}Mo^{m}) samples were made by melting a small piece of the irradiated niobium foil with an iron foil, yielding an alloy that was 0.6-at.% niobium. This alloy was then comelted with a previously prepared dilute Fe(^{60}Co) alloy, to provide a temperature reference, and rolled to a thickness of 10^{-2} cm. For NMR/ON studies the preparation was similar, but no ^{60}Co thermometer was added and the foils were successively annealed and rolled to a thickness of 10^{4} Å.

In all of these experiments low temperatures were achieved by contact cooling, using as a working substance cerium magnesium nitrate (CMN) which was adiabatically demagnetized from a magnetic field of 40 kOe and a bath temperature of 1.0 K. Temperatures of 7 and 9 mK were attained at the Fe(^{93}Mo^{m}) and Nb(^{93}Mo^{m}) samples, respectively. For the Fe(^{93}Mo^{m}) nuclear orientation work a magnetic polarizing field of 4.0 kOe was applied to the sample. In the NMR/ON experiments on Fe(^{93}Mo^{m}) the hysteresis properties of iron were used. The polarizing field was first raised to 4.0 kOe to polarize the sample, then reduced to 1.0 kOe before the radiofrequency field

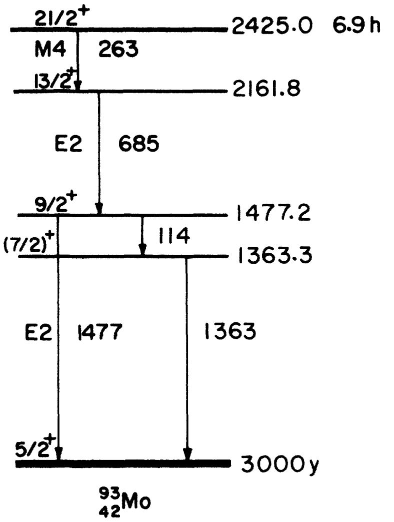

FIG. 1. Decay scheme of ^{93}Mo^m.

was applied, to maximize the hyperfine enhancement factor. The direct-field measurements were done in a special apparatus with a long (67-cm) heat link and a high-field, high-homogeneity polarizing magnet. Both cryostats have been described in detail elsewhere.[6,7]

γ-ray spectra were taken with Ge(Li) and NaI(Tl) detectors. Two Ge(Li) detectors, at 0 and 90° relative to the polarizing field, were used in the orientation experiments on Fe(^{93}Mo^m). Only one Ge(Li) detector, at 0°, was used in the direct-field experiment. The high-field polarizing magnet precluded the use of a 90° detector because of γ-ray absorption and scattering. In both cases continuous 15-min full-spectrum counts were taken as the samples warmed up. For the NMR/ON measurements intensity was far more important than spectral resolution. Thus a NaI(Tl) detector was set at 0°, and photons were counted over the energy range 230–1490 keV. The radio-frequency field $H_1 = 0.5$ mOe was frequency modulated at 100 Hz over a bandwidth of 1 MHz. Data processing was accomplished by standard procedures. A PDP-7 computer was used for data acquisition and preliminary analysis. Final least-squares fits were made on the LBL CDC 6600 computer by using nuclear orientation data analysis programs developed for this purpose.

III. RESULTS

The temperature dependence of the reduced intensities $W(\theta)=[I(\theta,1/T)]/[I(\theta,1/T=0)]$ of the 263-, 1479-, and 685-keV γ rays are shown in Fig. 2. The theoretical curves represent simultaneous fits of the 0 and 90° data to functions of the form

$$W(\theta)=1+f\sum_k B_kQ_kU_kF_kP_k(\cos\theta),$$

where the parameter f is inserted to describe the fraction of the nuclei that are behaving as expected for a perfect sample, Q_k is the solid-angle correction factor, and the remaining parameters have their usual significance.[8] Since the decay scheme in Fig. 1 implies $M4$, $E2$, and $E2$ multipolarities,

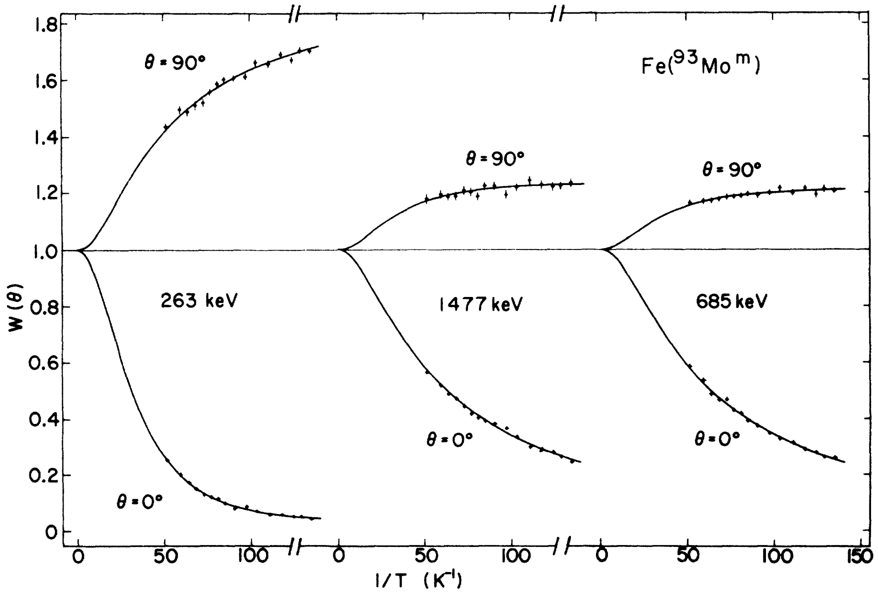

FIG. 2. Temperature dependence of the reduced intensities $W(\theta)$ of the 263-, 1477-, and 685-keV γ rays from a Fe(^{93}Mo^m) source parallel ($\theta = 0°$) and perpendicular ($\theta = 90°$) to an external polarizing field of 4 kOe, with fitted theoretical curves.

respectively, for these three γ rays, the angular momentum factors U_k and F_k were calculated on the assumption that these were pure-multipolarity transitions. The excellent agreement with experiment provides strong confirmation of the spin and multipolarity assignments in Fig. 1 for the transitions involving these three γ rays. The fitting procedure involved only the two parameters $|\mu H|$ and f. Values derived from the fits are given in Table I. The deviations of the values of $f = 0.96 - 0.97$ from unity suggest that the magnetization of the foil may not have been complete, some of the Mo atoms may not have been in proper lattice sites, the background, solid angle, and decay corrections may have been in error, unanticipated scattering may have occurred, or any combination of these sources of error. Since any one of these errors alone would have reduced the anisotropy, their cumulative effect of only 3–4% is very satisfactory.

The three values of $|\mu H|$ in Table I are in good agreement. Their weighted average,

$$|\mu H| = (12.15 \pm 0.20) \times 10^{-18}\ \text{erg},$$

is also in good agreement with the weighted average

$$|\mu H| = (12.08 \pm 0.20) \times 10^{-18}\ \text{erg},$$

obtained by fitting data from the six channels separately. In both averages the quoted errors are slightly larger than statistical, to account for scatter in the individual values. We shall use this latter value, as it is believed to be more reliable. The effective field in this case is -252 ± 5 kOe, the algebraic sum of the polarizing field, $+4.0$ kOe, and the hyperfine field of molybdenum in iron,[9] -256 ± 5 kOe. Thus the nuclear moment, as derived from the orientation experiments, is

$$\mu(^{93}\text{Mo}^{m}) = 9.49 \pm 0.22 \mu_N .$$

The sign of μ was, of course, not determined, but it is assumed to be positive.

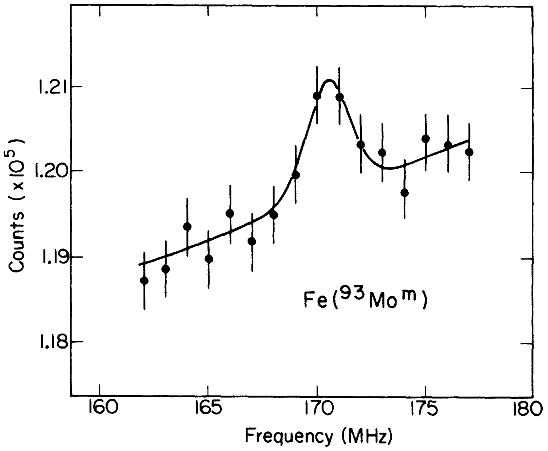

FIG. 3. Frequency dependence of γ-ray intensity emitted at $\theta = 0°$ relative to the external polarizing field of 1.0 kOe, with a perpendicular radiofrequency field of 0.5 mOe, frequency modulated at 100 Hz over a bandwidth of 1 MHz. The time interval between points was 2 min.

The NMR/ON experiment on Fe(^{93}Mo^{m}) gave the resonance shown in Fig. 3 at a frequency of 170.5 ± 0.4 MHz. In this case the effective field was -255 ± 5 kOe. Thus the moment, derived on the assumption that $I = \frac{21}{2}$, is

$$\mu(^{93}\text{Mo}^{m}) = 9.21 \pm 0.20 \mu_N .$$

The agreement between these two values of the magnetic moment confirms the value of the nuclear spin of this state as $I = \frac{21}{2}$. Table II gives a more detailed comparison of the ratio of γH as derived from orientation experiments to γH as derived from the NMR/ON experiment. As noted earlier,[10] the value of μH derived from a nuclear orientation experiment on a high-spin state is nearly independent of the assumed spin, while an NMR/ON measurement yields γH. Thus the nuclear spin can be uniquely determined as the value for which $(\gamma H)_{\text{ON}} \equiv (\mu H)_{\text{ON}}/I$ agrees with $(\gamma H)_{\text{NMR}}$. From Table II the spin $I = \frac{21}{2}$ is definitely preferred, although the sensitivity in this high-spin case is not as high as for lower spins.[6,10]

Most of the quoted error in either of the above values of $\mu(^{93}\text{Mo}^{m})$ arises from the uncertainty in H_{hf} Thus although the two moment values have about the same error, the NMR/ON determination of γH gives a result with 50 times the

TABLE I. Values of $|\mu H|$ and f from least-squares fits of Fe(^{93}Mo^{m}) data.

E_γ (keV)	$\lvert\mu H\rvert$ (10^{-18} erg)	f
263	12.24(19)	0.970(2)
685	11.89(36)	0.965(14)
1479	12.11(39)	0.961(14)

TABLE II. Ratios $(\gamma H)_{\text{ON}}/(\gamma H)_{\text{NMR}}$ for three trial spins in ^{93}Mo^{m}.

I	$(\gamma H)_{\text{ON}}/(\gamma H)_{\text{NMR}}$
$\frac{23}{2}$	0.94 ± 0.02
$\frac{21}{2}$	1.03 ± 0.02
$\frac{19}{2}$	1.14 ± 0.02

statistical weight of the orientation value. Since the latter is also more susceptible to systematic errors, we shall simply use the NMR/ON result as our final preferred value:

$$\mu(^{93}\mathrm{Mo}^m) = (+)9.21 \pm 0.20\mu_N ,$$

where the positive sign is assumed but not measured.

The direct-field measurements were qualitatively successful, giving changes in the counting rate as large as 20% for the 263-keV γ rays. Data for the 1477-keV γ rays are shown in Fig. 4. An approximate value of $\mu \sim 8.1\mu_N$, with an error of perhaps 10% or more, could be derived from these data. The 263-keV γ-ray result was somewhat lower but less reliable because of background. Although this experiment adds no new nuclear information, it suggests that direct-field polarization studies using γ radiation are feasible.

IV. DISCUSSION

Since 8^+ states appear at similar energies in both ^{92}Mo and ^{94}Mo, it is natural to interpret the $\frac{21}{2}^+$ state in ^{93}Mo as being derived from an 8^+ proton state. Indeed the large nuclear moment of $^{93}\mathrm{Mo}^m$ strongly supports this assignment, because the neighboring 8^+ states have large g factors, namely $g(8^+,{}^{92}\mathrm{Mo}) = +1.409 \pm 0.016$,[4] and $g(8^+,{}^{92}\mathrm{Mo}) = +1.31 \pm 0.02$.[5] A g factor of this size is very good evidence for proton $g_{9/2}$ character, since no other single-particle states in this region have such large g factors.

At a more quantitative level, we note that the observed moment of the $\frac{21}{2}^+$ state cannot be obtained by simply coupling a $d_{5/2}$ neutron to the 8^+ state in ^{92}Mo. This would give a moment

$$\mu = 8(1.409 \pm 0.016) - 1.30 = (9.97 \pm 0.13)\mu_N ,$$

well above the experimental value. The $d_{5/2}$ neutron moment used here[11] is that of the ground state of ^{91}Zr. This state was chosen because it has one neutron outside the closed shell at $N = 50$. An alternative approach would be to use a value of $-0.89\mu_N$, extrapolated from the known moments of $-0.9134\mu_N$ and $-0.9326\mu_N$ for the $\frac{5}{2}^+$ ground states in ^{95}Mo and ^{97}Mo, respectively.[12] This extrapolation is questionable, however, because nuclei with only one particle outside a closed proton or neutron shell (e.g., ^{93}Mo with $N = 51$) do not always follow such trends. If this extrapolated value is used the discussion is not changed very much: the calculated moment would be $10.38\mu_N$, still further above the experimental value.

The possibility that the $\frac{21}{2}^+$ state arises from another configuration is ruled out both on energy grounds and by the value of $\mu(\frac{21}{2}^+)$. Thus promotion of a $g_{9/2}$ proton to a $g_{7/2}$ state would require crossing a major shell ($Z = 50$) and would give a much smaller moment. Promoting the neutron to a $g_{7/2}$ state, then coupling it to the 8^+ proton core is energetically unfavorable, and it gives a still larger moment. The observed moment must therefore be interpreted within the context of a $[(\pi g_{9/2})_8{}^2; \nu d_{5/2}]_{21/2}$ coupling scheme.

The $g_{9/2}$-state proton g factor that can be derived from the $^{93}\mathrm{Mo}^m$ moment fits into the known trends in an interesting way. It was observed earlier[13] that the $g_{9/2}$ g factors in the $Z = 40-50$ region vary smoothly with Z. In Fig. 5 several $g_{9/2}$ g factors in this region are plotted. For the 8^+ states in ^{90}Zr,[4] ^{92}Mo,[4] and ^{94}Mo,[5] the measured

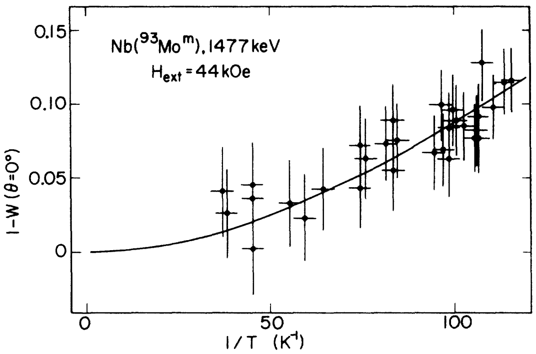

FIG. 4. Temperature dependence of the reduced intensity of the 1477-keV γ rays in the direct-field polarization experiment, observed parallel to the external field. The fitted curve, corresponding to a nuclear moment of $8.1\mu_N$, is in rough agreement with the Fe($^{93}\mathrm{Mo}^m$) results, but with a large error.

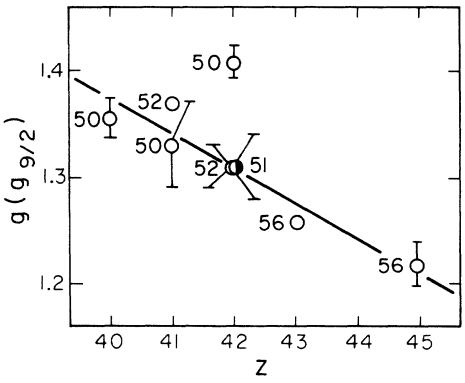

FIG. 5. Variation of empirical $g_{9/2}$ proton g factors with Z. The neutron number is given beside each point. The $^{93}\mathrm{Mo}^m$ result (shaded) appears to follow the main trend, indicated by a line, while the ^{92}Mo point is high.

g factors of 1.355(18), 1.409(16), and 1.31(2), respectively, were used directly, as were the g factors of 1.3707(1), 1.2625(1), and 1.22(2), respectively, measured on $\frac{9}{2}^+$ states of ^{93}Nb,[14] ^{99}Tc,[14] and ^{101}Rh.[7] A $g_{9/2}$ g factor of 1.33(4) was derived from the $I=\frac{17}{2}^-$, $g=1.24(4)$, 2368-keV state in ^{91}Nb,[5] based on von Feilitzsch's interpretation of this state as having a $[\pi(g_{9/2})_8{}^2;\ \pi p_{1/2}]_{17/2}$ structure, and assuming $g(p_{1/2}) = -0.275$. Each of the points in Fig. 5 is labeled with the neutron number of the state involved. The g factors appear to vary smoothly with Z except for the ^{92}Mo^m(8$^+$) case, which lies well above the rest. The reasons for the variation are believed to be $M1$ spin polarization and mesic exchange currents.[4]

A $g_{9/2}$ g factor of 1.31(3) is derived from the measured moment of the $\frac{21}{2}^+$ state in ^{93}Mo^m by uncoupling the $\nu d_{5/2}$ state with μ assumed to be $-1.30\mu_N$ from the experimental $\mu = 9.21(20)\mu_N$ if a configuration $[\pi(g_{9/2})_8{}^2;\ \nu d_{5/2}]_{21/2}$ is assumed. This value of $g(g_{9/2})$ fits nicely into the main sequence in Fig. 5, suggesting that the same variation of $g(g_{9/2})$ may hold for states with odd neutron numbers. Thus the $\frac{21}{2}^+$ state's moment can be estimated very accurately as $9.2\mu_N$ by coupling the $\nu d_{5/2}$ moment of $-1.30\mu_N$ observed in ^{91}Zr to an 8$^+$ proton configuration with a g factor of 1.31 estimated from the trend shown in Fig. 5. However, the direct approach of coupling this $\nu d_{5/2}$ moment to the actual measured moment of the 8$^+$ state in ^{92}Mo gives an estimate that is too large. Thus the mechanism that raises $g(g_{9/2})$ in ^{92}Mo above the other values is no longer operative in ^{93}Mo^m.

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