Nuclear moments of $^{102}Ag^m$ and $^{106}Ag^g$ †

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On-line atomic-beam-magnetic-resonance experiments at the Princeton cyclotron were used to measure the magnetic hyperfine structure transitions involving the isomeric state of ^{102}Ag ($T_{1/2}=8$ min, $I=2$) and the ground state of ^{106}Ag ($T_{1/2}=24$ s, $I=6$). The radioactive nuclei were formed by a (p,n) reaction on palladium inside the oven of the atomic beam apparatus. The values of magnetic dipole interaction constant are $A(102)=15\,060\pm900$ MHz and $A(106)=20\,345\pm600$ MHz. From these measurements we infer the values of the nuclear magnetic dipole moments to be $\mu(102)=+(4.12\pm0.25)\mu_N$ and $\mu(106)=+(2.83\pm0.2)\mu_N$.

[NUCLEAR MOMENTS $^{102}Ag^m$, $^{106}Ag^g$; measured a, g_I; deduced μ_I. Atomic beam magnetic resonance.]

I. INTRODUCTION

This paper reports the data of experiments to determine the nuclear dipole moments of $^{102}Ag^m$ and $^{106}Ag^g$ by the atomic-beam-magnetic-resonance method. Preliminary reports of these results have appeared earlier.[1] Other reports from this laboratory have described experiments on the decay scheme and nuclear spin of $^{102}Ag^m$[2] and on decay schemes, nuclear spins, and nuclear moments of both the isomer and ground state of ^{104}Ag.[3] Others have measured directly the spin of $^{102}Ag^g$.[4] The decay scheme of ^{102}Ag has recently been studied in great detail by Hnatowich, Munnich, and Kjelberg.[5] References to other silver isotopes' decay schemes may be most easily found in the compilation of Lederer, Hollander, and Perlman.[6] The isotopes' spins and moments are tabulated by Cohen and Fuller.[1]

II. EXPERIMENTAL PROCEDURE

The procedure of these experiments closely follows that of the work in this laboratory on the other silver isotopes, particularly that described in Refs. 2 and 3. The palladium target for the $^{102}Ag^m$ runs was that of Ref. 2; the target for the $^{106}Ag^g$ runs was natural palladium. In both cases the main reaction used to produce the activity was $Pd(p,n)Ag$ using approximately 16-MeV protons which bombarded a target contained in the atomic-beam-machine's oven. The Princeton FM cyclotron was used for the $^{106}Ag^g$ experiments. The $^{102}Ag^m$ experiment was begun using the old cyclotron, but the moment measurements were completed after the atomic-beam machine had been placed in the beam line of the new Princeton AVF cyclotron. The isotope to which a particular resonance was assigned was determined by measuring the radioactive half-life of the atoms which had made an atomic transition and had then been collected at the "flop" detector of the atomic-beam apparatus; this process is described in Ref. 2.

The strength of the homogeneous magnetic field in which atomic transitions are induced by the applied radio frequency field was gradually increased during the set of experiments on each isotope. No further increases were made when the uncertainties due to instabilities in the homogeneous magnetic field outweighed the potential increase in precision of the measured transition frequencies. Both single- and multiple-quantum transitions within a single F state were observed in each isotope, as in Ref. 3. Since $\Delta\nu$, the zero-field hyperfine splitting, is well into the microwave region in both isotopes, an attempt to observe transitions between F states was beyond the capability of our apparatus. The homogeneous field was measured for each experimental run by finding the resonance frequency in a beam of ^{39}K.

Figure 1(a) shows the hyperfine-structure level diagram for $^{106}Ag^g$; the diagram for $^{102}Ag^m$ is shown in Fig. 1(b). Since the silver atoms are in their $^2S_{1/2}$ ground state, the energy levels are given by the Breit-Rabi formula.[3,7] To a second-order approximation, transitions between two of these levels in the same F state at an applied homogeneous field H occur at a frequency

$$\nu_N(F,m_i\rightarrow F,m_f)=\left(\frac{g_J}{2}-\frac{\mu_I}{\mu_0}\right)\frac{\mu_0 H}{Fh} - \frac{(N+2m_f)}{\Delta\nu}\frac{(g_J-g_I)^2(\mu_0 H)^2}{4F^2h^2} = \nu_i-(N+2m_f)\delta\nu\,. \quad (1)$$

In this equation μ_I is the nuclear magnetic moment, μ_0 is the Bohr magneton, and m_f is the magnetic quantum number of the final state of the transition. The equation defines $\delta\nu$ and the so-called linear frequency ν_l. N is the quantum multiplicity of the transition.[3,8] For example, the frequency applied to induce the four quantum transition going from an initial state of $F=\frac{5}{2}$, $m_F=\frac{3}{2}$ to $F=\frac{5}{2}$, $m_F=-\frac{5}{2}$ would be

$$\nu=[W(\tfrac{3}{2})-W(-\tfrac{5}{2})]/4h.$$

This transition frequency is calculated by substituting $N=4$ and $m_f=-\frac{5}{2}$ in Eq. (1).

The second term in Eq. (1) indicates the presence of small splittings between transitions with different multiplicities going to the same final state. The frequency spectrum at a given magnetic field of the multiple-quantum transitions drawn on the level diagram of Fig. 1(b) is given in Fig. 1 (c); the solid lines indicate transitions observed in this experiment. For more detailed analysis of multiple-quantum transitions see Refs. 3 and 8.

Table I contains a list of the observed transitions in $^{106}Ag^g$ and $^{102}Ag^m$, respectively. Ordinarily the apparatus can only detect transitions of atoms going from states with $m_J>0$ to states with $m_J<0$. However, due to the very large $\Delta\nu$ of silver, the magnetic field in the deflecting magnets is not strong enough to completely decouple the atomic spin J from the nuclear spin I, leaving the total angular momentum F a fairly good quantum number. We therefore see some transitions from states with $m_F>0$ to states with $m_F<0$ for which the rule on m_J is not obeyed. This feature of this apparatus is discussed in more detail in Ref. 3.

The assignments of observed resonances to particular positions in the multiple-quantum spectrum

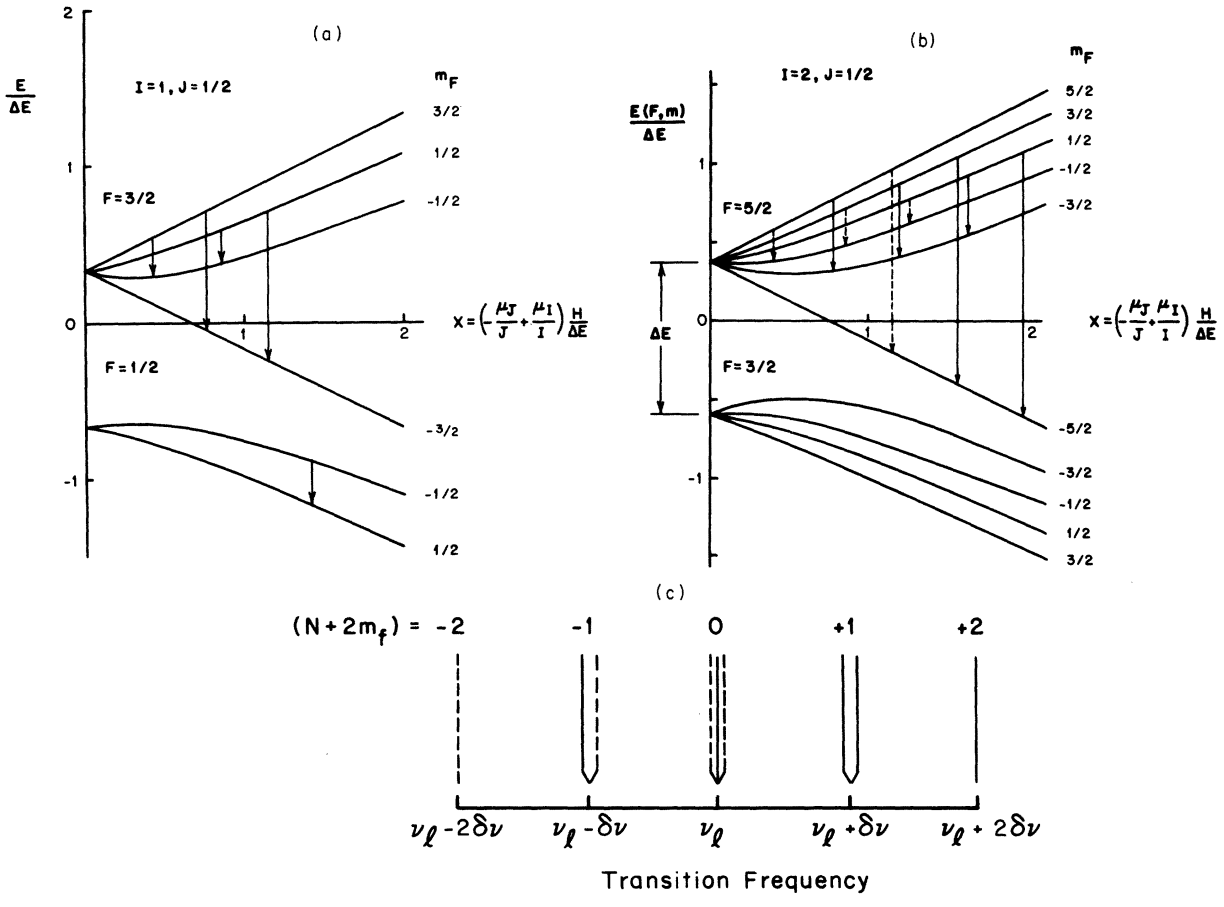

FIG. 1. (a) The hyperfine-structure levels of $^{106}Ag^g$. The solid arrows indicate transitions seen in this experiment. (b) The hyperfine-structure levels of $^{102}Ag^m$. The arrows indicate representative transitions; the solid arrows show transitions seen in this experiment. (c) A plot of the frequency spectrum at a given magnetic field of the hyperfine transitions shown in part (b). The transition frequencies are displaced from the linear frequency ν_l by amounts which depend upon the quantity $-(N+2m_f)$. All transitions with the same value of $-(N+2m_f)$ have the same frequency in second-order approximation; the members of each group are artificially split in the figure.

TABLE I. Resonance frequencies observed in the two silver nuclei. The quantum numbers are assigned primarily according to the amount of rf power needed to optimize the transition amplitude; as discussed in the text, transitions with the same value of $-(N+2m_f)$ have the same resonant frequency. The magnetic field is computed from the observed ^{39}K resonant frequency. The computer fitted the parameters A and g_I independently. For ^{106}Ag^g the nuclear moment corresponding to the fitted value of A was $2.69\mu_N$ using the Fermi-Segrè formula and the data for ^{107}Ag (Ref. 1); the moment corresponding to the fitted g_i was $2.96\mu_N$. The χ^2 for the fit was 16.4. For ^{102}Ag^m, the moments are $3.99\mu_N$ (from A) and $4.25\mu_N$ (from g_I). The χ^2 was 10.3.

Transition $(F_i, m_i; F_f, m_f)$	$-(N+2m_f)$	H (G)	Observed resonance frequency (MHz)	Residual ($\nu_{obs} - \nu_{computed}$) (MHz)
		^{106}Ag^g data		
$(\frac{3}{2}, -\frac{1}{2}; \frac{3}{2}, -\frac{3}{2})$	2	21.851(18)	23.380(20)	−0.027
$(\frac{3}{2}, \frac{1}{2}; \frac{3}{2}, -\frac{1}{2})$	0	64.679(8)	60.327(8)	0.004
$(\frac{3}{2}, \frac{1}{2}; \frac{3}{2}, -\frac{3}{2})$	1	64.679(8)	60.442(12)	−0.001
$(\frac{3}{2}, \frac{3}{2}; \frac{3}{2}, -\frac{1}{2})$	−1	64.618(6)	60.160(7)	0.013
$(\frac{3}{2}, \frac{3}{2}; \frac{3}{2}, -\frac{3}{2})$	0	64.618(6)	60.262(7)	−0.005
$(\frac{3}{2}, \frac{1}{2}; \frac{3}{2}, -\frac{1}{2})$	0	64.618(6)	60.255(12)	−0.010
$(\frac{3}{2}, \frac{1}{2}; \frac{3}{2}, -\frac{3}{2})$	1	64.618(6)	60.377(12)	−0.009
$(\frac{1}{2}, -\frac{1}{2}; \frac{1}{2}, \frac{1}{2})$	−2	64.618(6)	60.552(15)	−0.006
$(\frac{3}{2}, \frac{1}{2}; \frac{3}{2}, -\frac{1}{2})$	0	91.348(10)	85.207(10)	0.013
$(\frac{3}{2}, \frac{3}{2}; \frac{3}{2}, -\frac{1}{2})$	−1	91.334(13)	84.970(24)	0.026
$(\frac{3}{2}, \frac{3}{2}; \frac{3}{2}, -\frac{1}{2})$	−1	91.309(13)	84.882(5)	−0.039
		^{102}Ag^m data		
$(\frac{5}{2}, -\frac{3}{2}; \frac{5}{2}, -\frac{5}{2})$	4	15.207(19)	8.512(8)	0.000
$(\frac{5}{2}, -\frac{3}{2}; \frac{5}{2}, -\frac{5}{2})$	4	15.413(12)	8.625(10)	−0.002
$(\frac{5}{2}, -\frac{3}{2}; \frac{5}{2}, -\frac{5}{2})$	4	25.787(17)	14.430(20)	−0.012
$(\frac{5}{2}, \frac{1}{2}; \frac{5}{2}, -\frac{3}{2})$	1	90.679(7)	50.793(10)	0.017
$(\frac{5}{2}, \frac{3}{2}; \frac{5}{2}, -\frac{3}{2})$	0	93.105(10)	51.035(15)	−0.029
$(\frac{5}{2}, \frac{3}{2}; \frac{5}{2}, -\frac{5}{2})$	1	93.105(10)	52.127(10)	−0.010
$(\frac{5}{2}, \frac{1}{2}; \frac{5}{2}, -\frac{3}{2})$	1	93.105(10)	52.125(10)	−0.012
$(\frac{5}{2}, \frac{5}{2}; \frac{5}{2}, -\frac{3}{2})$	−1	93.113(7)	52.007(10)	−0.011
$(\frac{5}{2}, \frac{3}{2}; \frac{5}{2}, -\frac{3}{2})$	0	93.303(13)	52.170(10)	−0.005
$(\frac{5}{2}, \frac{3}{2}; \frac{5}{2}, -\frac{5}{2})$	1	93.303(13)	52.256(16)	0.009
$(\frac{5}{2}, \frac{1}{2}; \frac{5}{2}, -\frac{5}{2})$	2	93.303(13)	52.335(15)	0.014

were made on the basis of the amount of radio frequency power required to optimize the transition strength. A check on identification of resonances was the requirement that the final computer fit to all of the data be self-consistent; assignment of the wrong value of $[-(N+2m_f)]$ to a resonance caused the computer program to fit the data badly. Figure 2 shows the results of one experimental run in ^{106}Ag^g, clearly illustrating both the power dependence of multiple-quantum transition probabilities and the splittings in the multiple-quantum spectrum.

Table II gives the final results of the computer fit to all of the data for each of the isotopes. In each case the atomic g_J was assumed to be $-2.002\,341$,[9] and the computer did a least-squares fit to the data, assuming the nuclear moment and the atomic hyperfine-structure dipole-interaction

TABLE II. The values resulting from a least-squares fit to the data presented in Table I are listed. As explained in the text, the parameters A and g_I were allowed to vary independently. The resulting value of A is listed in the table; the value listed for the nuclear moment is that resulting from the average of the values obtained from the fitted g_I and from applying the Fermi-Segrè formula to the fitted A. The errors assigned to μ_I reflect the differences in the two components of the average. The fits show that the signs for both moments are definitely positive.

^{106}Ag^g
$A = 20\,345 \pm 600$ MHz
$\mu_I = +(2.83 \pm 0.2)\mu_N$
^{102}Ag^m
$A = 15\,060 \pm 900$ MHz
$\mu_I = +(4.12 \pm 0.25)\mu_N$

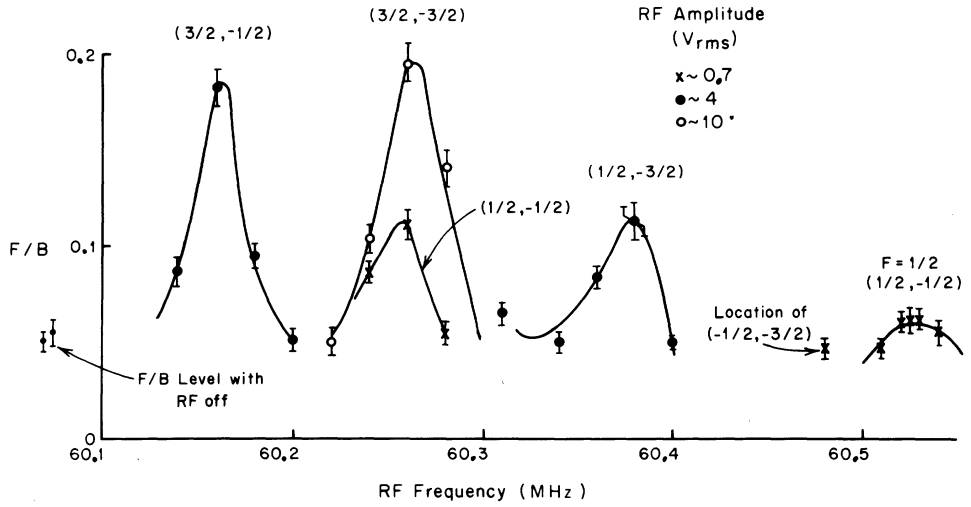

FIG. 2. The results of a single experimental run of $^{106}Ag^g$. The ratio of the number of detected "flopped" atoms, which have made an atomic transition, to the number of detected "beam" atoms is plotted as a function of the rf frequency. Different amounts of applied rf power are indicated by different symbols on the plot.

constant A to be independent parameters. The last column of Table I shows the residuals for each transition from this fit. The values of the nuclear moment quoted in Table II are the average of the value found from the computer's best value for g_I and the value found from the computer's value of A, using the Fermi-Segrè formula and the values of the moment and hyperfine splitting of ^{107}Ag.[3] Both nuclear moments are unambigously positive.

III. DISCUSSION

Silver has been a popular subject of study for nuclear moments for several reasons. In addition to being an odd-Z nucleus with properties adaptable to experimentation, there are many odd-odd isotopes and long-lived, low-lying isomers have been seen in most mass numbers reasonably near the stable isotopes. In terms of a simple shell model, one might say that the 47 protons are in states with three holes in the $g_{9/2}$ shell or with an $s_{1/2}$ hole. In the odd-odd nuclei, including the two levels which were the subjects of these experiments, the neutrons beyond $N=50$ seem primarily to be filling in the $g_{7/2}$ and $d_{5/2}$ shells. The neighboring nuclei with even-Z and the odd-A silvers seem to have spins and moments generally consistent with this simplified picture. It should be noted that the odd-A silvers have spin-$\frac{1}{2}$ ground states and spin-$\frac{7}{2}$ isomers for $A \geq 105$ and the inverted order for $A \leq 103$. In the even-A isotopes $^{106-110}Ag$ the ground-state spin is 1 and the isomers have spin 6; these spins are not inconsistent with the coupling rules of Brennan and Bernstein[10] for a configuration of $(g_{9/2})^{-3}{}_{7/2}$ protons and $(d_{5/2})$ neutrons. However, the even-A silvers with $A=102$, 104 have ground-state spins of 5 and isomers with spin 2, a departure from the simplest model.

The nuclear magnetic moments measured in these experiments are consistent with those of similar levels in other nuclei. The $^{102}Ag^m$ moment is very close to the moment of $^{104}Ag^m$[3] and to the 76-keV spin-2 level of ^{100}Rh.[1] The measured value of the $^{106}Ag^g$ moment is close to those recently measured for $^{108}Ag^g$[11] and $^{110}Ag^g$.[11,12] The moments are in agreement with simple calculations using empirical g factors obtained from the odd-A silvers for the protons and nearby cadmium and palladium nuclei for the neutrons, assuming either $d_{5/2}$ or $g_{7/2}$ neutrons. Satisfactory configuration-mixing calculations are difficult, due to the number of possible excitations which can be considered.

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[1]G. H. Fuller and V. W. Cohen, Nucl. Data A5, 433 (1969).

[2]B. Greenebaum, A. D. Jackson, Jr., and R. A. Naumann, Nucl. Phys. A106, 193 (1968).

[3]O. Ames, A. M. Bernstein, M. H. Brennan, and D. R. Hamilton, Phys. Rev. 123, 1793 (1961).

[4]B. Wannberg, J. O. Jonsson, and L. Sanner, Phys. Scr. 1, 238 (1970).

[5]D. J. Hnatowich, F. Munnich, and A. Kjelberg, Nucl. Phys. A177, 97 (1972).

[6]C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (Wiley, New York, 1968), 6th ed.

[7]N. F. Ramsey, *Molecular Beams* (Oxford U. P., London, 1956), p. 80.

[8]R. L. Christensen, D. R. Hamilton, H. G. Bennewitz, J. B. Reynolds, and H. H. Stroke, Phys. Rev. 122, 1302 (1961).

[9]G. S. Hayne and H. G. Robinson, Bull. Am. Phys. Soc. 5, 411 (1960); L. C. Balling and F. M. Pipkin, Phys. Rev. 139, A19 (1965); J. C. Wesley and A. Rich, Phys. Rev. A 4, 1341 (1971).

[10]M. H. Brennan and A. M. Bernstein, Phys. Rev. 120, 927 (1960).

[11]C. J. Cussens, G. K. Rochester, and K. F. Smith, J. Phys. A 2, 658 (1969).

[12]H. Ackermann, D. Dubbers, J. Mertens, A. Winnacker, and P. von Blanckenhagen, Z. Phys. 228, 329 (1969).