Speed of the $\Delta J=1$, $\Delta T=1$ $M1$ Transition in Al^{26}†

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The attenuated-Doppler-shift technique has been used to determine the mean life of the 1.059-MeV third excited state in Al^{26} to be $(3.1_{-0.8}^{+1.1})\times10^{-14}$ sec. The state decays primarily to the $J^\pi=0^+$, $T=1$, 0.229-MeV first excited state. The spin component in this pure $M1$ transition can be deduced from the analogous Gamow-Teller β decay from the Si^{26} ground state to the 1.059-MeV state in Al^{26}. The observed lifetime is only about half what would be predicted from the spin component alone. This indicates a strong orbital contribution which, in turn, implies a large $(d_{5/2})^{-2}$ component in the wave function. A summary of $M1$ transitions whose spin components are known from analogous β decays is given. A mean life of $(4.8\pm2.5)\times10^{-14}$ sec was found for the second excited state of Mg^{26}.

INTRODUCTION

IT has been pointed out[1] that the speed of a pure Gamow-Teller β decay and that of the spin component of the analogous $M1$ γ-ray transition are governed by the same matrix element. The $M1$ γ decay also contains an orbital contribution whose amplitude Kurath[1] has shown contains a factor of about $\frac{1}{5}$ relative to the spin component. The expression given by Kurath is

$$\Gamma_{M1}=\frac{129}{ft}E^3\frac{\langle T+1,1,T_z,0|T,T_z\rangle^2}{\langle T+1,1,T_z+1,\mp1|T,T_z\rangle^2}\times\left[1+0.2125\frac{\langle J_f,T\|l\tau\|J_i,T\pm1\rangle}{\langle J_f,T\|\sigma\tau\|J_i,T\pm1\rangle}\right]^{-2},\quad(1)$$

where T, T_z refer to the final state populated by the γ decay and E is the γ-ray energy in MeV. The matrix elements are reduced with respect to both angular momentum and isospin. Thus, the analogous Gamow-Teller β decay can be used to estimate the $M1$ transition speed. The estimate can be expected to be most valid where the log ft of the β decay is small (as here) and hence the spin component in the $M1$ transition is large. Indeed, the $Ne^{18}\rightarrow F^{18}$ β decay for which log $ft=3.049$ has been shown to give a reasonably accurate estimate of the lifetime of the J, $T=0$, $1\rightarrow1$, 0 transition[2] in F^{18}. However, the 0.68-MeV 0, $1\rightarrow1$, 0 transition in P^{30} has been found[3] to be considerably faster than can be accounted for exclusively by the spin component determined from the value log $ft=4.39$ for the $S^{30}\rightarrow P^{30}$ decay. A contribution from the orbital part is therefore indicated; the magnitude can be deduced from the measured lifetime. Another transition in this series is the 0.830-MeV 1, $0\rightarrow0$, 1 transition in Al^{26}; the measurement of its lifetime is the subject of this report.

The experiment is first described. It is shown that, in spite of the rather low value of log ft for the analogous $Si^{26}\rightarrow Al^{26}$ decay, the lifetime is so short that a substantial orbital contribution is required to explain the short lifetimes. In the final section we discuss the information about the wave functions in the light of these measurements.

LIFETIME MEASUREMENT

The energy-level diagram for Al^{26} is given in Fig. 1. The first excited state at 0.229 MeV is the analog of the ground states of Si^{26} and Mg^{26}. The third excited state, the $J^\pi=1^+$, $T=0$ state at 1.059 MeV, is fed by a 34% branch in the decay[4] of Si^{26}. This level decays virtually exclusively to the first excited state.[5] The lifetime obtained for this state from Kurath's relation, ignoring the orbital contribution, is 6.3×10^{-14} sec. This is in the range measurable by the attenuated-Doppler-shift technique.

In preliminary measurements, the state was populated by the $Na^{23}(\alpha,n)$ reaction at a resonance found at 4.95 MeV (230 keV above threshold). Spectra with good statistics were readily obtained with a peak-to-background ratio of about 4:3. Comparison of data from recoil into Au or Ni with those from recoil into vacuum indicated that very little attenuation ($\sim5\%$) was occurring. The indicated lifetime was considerably smaller than the 6.3×10^{-14} sec expected from the spin

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[1] D. Kurath, quoted in Ref. 2 and private communication.

[2] A. E. Blaugrund, D. H. Youngblood, G. C. Morrison, and R. E. Segel, Phys. Rev. **158**, 893 (1967).

[3] E. F. Kennedy, D. H. Youngblood, and A. E. Blaugrund, Phys. Rev. **158**, 897 (1967).

[4] G. Frick, A. Gallmann, D. E. Alburger, D. H. Wilkinson, and J. P. Coffin, Phys. Rev. **132**, 2169 (1963).

[5] R. W. Kavanagh, W. R. Mills, and R. Sherr, Phys. Rev. **97**, 248 (1955).

component alone and was thus in the range in which its determination was very sensitive to small changes in the shift. Small background lines could be very troublesome; in fact one, a line made by inelastic neutron scattering on germanium,[6] is known to exist at almost the exact energy (0.835 MeV) of the line of interest. It was therefore decided that a lifetime determination that is less susceptible to error could be made in a coincidence experiment.

The Al^{26} was formed in the $Mg^{24}(He^3,p)$ reaction, and a coincidence was required between the γ ray of interest and the protons feeding the 1.059-MeV state. This served to define the recoil direction and also eliminated virtually all of the possible sources of background, at the price of a greatly reduced yield. Figure 2 shows the experimental layout, details of which are given elsewhere.[7] Briefly, there is a single lithium-drifted germanium γ detector and two (silicon) proton detectors. The γ detector is at 30° to the incident beam and one proton detector is placed in a backward quadrant to select high-energy recoils that are moving toward the γ detector. The other proton detector is in a forward quadrant where it selects lower-energy recoils that are moving at some reasonably large angle relative to the γ detector. The placing of the detectors represents a compromise between maximum yield and maximum shift. In the present experiment the two proton detectors were placed at 45° and at 130°, respectively. The quantity to be measured is the difference between the energies of γ rays emitted by the two sets of recoils coincident with the protons at the two angles. Since the shifted and unshifted lines are measured simultaneously, problems associated with changes in energy calibration are minimized.

The system allows the shifts of up to four γ rays to be measured simultaneously.[7] Therefore, as a check, the shifts of the 418-keV γ ray from the decay of the second excited state were measured at the same time. Because of the long lifetime[8] of this state (1.23×10^{-9} sec), the Al^{26} recoils will come to rest in any solid before a significant number of γ rays have been emitted.

Measurements were made with targets consisting of a thin (20 $\mu g/cm^2$) Mg^{24} metallic layer deposited on either a 325-$\mu g/cm^2$ Cu foil or a 325-$\mu g/cm^2$ Ni foil so that most of the stopping occurred in the Cu or Ni backings. For each run, three targets were stacked so that the beam passed through them consecutively, a necessity to obtain sufficient yield. The thickness of the stopper, a compromise between slowing down of the recoils and degradation of the beam energy, was chosen so that virtually all decays of the state of interest occurred within this layer, although the recoils were not

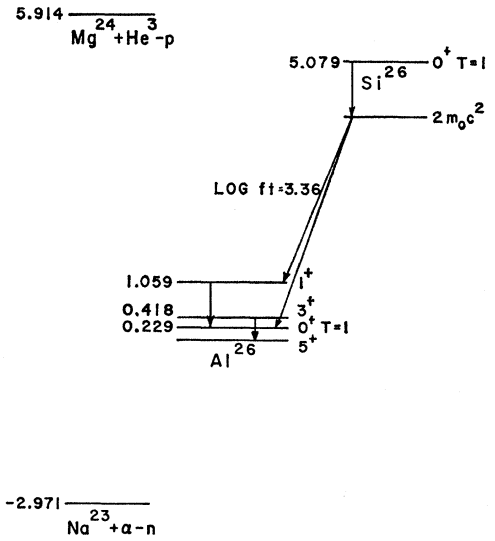

FIG. 1. Energy-level diagram showing the transition studied here and its environment.

completely stopped. Data were taken both with the recoils going into the copper or nickel and, by reversing the targets, with the recoils traveling in vacuum.

The He^3 particles were accelerated by the Argonne 4-MeV Van de Graaff. Since the excitation function showed the yield curve to be generally rising with increasing energy, the measurements were carried out at bombarding energies near 4.0 MeV—the maximum available. The germanium detector had a volume of 9 cc and an energy resolution width of about 2.5 keV under optimum conditions; during the run, at a total counting rate of ~12 000/sec, a typical resolution width was 3.0 keV.

Typical spectra are shown in Fig. 3. Although the statistics are somewhat limited, there is virtually no back-

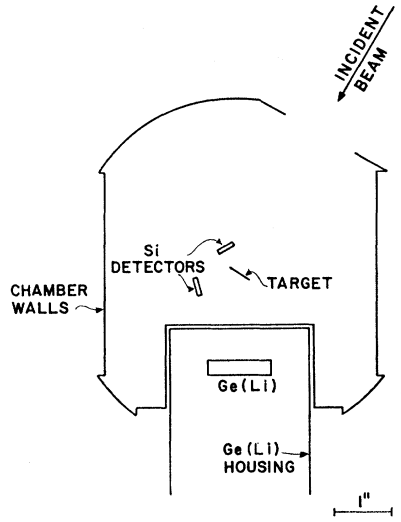

FIG. 2. Schematic diagram of the experimental arrangement used for the Doppler-shift measurements.

[6] C. Chasman, K. W. Jones, and R. A. Ristinen, Nucl. Instr. Methods 37, 1 (1965).

[7] S. I. Baker, thesis, Illinois Institute of Technology, 1967 (unpublished); S. I. Baker and R. E. Segel (to be published).

[8] S. Gorodetzky, R. Richert, R. Manquenouille, and A. Knipper, Compt. Rend. 251, 944 (1960).

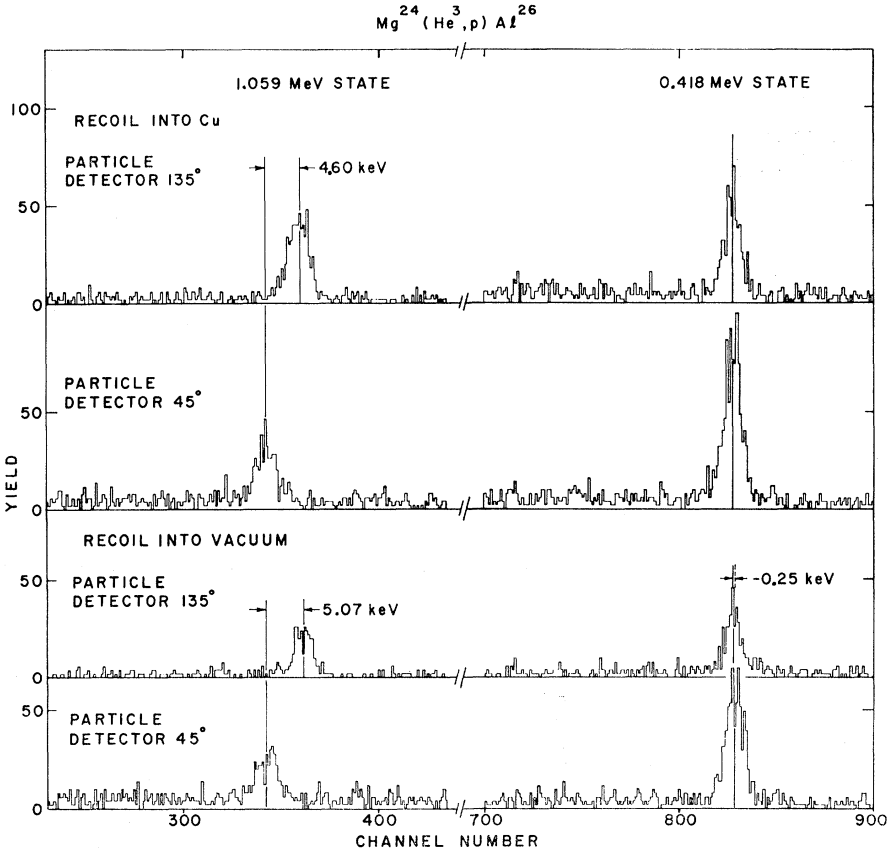

FIG. 3. Spectra showing the Doppler shifts for the 830- and 418-keV γ rays from the $Mg^{24}(He^3,p)Al^{26}$ reaction when the recoils were stopped in nickel and when they were allowed out into the vacuum.

ground. A computer program was used to find the centroid of each peak. Table I summarizes the results of the various Doppler-shift measurements. When the recoils were stopped in copper or nickel $(93\pm2)\%$ of the full shift was observed—the full shift being defined as the difference that would be observed if the recoils were not at all slowed down before decaying. When the γ energies were measured for recoils into vacuum, the observed shift was consistent with the small amount of slowing down that is expected to occur in the thin magnesium layer.

The γ rays from the long-lived second excited state showed a slight shift when the recoils were slowed down in copper. This was because foils were not quite thick enough to completely stop the recoils and therefore it was possible for them to emerge into the vacuum still having some velocity. The net effect could be only roughly estimated because it depended on the distance between the foils in the sandwich and this spacing could not be accurately measured. The expected shift was estimated to average 0.39 keV, in fair agreement with the measured shift of 0.10 ± 0.07 keV. When the recoils went out into the vacuum, a small "negative" shift was expected since the recoils in coincidence with the backward proton counter had to traverse more target material before escaping. The average measured shift of -0.29 ± 0.09 keV was in satisfactory agreement with the predicted -0.16 keV.

TABLE I. Doppler shifts observed for the recoils slowing down in various materials. The shift is observed as the difference in energy between γ rays coincident with protons at 130° and 45°.

Transition (MeV)	Mg thickness ($\mu g/cm^2$)	Backing	Calculated shift (keV)	Measured shift (keV)
$1.059\rightarrow0.229$	20	Ni	4.897[a]	4.48 ± 0.19
$1.059\rightarrow0.229$	20	Cu	4.897[a]	4.58 ± 0.13
$1.059\rightarrow0.229$	20	vacuum	4.911	4.95 ± 0.12
$1.059\rightarrow0.229$	279	vacuum	4.800	4.65 ± 0.11
$0.418\rightarrow0$	20	Cu	0.39	0.10 ± 0.07
$0.418\rightarrow0$	20	vacuum	-0.16	-0.29 ± 0.09

[a] Full shift.

The stopping-power theory of Lindhard *et al.*,[9] with the effects of nuclear scattering included according to the prescriptions given by Blaugrund,[10] was used to calculate the Doppler shift as a function of the lifetime expected for each recoil group. A mean life of $(3.1_{-0.8}^{+1.1})\times10^{-14}$ sec was found to fit the data for the 1.059-MeV state. With this lifetime, the shift predicted when the unbacked Mg^{24} foil was used was in satisfactory agreement with the measured value. The fact that the lifetime is only about half that predicted from the spin

[9] J. Lindhard, M. Scharff, and H. E. Schiott, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. 33, 14 (1963).
[10] A. E. Blaugrund, Nucl. Phys. 88, 501 (1966).

TABLE II. Comparison between $M1$ decay rates and the speed expected if only the spin component were present. The spin component is taken for the analogous Gamow-Teller β decay by use of the formula of Kurath.[a] The estimates of Moszkowski[b] are used in determining $|M|^2$, the ratio of observed transition speed to single-particle speed.

Nucleus	$E_i(J_i,T_i)$	E_f	(J_f,T_f)	$\log(2J_f{}^{\beta}+1)ft$	$T^{-1}(\text{sec}^{-1})$ From spin	$T^{-1}(\text{sec}^{-1})$ Measured	$\lvert M\rvert^2/(2J_f+1)$	Ref.
Li^6	3.56 (0,1)	0	(1,0)	3.40	0.85×10^{16}	$(1.25\pm0.20)\times10^{16}$	3.3	c
F^{18}	1.04 (0,1)	0	(1,0)	3.62	1.83×10^{14}	$(2.5_{-1.1}{}^{+2.5})\times10^{14}$	2.7	d
C^{12}	15.11 (1,1)	0	(0,0)	3.62	5.4×10^{16}	$(6.1\pm0.8)\times10^{16}$	0.63	e
Al^{26}	1.06 (1,0)	0.23	(0,1)	3.84	1.59×10^{13}	$(3.3_{-0.8}{}^{+1.7})\times10^{13}$	2.1	f
P^{30}	0.677 (0,1)	0	(1,0)	4.84	2.5×10^{12}	$(6.8\pm1.1)\times10^{12}$	0.29	g

[a] Reference 1.
[b] Reference 12.
[c] L. Cohen and R. A. Tobin, Nucl. Phys. **14**, 243 (1959).
[d] Reference 2.
[e] S. J. Skorka, R. Hübner, T. W. Retzschmidt, and H. Wahl, Nucl. Phys. **47**, 417 (1963).
[f] Present work.
[g] Reference 3.

component alone indicates a substantial orbital component. This point is discussed further below.

Incidental to the investigation of Al^{26} by the $Na^{23}(\alpha,n)$ reaction, the 2^+, 2.94-MeV second excited state in Mg^{26} was investigated. Data were taken at a bombarding energy $E_\alpha=3.0$ MeV where it is produced strongly in the $Na^{23}(\alpha,p)$ reaction. The measurements were made on the 1.13-MeV, 90% branch[11] to the first 2^+ state. At this energy the 3.58- and 3.94-MeV levels and the group of states at 4.32, 4.33, and 4.35 MeV may also be formed but no branching from the lower two states to the 2.94-MeV state is known and, in fact, no evidence was seen for the branching of these levels to the state of interest. No evidence was found for any significant population of the levels around 4.3 MeV. Spectra were taken with the Ge(Li) detector at 0° to the beam. Calibration sources (Mn^{54} and Na^{22}) were viewed while the data were taken. The unshifted energy obtained for the transition measured at 90° to the beam direction was 1.128 ± 0.001 MeV. Because the measurements were made well above threshold, the recoils could spread over a rather large cone ($\theta_{\max}=25°$) about the beam direction and therefore angular-distribution effects could be important. In fact, a shift of 5.34 ± 0.60 keV was observed when the recoils went into vacuum as against a full shift calculated to be 6.1 keV if the protons are emitted isotropically in the center-of-mass system; any discrepancy can be interpreted as implying a forward peaking in the proton angular distribution. With the γ detector at 0°, alternating between vacuum recoil and Ni stopper yielded an energy difference of 1.24 ± 0.56 keV. The attenuation in nickel was therefore 0.23 ± 0.10, which leads to a mean life of $(4.8\pm2.5)\times10^{-14}$ sec. Taking the mixing ratio $E2/M1=0.12$ in amplitude,[11] we find $|M|^2=0.47$ and 25 for the $M1$ and $E2$ parts, respectively, where $|M|^2$ represents the ratio of the observed transition probability to the single-particle estimate as given by Moszkowski.[12]

Our result is in disagreement with the value $(2.0\pm0.8)\times10^{-13}$ sec reported by Haüssen *et al.*[13] They also used the attenuated-Doppler-shift technique, populating the state by the $Mg^{26}(p,p')$ reaction well above threshold, and observing only singles γ spectra. However, they did not measure the unattenuated shift,[13] but instead calculated it on the assumption of isotropic emission of the protons in the c.m. system. We note that if the proton distribution is peaked forward in the $Mg^{26}(p,p')$ reaction, as it apparently is in the $Na^{23}(\alpha,p)$ reaction, the unattenuated shift would be smaller so that a shorter lifetime would be required.

DISCUSSION

Table II lists the various $M1$ transitions that can be compared with analogous Gamow-Teller β decays. In every case the measured $M1$ speed is greater than can be accounted for by the spin part alone, although for F^{18} and C^{12} the experimental uncertainty exceeds the difference. It therefore appears that there is usually some measurable contribution from the orbital part.

For the Al^{26} transition measured here, the orbital part significantly increases the transition speed in spite of the fact that the spin part makes a large contribution. Using Kurath's formula (1), we see that the amplitude of the reduced matrix element for the orbital part must be about twice that for the spin part. In terms of the shell model, the low-lying states of Al^{26} can be described as an O^{16} core plus valence nucleons in $2s_{1/2}$ and $1d_{5/2}$ orbits. The nucleons in the initial and final states will have the same orbital quantum numbers since the $M1$ operator does not involve a change in l. Since nucleons in an s state have no orbital angular momentum, the large orbital contribution to the transition speed indicates large d components in the wave functions. Indeed, an estimate of the transition speed taking the states to be pure $(d_{5/2})^{-2}$ (i.e., the $d_{5/2}$ shell closing at Si^{28}) yields about the observed value.[14]

[11] P. M. Endt and C. van der Leun, Nucl. Phys. **34**, 1 (1962).
[12] S. A. Moszkowski, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by Kai Siegbahn (North-Holland Publishing Company, Amsterdam, 1965), Vol. II, p. 865.
[13] O. Haüssen, T. K. Alexander, and C. Broude, Bull. Am. Phys. Soc. **12**, 555 (1967) and private communication.
[14] D. Kurath (private communication).

The speed of the transition in P^{30} is also much greater than can be accounted for by the spin component alone. Here, however, the relative importance of the orbital component can be attributed mainly to inhibition of the spin component. The reduced matrix element for the orbital component in P^{30} is only about a sixth of that in Al^{26} and thus the leading term in the wave function for the states in P^{30} could still correspond to two $s_{1/2}$ nucleons about a Si^{28} core. The lifetime measurements therefore point to a separation of the $d_{5/2}$ and $s_{1/2}$ subshells in the mass region near Si^{28}. The wave functions are certainly not pure; indeed, some valence nucleons in a d state are needed to account for the orbital component in P^{30}.

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Study of the (d,p) Reactions on $Zn^{64,66,68,70}$†

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Angular distributions from the (d,p) reactions on $Zn^{64,66,68,70}$ have been measured with 10.0-MeV deuterons from the Argonne Tandem van de Graaff accelerator. The energies, spins, parities, and spectroscopic factors of levels up to about 3.5-MeV excitation energy have been determined by use of distorted-wave Born-approximation calculations. Empirical J-dependence rules are used to distinguish between $\frac{3}{2}^-$ and $\frac{1}{2}^-$ states. The ground-state Q values of the $Zn^{64,66,68,70}(d,p)$ reactions, determined within ±10 keV, were 5.758, 4.827, 4.259, and 3.609 MeV, respectively. The sums of the spectroscopic factors are discussed briefly.

INTRODUCTION

INFORMATION on the energy levels in the odd-A zinc isotopes is available from β-γ decay studies,[1] the (d,p) and (p,d) reaction[2,3] for $A=65$, 67, and 69, and some Coulomb-excitation work[4] on Zn^{67}. In the present experiment we studied the (d,p) reaction with better energy resolution, statistically more accurate data, and more complete angular distributions than in past work. We have also obtained new information on the energy levels of Zn^{71}. Spins, parities, and spectroscopic factors for most states have been extracted from the data.

EXPERIMENTAL PROCEDURE

The 10.0-MeV deuteron beam from the Argonne Tandem Van de Graaff was used to obtain angular distributions between 25° and 165° in an 18-in.-diam scattering chamber.[5] Refrigerated surface-barrier Si detectors 2000 μ thick with a typical resolution of around 50 keV were used, subtending a solid angle of 10^{-3} sr. The targets were isotopically enriched[6] self-supporting metal foils ~0.5 mg/cm² in thickness. Beam currents $\leqslant 0.2$ μA were used with 100–200 μC of beam charge per point.

In order to be certain of resolving some closely spaced levels at the higher excitation energies and to avoid difficulties with the large number of elastically scattered deuterons at the extreme forward angles, the angular distributions between 5° and 40° were measured with the broad-range magnetic spectrograph.[7] The typical resolution was 10–15 keV. Here somewhat thinner targets evaporated on 20-μg/cm² carbon backings were used. The particles were detected in Kodak NTB emulsion 50 μ thick, covered with 10-mil acetate foils which stopped all particles except protons. The ground-state Q values of the $Zn^{70}(d,p)Zn^{71}$ reaction had not previously been determined. In addition to the data at

TABLE I. Ground-state Q values (MeV).

Reaction	$Zn^{64}(d,p)Zn^{65}$	$Zn^{66}(d,p)Zn^{67}$	$Zn^{68}(d,p)Zn^{69}$	$Zn^{70}(d,p)Zn^{71}$
Previous[a]	5.764±0.007	4.829±0.012	4.278±0.008	3.817±0.05
This experiment	5.758±0.01	4.827±0.01	4.259±0.01	3.609±0.01

[a] Reference 9.

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

[1] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C.), NRC 59-2-23.

[2] F. B. Shull and A. J. Elwyn, Phys. Rev. **112**, 1667 (1958); L. C. McIntyre, Phys. Rev. **152**, 103 (1966).

[3] E. K. Lin and B. L. Cohen, Phys. Rev. **132**, 2632 (1963).

[4] R. C. Ritter, P. H. Stelson, F. K. McGowan, and R. L. Robinson, Phys. Rev. **128**, 2320 (1962); D. G. Alkhazov, V. D. Vasil'ev, G. M. Gusinskii, I. K. Lemberg, and V. A. Nabichvrishvili, Izv. Akad. Nauk SSSR, Ser. Fiz. **28**, 1683 (1964) [English transl.: Bull. Acad. Sci. Phys. Ser. **28**, 1575 (1964)].

[5] J. T. Heinrich and T. H. Braid (to be published).

[6] The Zn^{64} target was enriched to 98.5%, the Zn^{66} to 97.8%, the Zn^{68} to 96.8%, and the Zn^{70} to 85.9%. The remainder of the Zn^{70} target consisted of 5.1% Zn^{64}, 3.7% Zn^{66}, 0.8% Zn^{67}, and 4.5% Zn^{68}.

[7] J. R. Erskine, Phys. Rev. **135**, B110 (1964).