# Measurement of the Magnetic Moment of the 279-kev State in $Tl^{203}$ Using Resonance Fluorescence*

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Using an ultracentrifuge, nuclear resonance fluorescence was observed by detecting the scattered gamma radiation from the 279-kev level in $Tl^{203}$. The rotation of the large anisotropic resonance-scattering pattern from this level was measured when a thallium scatterer was placed in an external field perpendicular to the plane of the scattering. The measured precession angle corresponds to a magnetic moment of the 279-kev state in $Tl^{203}$, $\mu_{279}=+0.35\pm0.26$ nm. The result agrees with two recent theoretical predictions of $\mu_{279}$: the single-particle model prediction of Kisslinger and the ($Hg^{202}$ core+odd particle) model calculation of de-Shalit.

## I. INTRODUCTION

THE recent growth of more accurate data concerning the well known nuclear parameters $E$, the energy level $\tau$, the lifetime of an excited state, and $\delta$ the mixing ratio, has given impetus to the measurement of the more elusive nuclear variables, for example, the determination of $\mu$, the magnetic moment of an excited state. The knowledge of $\mu$ is important from a long range point of view in that the gross accumulation of all information involving nuclear parameters will lead eventually to a better understanding of nuclear structure from first principles. Also, with the knowledge of $\mu$, one may be able to distinguish between various phenomenological theories of a particular nucleus as well. The case of $\mu_{279}$, the magnetic moment of the 279-kev level in $Tl^{203}$ is interesting especially as an example of the latter point. Recently, two opposing views have been proposed to explain the level structure of the excited states of $Tl^{203}$. They cannot be distinguished on the basis of lifetime measurements alone. One view held by Kisslinger[1] points out that the excited states in $Tl^{203}$ (see Fig. 1) are single-particle levels and that the $l$-forbidden $M1$ transition from the single particle $d_{\frac{3}{2}}$ 279-kev excited state to the $s_{\frac{1}{2}}$ ground state ($\Delta l=2$) can proceed only through configuration mixing. The other view, calculated by de-Shalit,[2] considers the excited states of $Tl^{203}$ to be composed of $Hg^{202}$ core excited levels coupled with the odd proton. To first order, the $M1$ transition also would be forbidden in that it can proceed only by the mixing of core-particle states. In the beginning of this experiment there were no theoretical calculations of the magnetic moment of the 279-kev state in $Tl^{203}$. Since in general, the theoretical calculations of the ground state magnetic moments are good only to about 0.3 nm, this initial attempt to use the resonance fluorescence technique with an ultracentrifuge for the measurement of a magnetic moment in an excited state aimed for an accuracy of the same order of magnitude in the experimental determination of $\mu$. However, during the course of the experiment, the theoretical values of the magnetic moment of the 279-kev state in $Tl^{203}$ were calculated. The single particle value of Kisslinger[3] is $\mu_{279}=0.48$ nm while the core model calculation of de-Shalit[4] results in $\mu_{279}=0.43\pm0.27$ nm.

In addition to this experiment, the measurement of only one other magnetic moment of an excited state employing resonance fluorescence techniques has been completed. Using a gaseous $Co^{56}$ source, Metzger[5] measured $\mu$ of the 845-kev state in $Fe^{56}$. No essentially new ideas are needed to obtain a magnetic moment of an excited state using resonance fluorescence. One still utilizes the classical method of precessing a radiation pattern from a nucleus with an applied magnetic field. However, now the pattern is not a gamma-gamma angular correlation but the angular distribution pattern of scattered resonance radiation. As a result, it is possible to profit from the large possible anisotropies that occur in some distribution patterns to measure

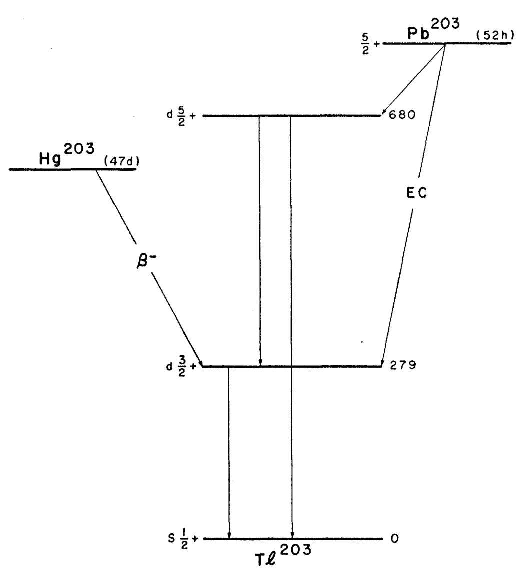


FIG. 1. The excited states of $Tl^{203}$. Energies are given in kev.

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[1] L. S. Kisslinger, Phys. Rev. **114**, 292 (1959).
[2] A. de-Shalit, Phys. Rev. **122**, 1530 (1961).
[3] L. Kisslinger (private communication).
[4] A. de-Shalit (private communication).
[5] F. R. Metzger, Nuclear Phys. **27**, 612 (1961).

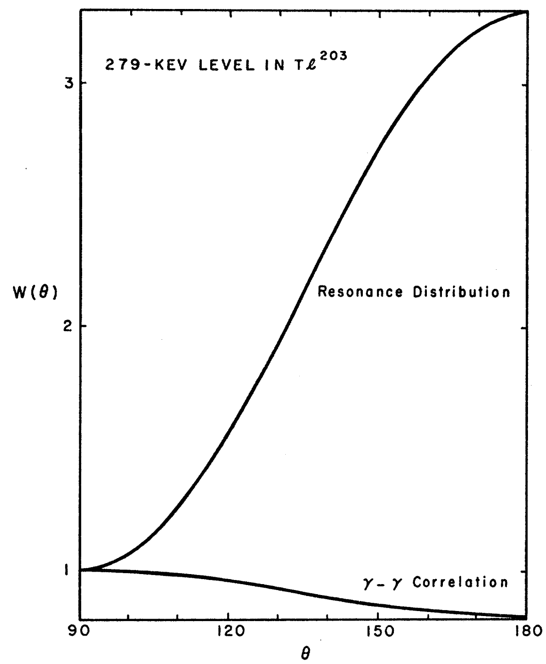


FIG. 2. A comparison of the resonance angular distribution pattern with the gamma-gamma angular correlation for the 279-kev state in $Tl^{203}$.

smaller angular precessions. For example, in the $Tl^{203}$ case (see Fig. 2), the slope[6] in the resonance angular distribution is 7 times steeper than in the $\gamma$-$\gamma$ angular correlation pattern.[7] The internal 320 000-gauss field in $Fe^{56}$ would shift an angular correlation pattern 0.28%/deg while it is 17 times larger in the resonance fluorescence measurement being 4.9%/deg.[5] The distribution pattern can be much larger than the angular correlation pattern for some cases due to the fact that the function from each transitional step which enters the anisotropy coefficient $A_\nu$ [$A_\nu$ is the coefficient of the $P_\nu(\cos\theta)$ term] "squares" in the resonance distribution. In the resonance distribution the emission and absorption processes are the same, and $A_\nu = A$(step 1) $\times A$(step 2) for the gamma-gamma cascade becomes $A^2$ (step 1 or 2) for the resonance distribution.

Perhaps the most important advantage of the resonance technique is the fact that as a result of the magnetic field being applied to an inert scatterer not a radioactive source, the method is both clean and gentle. Since the recoil energy loss is small, for example, 0.5 ev in the case of the 279-kev transition in $Tl^{203}$, the nucleus remains in its lattice site. As a consequence, the atomic electrons are undisturbed and except for paramagnetic and solid state effects, the applied magnetic field can be considered the effective precessing magnetic field. One does not have either the $\beta$-decay or $K$-capture effects that plague the gamma-gamma experiments. In fact, the determination of $\mu_{279}$ using resonance fluorescence may be useful as a calibration experiment for both the angular correlation and resonance techniques of measuring magnetic moments in excited states since the high counting rates in a gamma-gamma correlation measurement would make the latter experiment also feasible.

The fiberglass rotors that were developed for the magnetic moment experiments with the ultracentrifuge have a sufficiently high ratio of tensile strength to density to reach sufficient speeds which can compensate for the recoil energy losses resulting from the emission and absorption of the 279-kev gamma ray in $Tl^{203}$. In fact during the course of the experiment, the rotor turned about $2\times10^9$ times at 467 m/sec without visible effects of fatigue.

## II. EXPERIMENTAL PROCEDURE

Two sources were prepared with activities of about 30 and 300 mC of $Hg^{203}$, respectively. The first source was obtained from the Oak Ridge National Laboratory in the form of $Hg(NO_3)_2$, converted to 25 mg of HgS, and added to a small centrifuge tube. The strength of this source was limited by the specific activity available at the time of preparation and the capacity of the centrifuge tube. A second source was produced at the high flux Westinghouse test reactor by bombarding 25 mg of HgO enriched in 95% $Hg^{202}$ with a neutron flux of $2\times10^{14}$ n/sec for 2 reactor cycles. This source also was encapsulated in a small centrifuge tube.

A cutout view of the experimental apparatus is shown in Fig. 3. A thallium scatterer and its lead comparison scatterer automatically replaced one another every ten minutes. The scatterers were rectangular solids $1\frac{1}{2}$ in.$\times\frac{3}{4}$ in.$\times\frac{1}{4}$ in. and were located about 15 cm from the mean position of the source and 8 cm from the detector between the pole tips of the magnet. The detector, a 35-mm diameter and 40-mm long NaI(Tl) crystal mounted on an RCA 6342 photomultiplier tube, was shielded from the direct radiation. The shielding included gold around the centrifuge vessel itself, whereas, lead and armco iron encased the detector. The armco iron served an additional purpose. Together with two layers of mu metal and one layer of conetic-fernetic metal, it shielded the phototube from the stray fields of the 15 000-gauss magnet. A 0.014-in. lead absorber interposed between the scatterer and the detector attenuated the Compton scattered gamma rays from the first source. Due to pile up from the scattered radiation more absorber was needed with the second source and initially 0.031-in. lead and $\frac{1}{16}$-in. cadmium were used but this amount of absorber was decreased as the source decayed.

The experimental details of the operation of the centrifuge and its auxiliary electronic equipment have

[6] B. I. Deutch and F. R. Metzger, Phys. Rev. **122**, 848 (1961).
[7] See T. R. Gerholm, B.-G. Petterson, B. Van Nooijen, and Z. Grabowski, Nuclear Phys. **24**, 177 (1961), for a recent summary of the $\gamma$-$\gamma$ angular correlation measurements of the excited states in $Tl^{203}$.

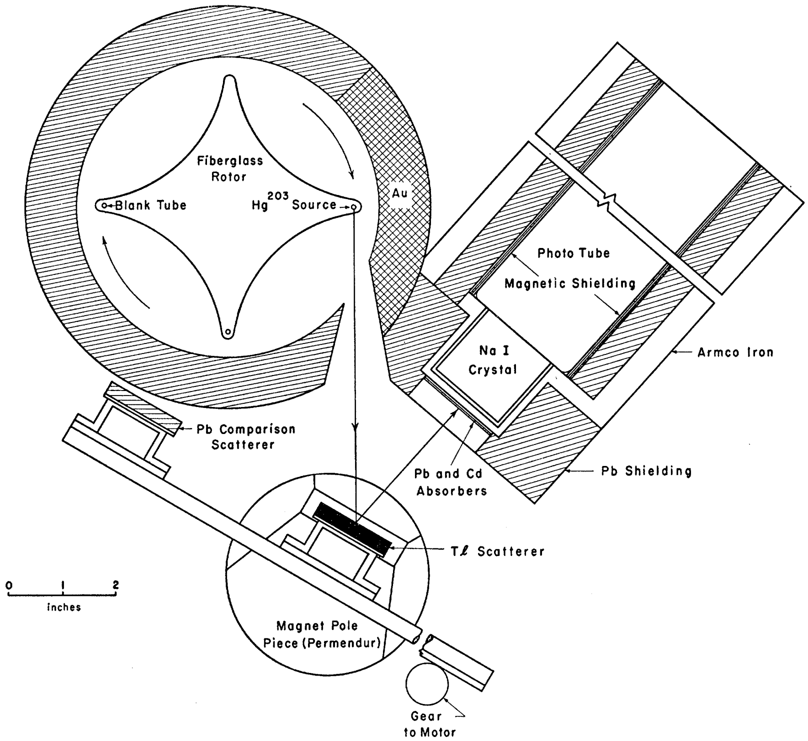


FIG. 3. A cut-out view of the experimental apparatus.

been described previously.[6] In the present experiment several changes were made. A star-shaped fiberglass rotor (see Fig. 3) composed of General Electric 11546 B fiberglass plastic was operated in the experiment in place of the usual metallic rotor to avoid problems with eddy currents that would have been generated from the inhomogeneous stray magnetic fields intersecting the rapidly spinning rotor. Two different magnets were used in the experiment. Only the higher flux magnet used with the second source will be described. This magnet, machined out of Armco iron, was constructed in the shape of a "C" containing an $11\frac{1}{4}$ in.$\times 4\frac{3}{4}$ in. $\times 3\frac{3}{4}$ in. body with two $12\frac{3}{4}$ in.$\times 4\frac{3}{4}$ in.$\times 3\frac{3}{4}$ in. arms each holding pole pieces $9\frac{3}{4}$-in. long$\times 3\frac{3}{4}$-in. diameter with permendur pole tips.[8]

A Lincoln shield arc welder rated for 600 amp at 40 v with 60% duty cycle generated the continuous 300-amp dc to produce fields across the scatterer of about 13 500 gauss with the magnet used with the first source and operating at 350 amp yielded 15 000 gauss with the magnet described above during the measurements with the second source. This field was reversed by slowly increasing the resistance in the exciter circuit of the generator until there was no current in the magnet coils before switching the direction of the current. This procedure prevented the steel shaft of the rotating centrifuge from being jolted by a rapid change of flux. The field was reversed every 20 min enabling both the scatterer and comparison scatterer to be in the experimental position before each change of field direction. The sources were rotated at a fixed source velocity of 467 m/sec, the velocity yielding the maximum scattering effect for the geometry used. The scattering angles were 135° and 131° for the first and second sources, respectively. These angles are close to where the counting rate change for a given applied magnetic field is a maximum. At frequent intervals throughout the experiment, the measurements were repeated with the source at rest to calibrate the apparatus for small magnetic or electronic drifts.

[8] The alloy containing 50% iron and 50% cobalt with the trade name permendur was donated by the Allegheny Ludlum Steel Co.

## III. EXPERIMENTAL RESULTS

Table I lists the data taken in the experiment for source 1 and the seven runs with source 2. The last column is the ratio of the change in the counting rate to the resonance counting rate at a fixed scattering angle $\theta$, in percent, resulting from the reversal of the applied magnetic field. It is corrected by the small effect found when the sources were at rest. The resonance effect was measured at 467 m/sec, the velocity which results in the maximum resonance counting rate for the geometry used. The combined data from source 1 and 2 contain a total of 600 000 resonance counts of which approximately half of this total are the resonance counts for a given direction of the applied magnetic field. The errors quoted are purely statistical. The large errors result from the statistical uncertainties in the total counting rate. This total counting rate is over 7 times the primary resonance effect because of the background from competing Compton and Raleigh scattering.

TABLE I. $W(v)$, the resonance counting rate, is the difference between the counting rate $N_{Tl}$ with the thallium scatterer and the counting rate $N_{Pb}$ with the lead scatterer for a given field direction, scattering angle, and centrifuge velocity $v$. $\Delta W'$ is the change in $W$ upon field reversal at a given source velocity. $\Delta W$ is $\Delta W'$ at the velocity of the maximum resonant effect (467 m/sec) minus $\Delta W'$ at zero velocity. The last column is the ratio of the change in the counting rate to the resonance counting rate at a fixed angle $\theta$, in percent, resulting from the reversal of the applied magnetic field. The data in this column are corrected by the small effect found when the sources were at rest.

| Source | Run | $W(467)=N_{Tl}-N_{Pb}$ (counts/10 min) | $\Delta W'(467)=W(467)_{\text{field up}}-W(467)_{\text{field down}}$ (counts/10 min) | $\Delta W=\Delta W'(467)-\Delta W'(0)$ (counts/10 min) | $\Delta W/W(467)$ (in percent) |
|---|---|---|---|---|---|
| 1 | 1 | 173 | $3.9\pm4.7$ | $3.8\pm5.7$ | $2.2\pm3.3$ |
| 2 | 1 | 1540 | $24\pm49$ | $17\pm55$ | $1.1\pm3.6$ |
| | 2 | 1050 | $58\pm28$ | $47\pm35$ | $4.5\pm3.3$ |
| | 3 | 968 | $-14\pm25$ | $-16\pm29$ | $-1.7\pm3.0$ |
| | 4 | 877 | $-3.1\pm23$ | $12\pm27$ | $1.4\pm3.1$ |
| | 5 | 956 | $28\pm28$ | $8.5\pm32$ | $0.89\pm3.4$ |
| | 6 | 797 | $-15\pm19$ | $-10\pm21$ | $-1.3\pm2.6$ |
| | 7 | 709 | $21\pm18$ | $22\pm19$ | $3.1\pm2.7$ |
| Av 2 | | | | | $1.03\pm1.15$ |

## IV. EVALUATION

The angular distribution of the resonant scattered gamma rays follows the distribution

$$W(\theta)=\frac{1}{1+\frac{1}{3}a}(1+a\cos^2\theta), \qquad (1)$$

where the experimental value of $a=2.31\pm0.40$.[9] When a magnetic field is applied to the Tl scatterer, the distribution pattern shifts a fraction of a degree $\Delta\theta$. To first order, for small precession angles there is no attenuation of the distribution and

$$\Delta\theta=2.74\times10^5 gH\tau \text{ deg/sec}, \qquad (2)$$

where $g$ is the nuclear $g$ factor, $H$ is the effective magnetic field at the site of the nucleus, and $\tau$ is the mean lifetime of the level. The ratio of the change in the counting rate $\Delta W$ to the resonance counting rate $W$ resulting from the reversal of the magnetic field for a distribution obeying Eq. (1) can be shown to be

$$\frac{\Delta W}{W}=\frac{a\sin2\theta\sin2\Delta\theta}{1+a\cos^2\theta}, \qquad (3)$$

where $\theta$ is the scattering angle.

Using Eqs. (2) and (3) to evaluate $g$, one can calculate the magnetic moment $\mu$ from $\mu=gI$ where $I$, the spin of the excited state, has the value $\frac{3}{2}$.

With the data from Table I, $\tau=4.08\times10^{-10}$ sec,[10] and $\theta=135°$, $H=13\,500$ gauss for source 1 and $\theta=131°$, $H=15\,000$ gauss for source 2, one arrives at the following final value for the magnetic moment of the 279-kev level in $Tl^{203}$:

$$\mu_{279}=+0.35\pm0.26 \text{ nm}.$$

The error in the value of $\mu_{279}$ results mainly from counting statistics but also includes the uncertainties in the anisotropy coefficient $a$.

There is evidence that the above value of $\mu_{279}$ is free from corrections due to crystalline fields. Any attenuation of the angular correlation of the resonance radiation or the polarization of Coulomb excitation in the thallium metal would have lowered the mixing amplitude $\delta$ in the 279-kev transition derived from the angular distribution. However, the agreement with the measured $\delta$ from the distribution and polarization with the $\delta$ determined from lifetime measurements indicates that there are no appreciable extranuclear effects which attenuate either the distribution or polarization of the radiation from that level.[6]

## V. DISCUSSION

The de-Shalit model[2] assumes that the 279-kev state is composed of a $Hg^{202}$ core with spin $J_c=2$ coupled to a proton with spin $j_p=\frac{1}{2}$ to form the excited level with resultant spin $J=\frac{3}{2}$. The $g$ factor of this state can be calculated from the Landé formula,

$$g=\tfrac{1}{2}(g_c+g_p)+\tfrac{1}{2}(g_c-g_p)\frac{J_c(J_c+1)-j_p(j_p+1)}{J(J+1)}, \qquad (4)$$

and is[4]

$$g_{279}=(6/5)g_c-(1/5)g_p. \qquad (5)$$

In the ground state $J=\frac{1}{2}$, the core has spin $J_c=0$, resulting in $g_0=g_p$. Using Eq. (9) in reference 2, one can show that for the 404-kev $M1$ transition probability $T_{\frac{3}{2}\to\frac{1}{2}}$,

$$T_{\frac{3}{2}\to\frac{1}{2}}/E^3=1.7\times10^{12}\,(g_c-g_p)^2 \text{ sec}^{-1}\text{ Mev}^{-3}, \qquad (6)$$

where $E=0.404$, the energy of the transition in Mev.

With the lifetime of the 680-kev level $=(7.7\pm1.0)\times10^{-13}$ sec,[11] the ratio of total cascade to crossover transitions from the 680-kev level $=6$,[11] and the total 404-kev conversion coefficient $=0.176$, one calculates from Eq. (6) that $(g_c-g_p)=\pm(2.43\pm0.15)$ nm. Using

[9] The value of the anisotropy listed in reference (6) was calculated for $A_2$. This is related to the value given above by the equation: $a=3A_2/(2-A_2)$.

[10] See reference 6 for a summary of the various lifetime measurements.

[11] F. K. McGowan and P. H. Stelson, Phys. Rev. **109**, 901 (1958).

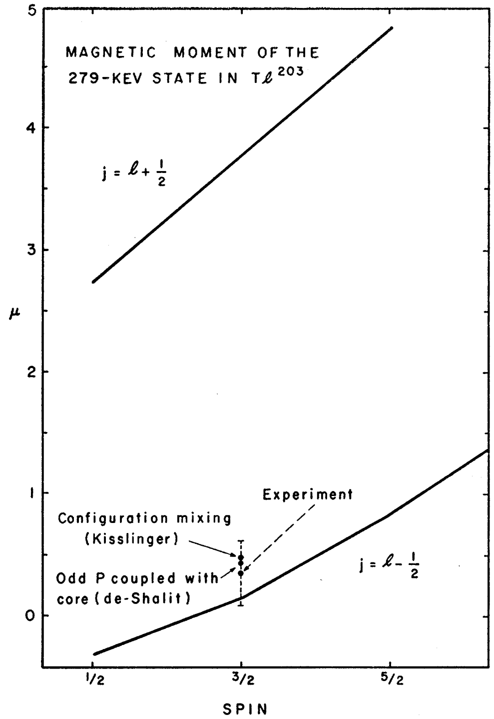


FIG. 4. A comparison of the theoretical values for the magnetic moment of the 279-kev state in $Tl^{203}$ with the experimental value. The dashed line is the experimental error in the measured value. The solid lines are the Schmidt lines for an odd-proton nucleus.

this value and $\mu_0 = 1.596$ nm, one finds with the aid of Eq. (5) that the de-Shalit model predicts $\mu_{279} = 0.43 \pm 0.27$ nm. The principal error in this value arises from the uncertainty in the experimental determination of the lifetime of the 680-kev level.

Kisslinger calculated the wave functions for particles in shell model levels interacting with a short-range force. These wave functions are corrected using the methods of Arima and Horie[12] and Blin-Stoyle[13] for changes in the magnetic moments due to the admixture of higher seniority states. Utilizing a force parameter which yields the correct magnetic moment for the ground state, Kisslinger predicts[3] $\mu_{279} = +0.48$ nm. There is no error assigned to this value.

TABLE II. A comparison of the experimental and theoretical values of $\mu_{279}$, the magnetic moment of the 279-kev level in $Tl^{203}$. The error in the de-Shalit theoretical value results from the uncertainties in the experimental determination of the lifetime of the 680-kev level in $Tl^{203}$.

| $\mu_{279}$ (nm) | Measurement or model | Investigator |
|---|---|---|
| $+0.35 \pm 0.26$ | Experimental | Deutch |
| $+0.48$ | Single particle (theoretical) | Kisslinger |
| $+0.43 \pm 0.27$ | $Hg^{202}$ core+odd particle (theoretical) | de-Shalit |

Table II compares the theoretical and experimental values of $\mu_{279}$, the magnetic moment of the 279-kev level in $Tl^{203}$. All three values agree within their expected errors. Figure 4 illustrates these values compared with the Schmidt value prediction for an odd-proton nucleus. The dashed line in the figure is the uncertainty in the experimental result. All values lie on the side of the $j = l - 1$ Schmidt line which is consistent with a shell-model prediction of a $d_{\frac{3}{2}}$ excited state.

Unfortunately the experimental result cannot be used to distinguish between the two theoretical predictions. One would have to decrease the theoretical uncertainties. As a first step towards this goal, the lifetime of the 680-kev level and its branching will be measured with greater precision.


## ACKNOWLEDGMENTS

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[12] A. Arima and H. Horie, Progr. Theoret. Phys. (Kyoto) **12**, 623 (1954); H. Horie and A. Arima, Phys. Rev. **99**, 778 (1955); A. Arima, H. Horie, and M. Sano, Progr. Theoret. Phys. (Kyoto) **17**, 567 (1957).

[13] R. J. Blin-Stoyle, Proc. Phys. Soc. (London) **A66**, 1158 (1953); R. J. Blin-Stoyle and M. A. Perks, *ibid.* **A67**, 885 (1954).