g-Factor Measurement of a Three-Particle Isomeric State of ^{209}Po Following Pulsed Generation in (α,xn) Reactions*

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A 100-nsec isomer was found in ^{209}Po. The time-differential angular distribution of delayed γ rays has been studied in the pulsed generation of aligned isomeric states in (α,xn) reactions with the use of cyclotron beam bursts. With a metallic lead target, no perturbation of the angular distribution during approximately 1 half-life could be detected. The g factor of the isomeric state was determined to be $g=+0.88\pm0.05$, which suggests an interpretation of this isomer as the $17/2^-$ three-particle state of the $[(h_{9/2}(p))^2p_{1/2}(n)]$ configuration.

1. INTRODUCTION

A RECENTLY developed method[1] of nanosecond time analysis of γ rays emitted in (particle, xn) reactions, utilizing natural beam bunches of a cyclotron and fast-time characteristics of a Ge(Li) detector, has revealed the presence of a number of high-spin isomers that were hitherto unknown. Because of the large angular momentum transfer, such states are at $t=0$ highly aligned perpendicularly to the beam direction.[2,3] This fact can be used to investigate hyperfine interactions in these isomeric states.

So far, hyperfine interactions of nuclear excited states have mainly been studied by means of perturbed angular correlation (PAC)[4] which involves successive radiations through an intermediate state with a half-life of less than 10^{-6} sec. The use of nuclear reactions to form aligned states is a natural extension of the PAC method. In principle, there are two possibilities: One can either study the time variation of the alignment by measuring the time-differential angular distribution, or one can destroy the alignment by inducing NMR transitions and observing the resonance frequencies. Here we report on a time-differential observation of a perturbed angular distribution following the pulsed generation of an aligned isomeric state in ^{209}Po.

Compared to PAC following radioactive decay (which is, for $T_{1/2}\gtrsim10^{-7}$ sec, limited by the choice of sources to only a very few cases) in-beam measurements of perturbed angular distributions (PAD) offer the following advantages: (1) By choosing the proper target and beam energy a large variety of new isomers can be reached. Since (particle, xn) reactions populate any isomeric state if it exists at all, the present method maximizes the use of existing isomers. Especially, very high spin states can be studied. (2) A large alignment is formed at $t=0$ and can be observed without measuring reemitted particles or preceding γ transitions in coincidence with the delayed γ radiation. This permits the use of only one detector, at an angle with respect to the beam. Furthermore, we do not lose yield by making time analysis, and therefore PAD counting rates can be made as fast as normal singles counting rates. (3) Large recoil energies are available and can be used to implant the product nuclei into different host environments. (4) For timing measurements a sufficiently sharp time width of the individual beam bursts [2–4 nsec full width at half-maximum (FWHM)] ensures measurement of the time-differential PAD with a time resolution of typically a few nanoseconds. This is comparable to the resolution achieved with conventional fast electronics and solid-state detectors.[1]

In the present paper we report such measurements with the $^{207(208)}$Pb$(\alpha,2(3)n)^{209}$Po reaction which populates a new 100-nsec isomer. The observation and interpretation of this isomer will be described in Sec. 3. The goal of our measurements was twofold. First, a suitable target structure had to be found in which any nuclear relaxation time was comparable to or longer than the half-life of the isomeric state. Second, after being able to preserve the alignment for sufficiently long time a determination of the g factor of the 100-nsec state in ^{209}Po was planned. As has been discussed elsewhere,[5] a diamagnetic metallic cubic target is most advantageous for half-lives that are shorter than typical nuclear relaxation times ($T_1T\sim10^{-2}$ sec °K for heavy elements). Thus a thick target of metallic lead seemed to be a perfect choice for the reaction Pb(α,xn)Po. No static quadrupole interaction is expected since in a thick lead target the product nuclei will be stopped ultimately at a site of cubic symmetry. It is not known whether there occurs any time-dependent interaction in connection with the slowing down and stopping mechanism in thick targets since, in general, the available information

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[1] T. Yamazaki and G. T. Ewan, Phys. Letters **24B**, 278 (1967); Nucl. Instr. Methods **62**, 101 (1968).
[2] H. Ejiri, M. Ishihara, M. Sakai, K. Katori, and T. Inamura, Phys. Letters **18**, 314 (1965).
[3] R. M. Diamond, E. Matthias, J. O. Newton, and F. S. Stephens, Phys. Rev. Letters **16**, 1205 (1966).
[4] See, e.g., H. Frauenfelder and R. M. Steffen, in *Alpha-, Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Co., Amsterdam, 1965), Vol. 2, Chap. XIX, p. 997.
[5] E. Matthias, in *Hyperfine Interaction in Matter*, edited by A. J. Freeman and R. B. Frankel (Academic Press Inc., New York, 1967), Chap. 13, p. 595.

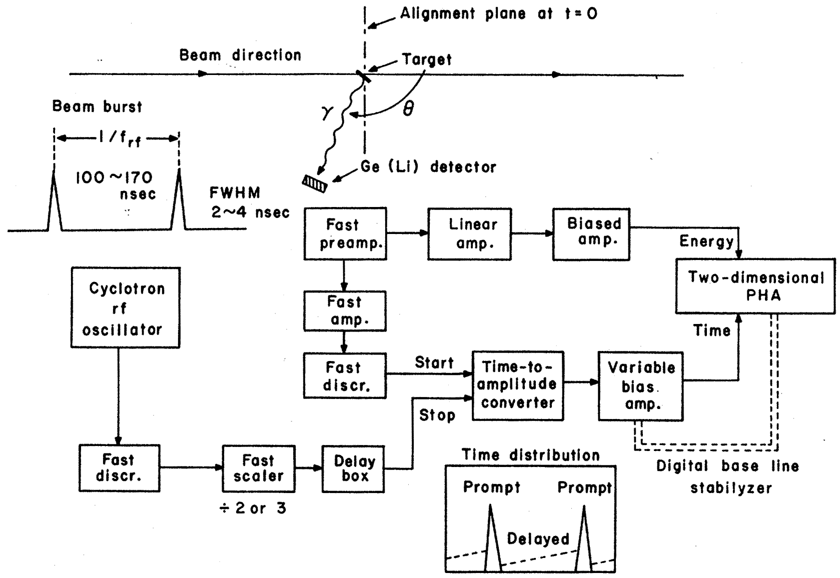

FIG. 1. Block diagram of the electronics system. A schematic time distribution and alignment plane are also shown.

on perturbations of angular distributions following nuclear reactions is very scarce. For this reason we found it important to measure the anisotropy as a function of time and to determine how long the nuclear alignment is preserved.

2. EXPERIMENTAL METHOD

The α-particle beam from the 88-in. sector-focused cyclotron at the Lawrence Radiation Laboratory in Berkeley was focused at the target position. The size of the beam spot was about 4×2 mm. We used targets of a strip form of 2 mm width in order to keep the beam position always at the center of the target by watching the counting rate of the radiation from the target.

For the measurements of angular distribution, a movable Ge(Li) detector was placed 25 cm from the target and rotated around the target from 90 to 159 deg with respect to the beam direction. In addition another Ge(Li) detector was fixed at 45 deg and used for the normalization of the total events for each position of the movable detector. The background radiation from anywhere else turned out to be negligible at any position of the detector. When a thick target was used, the self-absorption of low-energy γ rays was considerable at a glancing angle. Therefore, the facing angle of targets was carefully chosen.

For the g-factor measurement only one detector was placed at 135 deg. An external magnetic field of 2.76 kG was produced at the target in the direction perpendicular to the beam-detector plane with use of a small electromagnet that had a pole gap of 4 cm. Under the presence of the magnetic field, the beam position changed by 2 mm at the target, indicating the deflextion angle of approximately 10 deg, but this caused no trouble in the time-differential measurement.

The block diagram of the electronic system was similar to the one used in Ref. 1 and is presented in Fig. 1. The fast signal from the preamplifier was amplified and discriminated to generate the "start" signal for the time-to-amplitude converter, while every second and third signal from the cyclotron rf oscillator served as the "stop" signal. The curve in Fig. 1 shows a time pulse-height spectrum indicating two prompt peaks and a delayed part between them. The time interval between bursts, the inverse of the rf frequency, was 163 and 142 nsec for the 30- and the 40-MeV α beam, respectively. The output of the time-to-amplitude converter as well as the energy signal were fed into a two-dimensional pulse-height analyzer. The time resolution (FWHM) of prompt spectra was 5–8 nsec, including the width of each burst.

The phase drift of the rf signal with respect to real zero time of each beam burst caused a shift of the time spectrum. This was serious when time-differential angular distribution was measured. When the drift was too large to yield satisfactory results, such data were abandoned.

For the g-factor measurement, a system that could compensate for such a drift completely was employed. Since any possible phase drift results only in displacement of a prompt peak, a digital base-line stabilizer, as shown in Fig. 1, was used. In this way the drift was kept within 1 nsec.

For the reason discussed in Sec. 1, metallic lead targets were used throughout the experiments. Enriched lead metal was rolled to prepare about 20-mg/cm^2 thick foil.

3. 100-nsec ISOMERIC STATE IN ^{209}Po

A 100-nsec isomer of ^{209}Po was discovered when searching for isomers at the beginning of these experiments. Figure 2 shows an example of prompt and de-

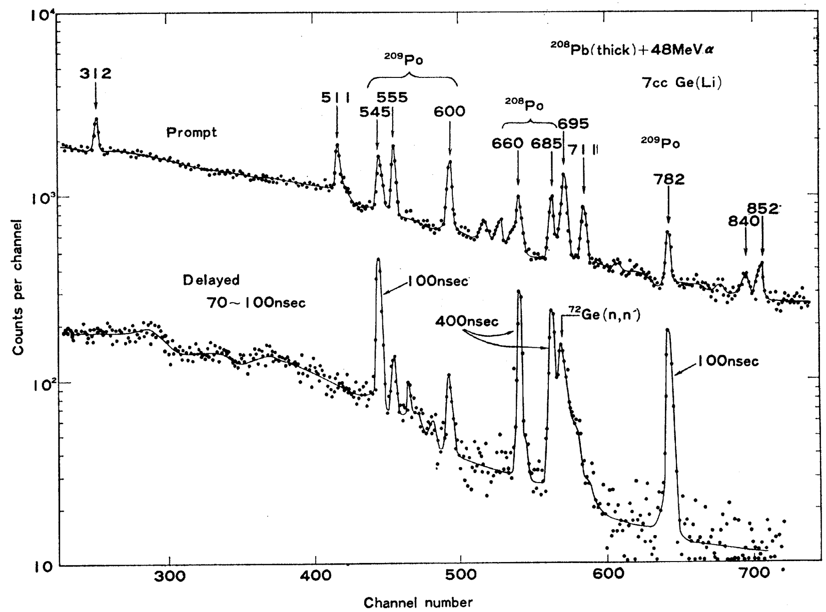

FIG. 2. Example of prompt and delayed γ-ray spectra in the ^{208}Pb$(\alpha, 4(3)n)$ $^{208(209)}$Po reactions, where a thick target (50 mg/cm^2) was bombarded with 48-MeV α beam.

layed (70–100 nsec) energy spectra of γ rays, when a thick ^{208}Pb target was bombarded with 48 MeV α beam. Predominant reactions were ^{208}Pb$(\alpha,4n)^{208}$Po and ^{208}Pb$(\alpha,3n)^{209}$Po. There are many delayed lines observed, of which the 545- and 782-keV γ rays were identified as belonging to ^{209}Po. The half-life of these γ rays was found to be about 100 nsec, but neither of them is the isomeric transition itself because of the presence of a prompt component. As in the case of ^{210}Po,[1] the isomeric transition is missing in the observed γ-ray spectra, presumably because it is highly converted.

The intensity of the delayed 545-keV γ ray was found to be equal to that of the delayed 782-keV γ ray, while the prompt intensity of the former γ ray was larger than that of the latter. This fact implies that the two transitions are in cascade and that the 545-keV transition is lower lying. The angular-distribution measurements described later, established a spin sequence of $\frac{9}{2}(782,Q)\frac{5}{2}(545,Q)\frac{1}{2}$.

Figure 3 shows a tentative level scheme relevant to this isomeric state which was conjectured by comparison with the ^{210}Po [1] and ^{207}Pb [6] levels. One can understand this level structure in terms of the $(h_{9/2}{}^2(p))J_p$ states appearing in ^{210}Po [1,7,8] coupled to the $p_{1/2}$ neutron hole. The residual interaction between proton and neutron may make this sequence $(I=J_p+\frac{1}{2})$ energetically favorable.

The half-life of about 100 nsec supports this interpretation. Theoretically there is an identity that

$$B[E2, (h_{9/2}{}^2)J_p, j_n, I=J_p+j_n \to (h_{9/2}{}^2)J_p', j_n, I=J_p'+j_n] = B[E2, (h_{9/2}{}^2)J_p \to (h_{9/2}{}^2)J_p'].$$

Therefore the $B(E2, 17/2^- \to 13/2^-, {}^{209}\text{Po})$ is expected to be equal to $B(E2, 8^+ \to 6^+, {}^{210}\text{Po})$. This implies that, although the transition energy is not known, the predicted half-life is approximately equal to 150 nsec, since the half-life is insensitive to energy for a low-energy $E2$ transition due to the competing conversion process. The experimental value of 100 nsec observed with ^{209}Po is

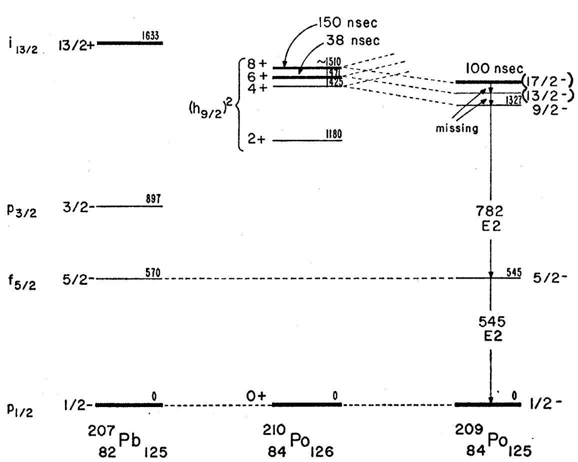

FIG. 3. Proposed level scheme of ^{209}Po in comparison with related levels in ^{207}Pb and ^{210}Po. The time distributions and angular distributions of the 545- and 782-keV γ rays established the first two excited states without ambiguity, while the upper two are proposed mainly from theoretical consideration of the relevant states of ^{210}Po and the half-life. See text.

[6] See, for instance, C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (John Wiley & Sons, Inc., New York, 1967), 6th ed.

[7] T. Yamazaki, E. Matthias, S. G. Prussin, C. M. Lederer, J. M. Jaklevic, and J. M. Hollander, in Proceedings of the International Conference on Nuclear Structure, Tokyo, 1967 (unpublished).

[8] T. Yamazaki, in International School of Physics, "Enrico Fermi," Course XL, edited by M. Jean (Academic Press Inc., New York, to be published).

quite close to this prediction. On the other hand, an assignment of $I=J_p-\frac{1}{2}$ spin to the isomeric state seems to be unreasonable, because such a state would then proceed promptly to the lower level via $M1$ transition.

The $13/2^-$ state can also be an isomeric state, but we tentatively assign the upper level as the 100-nsec state. If such an isomer doublet is present, the decay curve of the 545- and 782-keV transitions must be complex, depending upon initial population of both isomers. This might be the reason why a different value of the half-life, 130 nsec, is obtained in Fig. 5. This ambiguity, however, is unlikely to affect the g-factor measurement, since the g factors of both states are expected to be equal, as shown later.

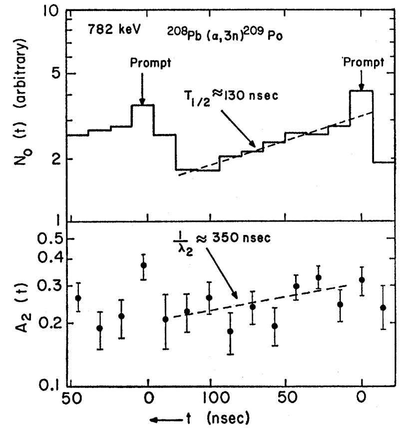

FIG. 5. Time-differential angular distribution of the 782-keV γ rays of ^{209}Po to check for perturbations in the target. The quantities $N_0(t)$ and $A_2(t)$ are defined in the text.

4. ANGULAR DISTRIBUTION OF DELAYED γ RAYS

First, we measured the angular distribution of the 545- and 782-keV γ rays in the ^{208}Pb$(\alpha,3n)^{209}$Po reaction at $E_\alpha=40$ MeV. Only the time-integrated portion outside the prompt region was taken into account. Within the statistical error the angular distribution is identical for both γ rays (see Fig. 4) and the coefficients are

$$A_2=0.24\pm0.02, \quad A_4=0.01\pm0.03,$$

which is compatible with the proposed spin sequence of $\frac{9}{2}^-$ (782, $E2$)$\frac{5}{2}^-$(545, $E2$)$\frac{1}{2}^-$ (Fig. 3). This result indicated that the large alignment is preserved at least for the period of about one half-life.

A measurement of the time-differential angular distribution of the 545 keV γ ray proved this indication. The quantities $N_0(t)$ and $A_2(t)$ of the time spectrum

$$I(\theta,t)=N_0(t)[1+A_2(t)P_2(\cos\theta)+A_4(t)P_4(\cos\theta)]$$

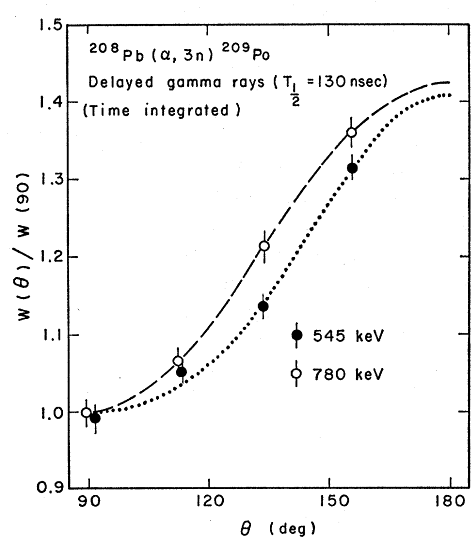

FIG. 4. Angular distribution of time-integrated delayed components of the 545- and 782-keV γ rays, which is compatible with the proposed level scheme in Fig. 3.

are plotted in Fig. 5. Within statistics the anisotropy is not attenuated. Any possible perturbation, if present at all, must be very weak; a lower limit of the relaxation time $1/\lambda_2$ is 350 nsec and is indicated by the dashed line. Of course, from these data it is impossible to distinguish between a static and a time-dependent perturbation. These questions must be left open for further investigation with sufficiently longer in-between-beam intervals, allowing longer time ranges without additional effects originating from preceding beam bursts.

5. g-FACTOR MEASUREMENT

After it was clear that with a metallic lead target there was little or no attenuation of the alignment in the isomeric state, a spin-rotation measurement was carried out in an external magnetic field. A 30 cm^3 Ge(Li) detector was placed at 135 deg with respect to the beam direction and a field of 2.76 kG was applied perpendicular to the beam-detector plane. Figure 6 displays the time distributions of the 782-keV γ ray in the ^{207}Pb$(\alpha,2n)^{209}$Po reaction at $E_\alpha=30$ MeV with magnetic field up and down.

Since it was established before that $A_4\approx0$, the time-differential angular distribution has the form

$$N(\theta,t)=N_0\lambda e^{-\lambda t}[1+b_2\cos2(\theta-\omega_Lt)],$$

where λ is the decay constant and ω_L is the Larmor precession frequency. In the present case, contribution of preceding bursts should be taken into account. The modified function for periodic events with interval T is

$$\bar{N}(\theta,t)=\sum_{n=0}^{\infty}N(\theta,t+nT)$$

$$=N_0\lambda\frac{e^{-\lambda t}}{1-e^{-\lambda T}}\{1+\alpha b_2\cos[2(\theta-\omega_Lt)-\varphi]\},$$

where

$$\alpha\equiv(1-\beta)/[(1-\beta)^2+4\beta\sin^2\omega_LT]^{1/2}$$

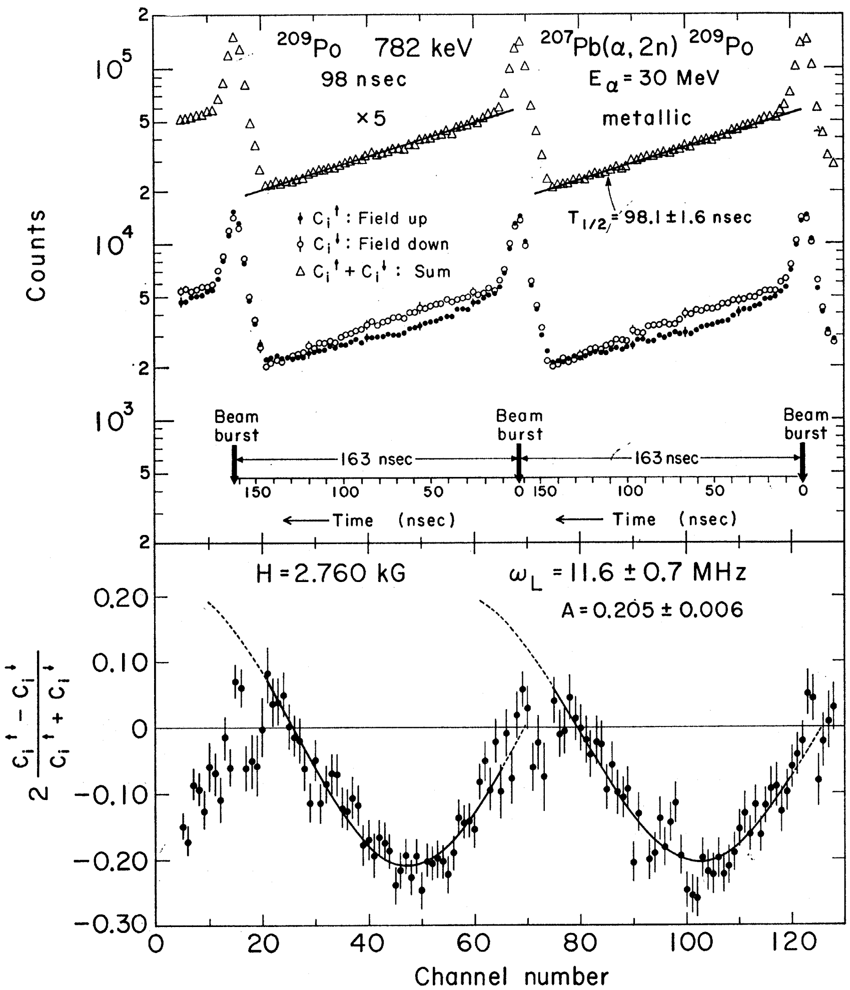

FIG. 6. Time spectra of the 782-keV γ radiation of ^{209}Po in the presence of an external magnetic field. The data were taken for opposite field directions and show the opposite direction of the Larmor precession. Normalized differences are plotted in the lower part of the figure including the result of a least-squares fit (solid line).

represents attenuation due to the addition of preceding events,

$$\varphi \equiv \tan^{-1}[\beta \sin 2\omega_L T/(1-\beta \cos 2\omega_L T)]$$

is a change of phase, and

$$\beta \equiv e^{-\lambda T}$$

stands for the decay fraction in a period. Therefore, the normalized difference of counts $C_i^{\uparrow}$ and $C_i^{\downarrow}$ with field up and down, respectively, is given by

$$R_i = 2(C_i^{\uparrow}-C_i^{\downarrow})/(C_i^{\uparrow}+C_i^{\downarrow}) = 2\alpha b_2 \sin(2\omega_L t+\varphi).$$

These ratios, plotted in the lower part of Fig. 6, were fitted by a function $A \sin(2\omega_L t+\varphi)$ with

$$A = 0.205 \pm 0.006$$

and

$$\omega_L = 11.6 \pm 0.7 \text{ MHz}.$$

On the other hand, the known value of $A_2 = 0.24$ and $\beta = 0.32$ yield

$$A = 2\alpha b_2 = 0.18 \pm 0.02,$$

which is in good agreement with the above value. With the magnetic field of 2.76 kG, we obtain

$$g = 0.88 \pm 0.05.$$

This g factor is extremely far off the Schmidt limits; -0.22 and 0.20 for an odd neutron state of 17/2 spin. This fact strongly suggests that this 100-nsec state is not a single-particle state at all but the three-particle state, as indicated in Fig. 3. The g factor can then be expressed in terms of the known g factors of the ^{209}Bi and ^{207}Pb ground states in the following way:

$$g[(h_{9/2}(p))^2 J_p,\ j_n = \tfrac{1}{2};\ I = J_p + \tfrac{1}{2},\ ^{209}\text{Po}]$$
$$= [(2I-1)/2I]g(h_{9/2},\ ^{209}\text{Bi}) + (1/2I)g(p_{1/2},\ ^{207}\text{Pb}),$$
$$= 0.923 \quad \text{for} \quad I = 17/2^-$$
$$= 0.928 \quad \text{for} \quad I = 13/2^-.$$

The contribution of the neutron hole is almost negligible. The present experimental value agrees well with this prediction, but, as for the $\frac{9}{2}^-$ ground state of ^{209}Bi, it deviates seriously from the single-particle estimate.

The g factor of the 8^+ state of ^{210}Po was investigated in the same way and a preliminary result was reported elsewhere.[7,8] These two results have demonstrated that the anomalous magnetism of the isomeric states in ^{209}Po and ^{210}Po must be ascribed to the same origin as in ^{209}Bi, i.e., to the magnetic core polarization of the $h_{9/2}$ proton.[9]

6. SUMMARY

It was our intention to use the interesting case of ^{209}Po as an example to demonstrate the usefulness of this type of measurement. When a metallic lead target was used, the initial alignment of the isomeric state of ^{209}Po was found to persist for at least 300 nsec. This made it possible to perform a spin rotation to determine its g factor. The measured g factor is extremely far off the Schmidt line, but is consistent with the interpretation of this isomer as a $17/2^-$ (or $13/2^-$) three-particle state of the $(h_{9/2}(p))^2p_{1/2}(n)$ configuration. In this odd-neutron case, the proton configuration plays a leading role in producing the magnetic moment. Starting from the anomalous magnetic moment of the $h_{9/2}$ ground state of ^{209}Bi, we could explain the present value.

It is worthwhile to note that a number of new high-spin isomeric states in Po and Sn isotopes have been found.[1,7,8,10,11] In general, high-spin isomeric states result from stretch coupling of a few particles in large j shell-model orbits, and wave functions are relatively simple. Therefore measurements of their g factors will provide important information about the magnetic core polarization effect.

In view of the great number of existing isomers in the half-life range between 10^{-9} and 10^{-6} sec, and those which will undoubtedly be discovered in the near future, we believe that this is a most promising way to study hyperfine interactions with a cyclotron beam. Such investigations should not only involve g-factor measurements, but also studies of quadrupole interactions and relaxation phenomena.

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[9] See, e.g., E. Bodenstedt and J. D. Rogers, in *Perturbed Angular Correlations*, edited by E. Karlsson, E. Matthias, and K. Siegbahn (North-Holland Publishing Co., Amsterdam, 1964), Chap. II, p. 93.

[10] Po isotopes: T. Yamazaki, E. Matthias, S. G. Prussin, C. M. Lederer, J. M. Jaklevic, and J. M. Hollander (to be published); W. J. Treytl, E. K. Hyde, and T. Yamazaki, Nucl. Phys. **A117**, 481 (1968).

[11] Sn isotopes: T. Yamazaki, G. T. Ewan, and S. G. Prussin, Phys. Rev. Letters **20**, 1376 (1968).