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Magnetic Moment of the First Excited State of Pb^{204}†

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THE g factor of an excited nuclear level can in principle be determined if the level is the intermediate state of a $\gamma-\gamma$ cascade and if its spin is larger than $\frac{1}{2}$. One measures the directional correlation $W(\theta)$ of the two γ rays as a function of an external magnetic field H applied to the radioactive source perpendicular to the plane of the two counters. Classically, the magnetic field induces a precession of the nucleus through an angle $\omega\tau$ during the mean life τ of the intermediate nuclear state; $\omega=g\mu_N H/\hbar$ is the Larmor frequency. The precession is displayed in the $\gamma-\gamma$ correlation and the g factor can be obtained by measuring $W(\theta,H)$ and τ.[1,2] The method is, however, applicable only to nuclei with mean lives between about 10^{-9} sec and 10^{-5} sec. Consequently, the selection of available nuclides is very restricted and the g factor of only one excited state (Cd^{111}) has been measured to date.[3] We report here a second case, the determination of the g factor of the first-excited state of the even-even nucleus Pb^{204}.

The isomer Pb^{204*} ($T_{\frac{1}{2}}=65$ min) decays through a $\gamma-\gamma$ cascade [$E(\gamma_1)=0.905$ Mev, $E(\gamma_2)=0.374$ Mev]; the intermediate state has a spin 2 and a mean life $\tau=4.3\times10^{-7}$ sec[4] (Fig. 1). We have shown in a previous paper[5] that the directional correlation between γ_1 and γ_2 is strongly perturbed in almost all types of sources by the interaction between the nuclear quadrupole moment and electric field gradients of the surroundings. We found, however, that the anisotropy $A\equiv[W(180°)/W(90°)]-1$ is highest when the Pb^{204} is imbedded in metallic thallium, the thallium being in its liquid or body-centered cubic phase.[5,6] We moreover showed that this value represents, within the limits of error, the undisturbed correlation.[5] For these reasons, such sources were used in the present investigation.

The experimental arrangement consisted of two scintillation counters and a magnet with its field perpendicular to the plane of the two counters. The source, contained in a Pyrex glass tube, was placed in a small oven between the pole pieces and heated either to about 270°C (bcc phase) or to about 400°C (liquid phase). The essential counter data are given in Table I.

Under these conditions, counter I responded only to γ_1. The delay in channel I caused to be recorded as coincidences only those decays in which γ_2 followed γ_1 during the time interval $T_1=0.08$ μsec to $T_2=0.66\mu$sec. The measured correlation function was corrected for the finite angular resolution of the counters and for scattering in the source, in the oven, and in the pole pieces by

TABLE I. Characteristics of the counting system.

Counter	Lead shielding Lateral	Lead shielding Front	Discriminator level	Delay	Resolving time
I	1.5 cm	none	0.60 Mev	0.37μsec	0.290μsec
II	1.5 cm	0.2 cm	0.25 Mev	none	

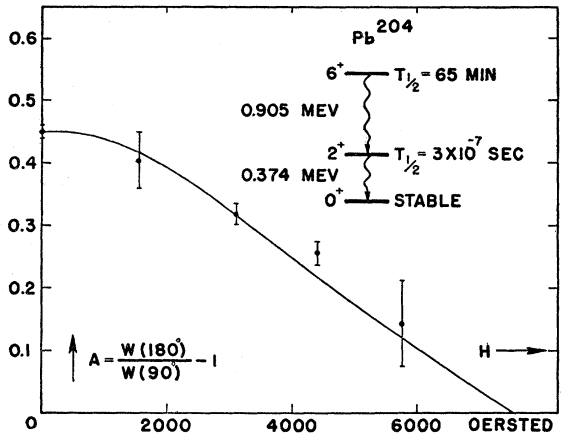

FIG. 1. Decay scheme of Pb^{204} and anisotropy A of the Pb^{204} $\gamma-\gamma$ cascade as a function of an external magnetic field H. The solid line represents the theoretical curve for a g factor with an absolute value of 0.07.

comparing the zero-field anisotropy with the anisotropy determined in an experiment with much less scattering material around the source and with known geometry.[5]

We have performed two sets of experiments. In the first set, we determined the anisotropy A as a function of the field strength H. The results are shown in Fig. 1. Such a measurement clearly yields the magnitude but not the sign of g. In the second set, we measured the correlation function at the angles $\theta=75°$, 105°, 140°, 180°, and 220°, for two different field strengths H. Without field, the correlation function assumes the same values for 75° and 105° and for 140° and 220°. With field, the correlation function shifts and at the same time decreases in amplitude (Fig. 2). The direction of the magnetic field and the sense of the angular shift immediately determine the sign of g. For Pb^{204*}, g was found to be positive.

In order to calculate g from the experimental data, we integrated the theoretical expression for the delayed correlation function $W_d(t)$ [Eq. (127) of reference 2] from T_1 to T_2, inserted the experimental values, and solved the resulting lengthy expression numerically. The final result (solid line in Fig. 1 and dotted line in Fig. 2) is

$$g\ (Pb^{204},\ \text{first-excited state})=+\left(0.07^{+0.06}_{-0.03}\right).$$

The main contributions to the symmetric part of the error, ±0.03, arise from statistics and from uncertainties in magnetic field, lifetime, delay time, and resolving time. The asymmetric part, $+0.03$, stands as an insurance against possible perturbations from remaining electric field gradients, which tend to lower the measured g factor.[7]

With the known spin 2 of the first-excited state of Pb^{204}, the magnetic moment becomes

$$\mu\ (Pb^{204},\ 2^+)=\pm\left(0.14^{+0.12}_{-0.06}\right)\mu_N.$$

Even though this is only a preliminary value, the following conclusions can be drawn.

The small magnetic moment supports Bohr and Mottelson's supposition[8] that the 2^+ state in Pb^{204} is not a rotational state, but is due to pure neutron excitation (Pb is proton magic). Ford has calculated the excitation energy of the first, excited state in Pb^{204} in a strong-coupling approximation and gets best agreement with the experimental value for the states $[(i_{13/2})^{-4}]_N$ and $[(p_{1/2})^{-2}(i_{13/2})^{-2}]_N$.[9] A mixture[10,11] of these two states would probably yield a moment in agreement with our experimental value.

The small g factor also supports the, perhaps questionable,[10] mass assignment 204 to the 65-min activity, because both Pb^{203} and Pb^{205} are expected to have a larger g factor. We have more-

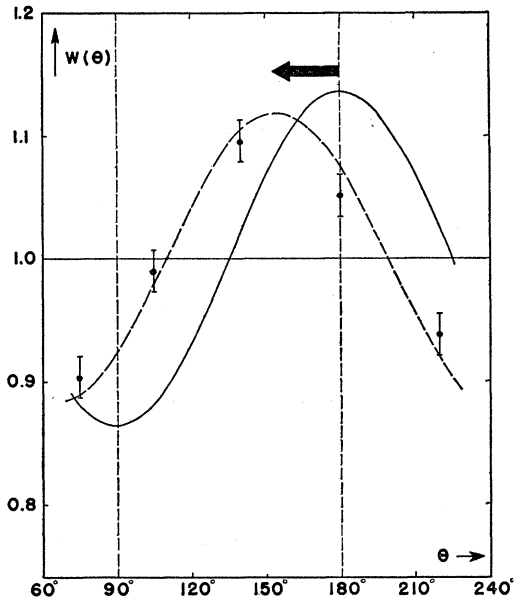

FIG. 2. Angular shift of the directional correlation function $W(\theta)$ of the Pb^{204} $\gamma-\gamma$ cascade in an external magnetic field H. The solid line represents the zero-field correlation; the dotted line is the theoretical curve for $g=+0.07$ and $H=4300$ oersteds. The arrow indicates the classical precession angle of a magnetic dipole.

over shown by simultaneous irradiation of natural Tl and of Tl enriched in Tl^{203} with deuterons, that the 65-min activity is produced from Tl^{203} and therefore cannot be Pb^{205}.

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Scattering of High-Energy Electrons by Heavy Nuclei*

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THE elastic scattering of high-energy electrons is a tool which can be used to obtain information on the radius and charge distribution of nuclei. There have been several numerical calculations of this process.[1,2] Although the numerical method will undoubtedly remain the most accurate, it may be thought that an analytical solution, even if approximate, would help in the understanding of the physical happenings and would show more clearly the dependence on the various parameters involved. The Born approximation is such an analytical method; however, it cannot be trusted for such heavy nuclei as gold or lead, because $Ze^2/\hbar c$ is too large.

The purpose of this letter is to report on some results obtained with the WKB method. This method is applicable if the potential varies slowly over distances of the order of the electron wavelength. This is the case if $kR\gg1$, where R is the radius of the nucleus and $k=\lambda\!\!\!^{-}{}^{-1}$ is the electron wave number. At the energies at which the experiments of Hofstadter, Fechter, and McIntyre[3] have been done (~125 Mev), kR is about 5 for heavy nuclei. This is about the lower limit of the energy region where the WKB method can be considered valid.

We start from the Dirac equation and neglect the mass of the electron. In that case the phase shift η depends only on the angular momentum j, and not on the parity.[4] We apply the WKB method in the form given by Bessey and Uhlenbeck,[5] with the result

$$\eta_j=\lim_{r\to\infty}\left\{\int_{r_0}^{r}Q(r')dr'-kr-\alpha\ln 2kr+l\frac{\pi}{2}\right\}, \quad (1)$$

where $Q(r)=[(k-V(r)/\hbar c)^2-l^2/r^2]^{\frac{1}{2}}$; $V(r)$ is the potential energy; r_0 is the turning point, i.e., $Q(r_0)=0$; $\alpha=Ze^2/\hbar c$; and l is *defined* as $j+\frac{1}{2}$.

For instance, with a uniform charge distribution, of external radius R, the phase shift is

$$\eta_j=\alpha(1-x^2)^{\frac{1}{2}}+\tfrac{1}{3}\alpha(1-x^2)^{\frac{3}{2}}-\alpha\ln[1+(1-x^2)^{\frac{1}{2}}]-\alpha\ln kR$$
$$+(\alpha^2/2kR)[x^{-1}\sin^{-1}x-(1-x^2)^{\frac{1}{2}}+\tfrac{2}{3}(1-x^2)^{\frac{3}{4}}x^2(4-x^2)], \quad \text{for } l<kR; \quad (2)$$
$$\eta_j=\eta_j{}^c, \quad \text{for } l>kR,$$

where $x=1/kR$, and $\eta_j{}^c$ is the Coulomb phase shift. In going from (1) to (2), we kept only the first two terms of the expansion in powers of the small parameter α/kR.

The cross section is conveniently written in the following form:

$$d\sigma/d\Omega=\sec^2\tfrac{1}{2}\theta\,|f(\theta)|^2,$$
$$f(\theta)=f^c(\theta)+(2ik)^{-1}\Sigma_j\, l[\exp(2i\eta_j)-\exp(2i\eta_j{}^c)]$$
$$\times[P_l(\cos\theta)+P_{l-1}(\cos\theta)], \quad (4)$$

where $f^c(\theta)$ is the Coulomb scattering amplitude which has been calculated, at high energies, by Feshbach,[6] and more recently by Yennie *et al.*[2]

The number of terms in the summation in (4) is of order kR. Doing this sum exactly, but using the WKB phase shifts, we obtain the results shown in Figs. 1, 2, 3. It should be noted that the cross section depends only on the combination kR, except for a factor $1/k^2$. In Fig. 1, it is seen that the result compares favorably with the numerical one of Yennie *et al.* There is no agreement between this calculation and the Born approximation. The maxima

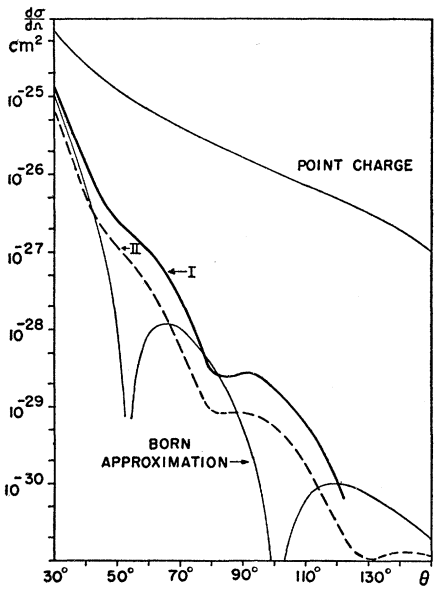

FIG. 1. The differential scattering cross section for a uniform charge distribution. Curve I is the result of the WKB method for $Z=80$, with $kR=5$, $R=1.4A^{\frac{1}{3}}\times10^{-13}$ cm. Curve II is the result obtained by Yennie *et al.* for $Z=79$, $kR=5.4$, $R=1.22A^{\frac{1}{3}}\times10^{-13}$ cm.