Beta-Gamma Angular Correlation Measurements on Au^{198}. II. Transverse Polarization of the Beta Particles*

P. C. SIMMS† AND R. M. STEFFEN
Department of Physics, Purdue University, Lafayette, Indiana

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As a consequence of the nonconservation of parity in beta decay, beta particles emitted in first-forbidden beta transitions exhibit a small degree of polarization transverse to their momentum. The direction of the transverse polarization is defined with respect to a plane which is introduced by observing the direction of emission of the beta particle and the direction of emission of a gamma ray following the beta transition. The degree of the transverse polarization parallel to the beta-gamma plane $P_{T\parallel}$, and the degree of polarization perpendicular to the beta-gamma plane $P_{T\perp}$ has been measured for Au^{198}. The beta polarization has been detected by means of the left-right asymmetry in a Mott scattering process for an average electron energy $W=2.0$ mc^2 and for an angle $\Theta=135°$ between the beta momentum and the gamma direction. The results of the measurements, $P_{T\parallel}=+0.011\pm0.005$ and $P_{T\perp}=+0.03\pm0.008$, agree satisfactorily with the values calculated on the basis of the ξ approximation from the anisotropy of the Au^{198} beta-gamma directional correlation.

I. INTRODUCTION

THE original objective of this investigation was to obtain information on the time-reversal invariance of the beta interaction. Curtis and Lewis[1] proposed in early 1957 that the observation of the transverse polarization of beta particles in a beta-gamma angular correlation experiment could provide a test for time-reversal invariance. Their calculation, based on a $Z=0$ approximation, indicated that in a first-forbidden beta decay the mere presence of a transverse polarization perpendicular to the beta-gamma plane would indicate a violation of time-reversal invariance. It was soon realized, however, that the effect of the nuclear charge on the electron final state wave function cannot be neglected in this problem, even if Z is small. In fact, Iben[2] and Kotani and Ross[3] have shown that the character of the beta polarization-gamma directional correlation is completely changed when the effects of the Coulomb field are taken into account. Only a very accurate measurement of the energy dependence of the perpendicular transverse polarization of the beta particles could possibly allow a separation of the time-reversal testing terms and could lead to information on time-reversal invariance.[4,5] At present such an experiment seems to be very difficult to perform. In the meantime experiments on the beta decay of polarized neutrons[6] and on RaE[7] have shown the validity of time-reversal invariance in the beta interaction.

In the following, results will be presented of measurements of the transverse polarization of the Au^{198} beta particles in coincidence with the gamma radiation which follows the beta transition. The beta emitter Au^{198} was chosen mainly on the basis of experimental considerations such as convenient half-life, high specific activity sources, convenient energy values of beta and gamma radiation, low intensity competing beta-gamma cascades, etc. The decay scheme of Au^{198} is well known. The main beta transition of 0.97-Mev maximum energy (99%) is first-forbidden.[8] The shape of the beta spectrum and the beta-gamma directional correlation as well as the beta-gamma circular polarization correlation of Au^{198} have been extensively investigated.[8]

2. TRANSVERSE POLARIZATION OF BETA PARTICLES IN THE ξ APPROXIMATION

As shown in the preceding paper[8] the ξ approximation is very successful in representing the shape of the Au^{198} beta spectrum as well as the directional correlation and the circular polarization correlation of the Au^{198} beta-gamma cascade. In the following, expressions of the transverse polarization of the beta particles in a first-forbidden decay as calculated by Kotani and Ross[3] will be given in the ξ approximation. For the decay scheme $I_0(\beta)I_1(\gamma)I_2$ the transverse polarization of the beta particles parallel to the plane of β and γ in the direction $[\mathbf{p}_\beta\times\mathbf{p}_\gamma]\times\mathbf{p}_\beta$ is expressed by

$$P_{T\parallel}(\Theta,W)=-\tfrac{3}{2}\sin\Theta\cos\Theta\lambda_6(Z,W)\frac{p}{W}\frac{K(I_0I_1)}{C(W)}F_2(LLI_2I_1), \quad (1)$$

$\lambda_6(Z,W)$ contains Coulomb corrections of order $(\alpha ZW/p)$ and is defined in reference 3. $K(I_0I_1)$ is an energy-independent factor which depends on the

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† Present address: Pupin Physics Laboratory, Columbia University, New York, New York.

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nuclear matrix elements for the beta decay. It is defined in the preceding paper.[8] The F coefficients $F_2(LLI_2I_1)$ are tabulated by Alder *et al.*[9] L is the multipole order of the (pure) gamma transition. $C(W)$ is the shape correction factor, which, within the framework of the ξ approximation, is energy-independent. The transverse beta polarization perpendicular to the plane of β and γ in the direction $\mathbf{p}_\beta \times \mathbf{p}_\gamma$ is given by

$$P_{T\perp}(\Theta,W) = \frac{9}{8}\alpha Z \sin\Theta \cos\Theta \lambda_8(Z,W)\frac{p}{W}\frac{K(I_0I_1)}{C(W)}F_2(LLI_2I_1), \quad (2)$$

where

$$\lambda_8 = \tfrac{4}{3}\lambda_6(\gamma_1+\gamma_2+3)/(1+\gamma_1)(1+\gamma_1+\gamma_2),$$
$$\gamma_k = [k^2-(\alpha Z)^2]^{\frac{1}{2}}. \quad (3)$$

There is a close connection between the transverse polarization of the beta particles in a beta-gamma cascade and the anisotropy factor $A_2(W)$ of the beta-gamma directional correlation $\mathcal{W}_{\beta\gamma}(\Theta,W) = 1 + A_2(W) \times P_2(\cos\Theta)$. The beta-gamma directional anisotropy factor $A_2(W)$ is given by (refer to the preceding paper[8]):

$$A_2(W) = \lambda_2(Z,W)\frac{K(I_0I_1)}{C(W)}F_2(LLI_2I_1), \quad (4)$$

$\lambda_2(Z,W)$ again contains Coulomb correction factors. Combining Eqs. (1), (2), and (4) one obtains for the polarization in the β-γ plane:

$$P_{T\parallel}(\Theta,W) = -\frac{3}{2}\sin\Theta\cos\Theta\frac{\lambda_6(Z,W)}{\lambda_2(Z,W)}\frac{1}{p}A_2(W), \quad (5)$$

and for the polarization perpendicular to the β-γ plane

$$P_{T\perp}(\Theta,W) = \frac{9}{8}\alpha Z \sin\Theta\cos\Theta\frac{\lambda_8(Z,W)}{\lambda_2(A,W)}\frac{1}{p}A_2(W). \quad (6)$$

The expressions (1) to (6) are correct if time-reversal invariance of the beta interaction is assumed.

3. MEASUREMENT OF THE TRANSVERSE POLARIZATION OF THE Au^{198} BETA PARTICLES

a. Experimental Method

The most direct method of measuring the degree of transverse polarization of electrons is to observe the left-right asymmetry in a Mott scattering process on a heavy nucleus. The azimuthal variation (angle ϕ) of the scattered intensity for an incident electron polarized in the direction $\phi=0$ is proportional to $\sin\phi$. The asymmetry δ_θ in intensity $I(\phi)$ between the azimuth 90° and the conjugate azimuth 270° for a scattering angle θ is defined as

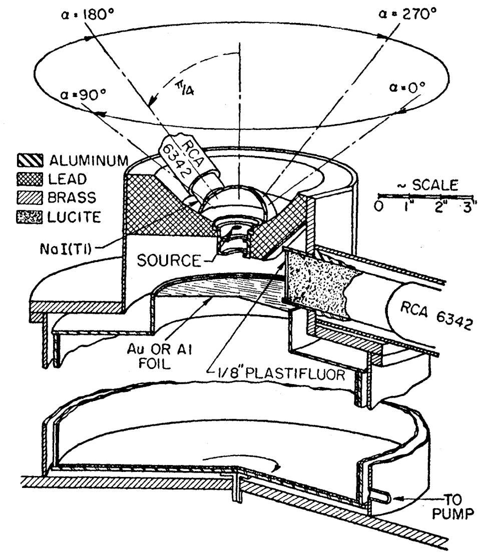

FIG. 1. Vacuum chamber and counter arrangement for the measurement of the transverse polarization of beta particles in a beta-gamma correlation experiment.

$$\delta_\theta = \frac{I_\theta(90°) - I_\theta(270°)}{I_\theta(90°) + I_\theta(270°)}. \quad (7)$$

The degree of transverse polarization P_T

$$P_T = \frac{N(0°) - N(180°)}{N(0°) + N(180°)}, \quad (8)$$

where $N(\alpha)$ is the number of electrons with their spin pointing in the direction α is related to the asymmetry δ_θ:

$$\delta_\theta = S(E,\theta)P_T. \quad (9)$$

The asymmetry coefficient[10] $S(E,\theta)$ which depends on the electron energy E and the scattering angle θ has been calculated by Sherman[11] for a point nucleus. Screening by the atomic electrons has been neglected in these calculations.

In an actual Mott scattering experiment a foil of finite thickness of high Z (e.g., Au) is used as scatterer. The choice of the foil thickness and of the scattering angle θ is a compromise between intensity considerations and keeping the probability of multiple (small angle) and double (large angle) scattering small. Wegener[12] has developed a method of taking the latter effects into account by introducing a correction factor $\Delta S(E,\theta,d\rho)$ into Eq. (9):

$$\delta_\theta = [S(E,\theta) + \Delta S(E,\theta,d\rho)]P_T, \quad (10)$$

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TABLE I. Transverse polarization of the Au^{198} beta particles ($\bar{W}=2.0$ mc²; $\Theta=135°$).

Experiment	Scatterer	$\delta(\alpha)$	$P_T(\Theta=135°)$
$P_{T\parallel}(\alpha=90°)$	Au Al	$+0.0030\pm0.0011$ -0.0008 ± 0.0009	$P_{T\parallel}(135°)=+0.011\pm0.005$
$P_{T\perp}(\alpha=0)$	Au Al	$+0.0035\pm0.0015$ $+0.0025\pm0.0015$	$P_{T\perp}(135°)=+0.011\pm0.005$

$\Delta S(E,\theta,d\rho)$ depends on the surface density $d\rho$ of the scattering foil.

In the present experiment an average scattering angle $\theta=117°$ and a gold foil of surface density $d\rho=1.45$ mg/cm² was chosen.

b. Experimental Arrangement

The details of the vacuum chamber used in the beta polarization gamma directional correlation experiment are shown in Fig. 1. The electrons emitted from the Au^{198} source are collimated by a baffle system and scattered by the gold foil into the beta detector. The foil rotated continuously to provide, on the average, a perfectly plane scattering surface of well defined position. In this way possible asymmetries due to variations in the foil thickness and in the foil orientation were averaged out. The beta detector was a $\frac{1}{8}$-inch plastic scintillator disc. The energy resolution for the Cs^{137} conversion electrons was 16%. The gamma detector was located at an angle $\Theta=135°$ with respect to the geometric axis of the beta beam in order to maximize the $\sin\Theta\cos\Theta$ product which appears in the expression for both $P_{T\parallel}(\Theta,W)$ and $P_{T\perp}(\Theta,W)$.

The beta-gamma coincidence electronics was of the usual fast-slow type with a resolving time of 8 millimicroseconds.

c. Experimental Procedure and Results

The beta polarization gamma directional correlation measurements were executed with Au^{198} sources which were obtained by bombarding gold foils in the high neutron flux of the Argonne CP 5 reactor and evaporating the radioactive gold onto a 180 μg/cm² Al backing. The sources were less than 10 μg/cm² thick.

The pulse-height analyzer in the beta channel of the coincidence spectrometer was adjusted to accept scattered electrons above 0.35 Mev. The gamma detector accepted the photopeak of the 0.411-Mev gamma radiation which follows the beta decay of Au^{198}.

The azimuthal position of the gamma detector axis, which is characterized by the angle α between the vertical beta-counter plane and the vertical gamma-counter plane (refer to Fig. 1) was automatically changed at 15-minute intervals and the beta-gamma coincidence rates $N_{\beta\gamma}''(\alpha)$ and the single counting rates $S_\beta(\alpha)$ and $S_\gamma(\alpha)$ recorded.

The coincidence rates $N_{\beta\gamma}''(\alpha)$ were corrected for chance coincidences and for the presence of a small background (including coincidences with electrons scattered from the walls of the vacuum chamber, gamma-gamma coincidences, etc.) which was measured with the scattering foil removed and the source in position. The corrected coincidence rates $N_{\beta\gamma}'(\alpha)$ were divided by the products of the single counting rates. From $N_{\beta\gamma}(\alpha)=N_{\beta\gamma}'(\alpha)/[S_\beta(\alpha)\cdot S_\gamma(\alpha)]$ the asymmetry

$$\delta(\alpha)=[N_{\beta\gamma}(\alpha+180°)-N_{\beta\gamma}(\alpha)]/[N_{\beta\gamma}(\alpha+180°)+N_{\beta\gamma}(\alpha)]$$

was computed.[13] Table I summarizes the results of 450 days of continuous measurement. The asymmetry $\delta(0)$ measures the polarization $P_{T\perp}$ of the beta particles perpendicular to the β-γ plane, $\delta(90°)$ is a measure of the polarization $P_{T\parallel}$ in the β-γ plane (refer to Fig. 1).

The symmetry of the experimental arrangement was tested by measuring $\delta(\alpha)$ with an aluminum scattering foil, which is (for all practical purposes) not sensitive to the electron spin polarization. These calibration measurements are included in Table I.

The asymmetry $\delta(90°)$ measured with the aluminum foil in the $P_{T\parallel}$ position is zero within limits of error. In the $P_{T\perp}$ position, however, a small asymmetry $\delta(0°)$ exists. This is not too surprising since the relative positions of the beta and gamma counters are less symmetric in the $P_{T\perp}$ measurement than in the $P_{T\parallel}$ measurement. In addition, the effective center of the beam of electrons emitted from the Au^{198} source does not coincide with the axis of the scattering chamber, because the detection probability of an electron which is scattered from the side of the foil near the beta detector, is larger (smaller scattering angle, larger solid angle) than the detection probability of an electron which is scattered from the other half of the foil. Thus the effective center of the electron beam is shifted towards the beta detector. This effect is negligible in the $P_{T\parallel}$ measurement, but introduces an asymmetry in the $P_{T\perp}$ experiment, if the ordinary beta-gamma directional correlation exhibits an anisotropy. The asymmetry $\delta(0°)$ observed with the polarization insensitive aluminum foil has the correct sign and magnitude to be explained by the anisotropic beta-gamma directional correlation of Au^{198}.[8]

The asymmetries $\delta(\alpha)$ measured with the gold foil were corrected on the basis of the aluminum foil calibration measurements. From the corrected $\delta(\alpha)$ values the degrees of polarization $P_{T\parallel}$ and $P_{T\perp}$ of the

[13] $\delta(\alpha)$ is here defined in such a way that its sign is consistent with Eqs. (1), (2), and (9).

Au^{198} beta particles were computed according to Eq. (10). The results are shown in Table I. The geometrical corrections for the finite sizes of the gamma detector and of the scattering foil were taken into account on the basis of the Θ dependence given by Eqs. (5) and (6).

4. DISCUSSION

In the ξ approximation the degree of transverse polarization $P_T(\Theta,W)$ of the beta particles in a beta-gamma correlation experiment is related to the anisotropy factor $A_2(W)$ of the corresponding beta-gamma directional correlation according to Eqs. (5) and (6).

The present measurements of the transverse polarization were made at an average beta energy of $\bar{W}=2.0$ mc^2, for which one takes from reference 8, $A_2(\bar{W}=2.0)=+0.018\pm0.001$. With this value one obtains for the degree of transverse polarization in the beta-gamma plane:

$$P_{T\parallel}(\Theta=135°, \bar{W}=2.0)=+0.006,$$

and for the polarization perpendicular to the beta-gamma plane:

$$P_{T\perp}(\Theta=135°, \bar{W}=2.0)=-0.003.$$

Within limits of error the experimental values of P_T agree satisfactorily with the values predicted by the ξ approximation for first-forbidden nonunique beta transition.

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Fission of Ra^{226} by Deuterons and Helium Ions*†

R. C. JENSEN‡ AND A. W. FAIRHALL
Departments of Chemistry and Physics, University of Washington, Seattle, Washington

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Fission induced in Ra^{226} by 14.5- and 21.5-Mev deuterons, and by 23.5-, 31-, and 43-Mev He ions has been studied using radiochemical techniques. The mass distributions of fission products for deuteron-induced fission is triple-humped, corresponding to separate symmetric and asymmetric fission modes. The symmetric mode dominates at the higher bombarding energy. The mass distributions observed for fission products from He-ion induced fission look more "normal": asymmetric at the lowest bombarding energy, becoming a single broad peak at the highest bombarding energy. These results are interpreted in terms of a symmetric fission mode which increases strongly with increasing excitation energy, and an asymmetric fission mode which occurs mainly at low excitation energies following neutron evaporation from highly excited compound nuclei. Asymmetric fission is interpreted to be disappearing as a fission mode for nuclei of lower atomic number than thorium.

I. INTRODUCTION

In a previous paper[1] we reported the mass distribution of fission fragments from fission induced in Ra^{226} by 11-Mev protons. In those experiments, where radiochemical techniques were employed, the mass distribution of fission fragments was found to be a novel one: the mass-yield curve was triple-humped, corresponding to separate symmetric and asymmetric fission modes. Indications of a similar result have been reported[2] for neutron-induced fission of Ra^{226}, where counter techniques were employed: at low neutron energies the distribution of fragment kinetic energies falls into two groups, indicating asymmetric fission. At neutron bombarding energies around 15 Mev a prominent single peak is observed for the fragment kinetic energies, corresponding to symmetric fission. At intermediate neutron bombarding energies the fragment kinetic energy distribution indicates a transition from asymmetric to symmetric mass division with increasing bombarding energy. Along with the changing character of the mass distribution the cross section for fission was observed to increase sharply with neutron bombarding energy.

Preliminary results of fission incuded in Ra^{226} by 23-Mev bremsstrahlung[3] indicate that the mass-yield

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‡ Now in the Department of Chemistry, San Diego State College, San Diego, California.
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