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Transverse Polarization of K-Conversion Electrons Following the β Decay of Au^{198}†*

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The degree of transverse polarization $P_{\|}(\theta)=K_K(v/c)\sin\theta$ of the K-conversion electrons following the beta decay of Au^{198} has been measured with a view to the determination of the particle parameter $b_{1,\|}(E2)$. The experimental result was obtained using a lens spectrometer to focus the conversion electrons on a thin gold foil, and measuring the Mott-scattering asymmetry δ of the counts in coincidence with those detected in a beta detector placed opposite the source at an angle θ of 90° with the spectrometer axis. The measured asymmetry of $\delta=-0.044\pm0.013$ yields a value of $K_K=+0.43\pm0.17$, with all instrumental corrections applied. Given the beta-decay angular correlation coefficient $A_1(\beta)$ known from beta circularly polarized gamma correlations, the particle parameter is found to be $b_{1,\|}(E2)=-1.0\pm0.4$. This value, although in disagreement with previous measurements, agrees with the value calculated by Becker and Rose.

INTRODUCTION

THE ensemble of daughter nuclei following beta decay is polarized with respect to the beta momentum direction on account of the nonconservation of parity in the beta-decay interaction. Knowledge of the state of polarization of this ensemble is useful for the determination of the matrix elements of the beta decay. The principal tool used for the investigation of this quantity has been the measurement of the beta-circularly polarized gamma correlation. However, limitations on experimental technique restrict the use of this method to gamma transitions whose energies are larger than about 400 keV. Frauenfelder, Jackson, and Wyld[1] suggested several other polarization correlations which could be used for the same purpose; among these were the longitudinal polarization of internal conversion electrons following beta decay. The existence of the transverse component of the polarization was first pointed out by Rose and Becker,[2] and independently by Berestetskii and Rudik.[3] Calculation of the expected effects was carried out for K conversion by Becker and Rose,[4] and extended to L conversion as well by Lewis and Albers,[5] Geshkenbein,[6] and Baikov.[7]

The theoretical analysis is carried out by resolving into three components the polarization $\mathbf{P}(\theta)$ of the conversion-electron beam whose momentum $\mathbf{c}$ is at an angle θ with the preceding beta momentum $\mathbf{p}$. One of these three components is taken to be parallel to $\hat{c}$ (longitudinal polarization); the other two, normal to $\hat{c}$ (transverse polarization). Of the transverse components, one is parallel to and one is normal to the plane defined by $\mathbf{p}$ and $\mathbf{c}$. These are referred to as transverse in-the-plane and transverse out-of-the-plane polarizations, respectively. Symbolically,

$$\mathbf{P}(\theta)=P_l(\theta)\hat{c}+P_{\|}(\theta)\hat{t}_{\|}+P_{\perp}(\theta)\hat{t}_{\perp}, \tag{1}$$

where

$$\hat{t}_{\perp}=\hat{p}\times\hat{c}/\sin\theta,\quad \hat{t}_{\|}=\hat{c}\times\hat{t}_{\perp}/\sin\theta. \tag{2}$$

For experimental reasons, it is easier to measure the transverse components than the longitudinal component

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[1] H. Frauenfelder, J. D. Jackson, and H. W. Wyld, Jr., Phys. Rev. **110**, 451 (1958).

[2] M. E. Rose and R. L. Becker, Phys. Rev. Letters **1**, 116 (1958).

[3] V. B. Berestetskii and A. P. Rudik, Zh. Eksperim. i Teor. Fiz. **35**, 159 (1958) [English transl.: Soviet Physics—JETP **8**, 111 (1959)].

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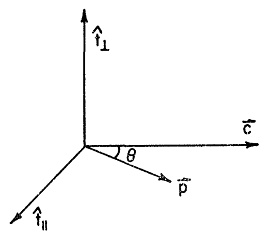

FIG. 1. Vectors used in the description of transverse polarization of conversion electrons.

(see Fig. 1). Furthermore, if only allowed transitions or first-forbidden nonunique transitions that are well described by the Coulomb, or ξ approximation are considered, the transverse out-of-the-plane component is zero or very small. Under these conditions, the degree of transverse in-the-plane polarization may be written as a function of angle in the form

$$P_{\parallel}(\theta)=[K_X(v/c)\sin\theta]/W(\theta)\,, \qquad (3)$$

for internal conversion from the X shell ($X=K,L,\cdots$). The velocity (v/c) refers to the beta particle, and $W(\theta)$ is the beta-conversion electron directional correlation. The details of the interaction are contained in K_X, which is

$$K_X=-A_1(\beta)C_{1,\parallel}(e_X)c/v\,. \qquad (4)$$

Here $A_1(\beta)$ is the usual[8] angular correlation coefficient for the beta step in the cascade, and $C_{1,\parallel}(e_X)$ that of the conversion electron part. For a transition of pure multipole order L and parity π between an intermediate state of spin I and a final state of angular momentum I_f, the latter coefficient is written

$$C_{1,\parallel}(e_X)=F_1(LLI_fI)b_{1,\parallel}(L\pi,e_X)\,. \qquad (5)$$

The coefficients $F_\nu(LLI_fI)$ are tabulated for odd ν by Alder, Stech, and Winther[9]; the particle parameters $b_{1,\parallel}(L\pi,e_K)$ are calculated for various values of L and π by Becker and Rose.[4]

Measurement of the transverse components of the conversion electron polarization can be accomplished by detection of the asymmetry of Mott scattering from thin foils of high-Z materials. Both the cross section and scattering asymmetry for this process increase with decreasing energy, as do the conversion coefficients involved. Measurement of the transverse polarization of conversion electrons following beta decay would therefore appear to be a method complementary to beta-circularly polarized gamma correlation for the determination of the character of the beta decay, suitable for use in the investigation of nuclides whose final de-excitation energies are low.

In order to verify the validity of these calculations, it would be useful to investigate a cascade for which the beta decay coefficient is known, either by calculation (i.e., allowed or unique forbidden) or by direct measurement using the beta-circularly polarized gamma correlation. There are only two such cascades that fit the experimental requirements, one in I^{131}, and one in Au^{198}. The former, however, involves a mixed transition as the final step in the cascade, thus involving up to three particle parameters. Furthermore, the mixing ratio is not known with a great deal of certainty.[10] The decay of Au ^{198} does not suffer from this drawback (see Fig. 2). The final step in the main decay cascade is a 412-keV pure $E2$ cascade and therefore the coefficient $C_{1,\parallel}(e_K)$ involves but one particle parameter $b_{1,\parallel}(E2)$. This parameter is relatively insensitive to finite nuclear size and screening corrections, and should be in agreement with the calculations of Becker and Rose, which are made with point-nucleus, unscreened radial matrix elements. The beta decay is first-forbidden nonunique and has been shown[11] to be adequately described by the Coulomb, or ξ approximation. The coefficient $A_1(\beta)$ has been measured by several groups[12–16] with general agreement in the results.

There have been two previous experiments[17,18] performed on the beta conversion-electron transverse-polarization correlation in this cascade in Au^{198}. The results,[19] although in fair agreement with each other, disagree both in sign and magnitude with the value of the particle parameter $b_{1,\parallel}(E2)$ given by Becker and Rose. Since, as mentioned above, there is no obvious

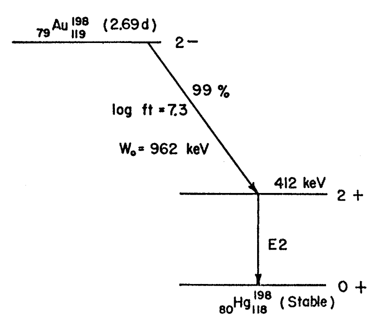

FIG. 2. Partial decay scheme of Au^{198}.

[8] The sign convention used here is that given by H. Frauenfelder and R. M. Steffen in *Alpha- Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1965), Chap. XIX.A.

[9] K. Alder, B. Stech, and A. Winther, Phys. Rev. **107**, 728 (1957).

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[11] R. M. Steffen, Phys. Rev. **123**, 1787 (1961).

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[14] J. Berthier, P. Debrunner, W. Kündig, and B. Zwahlen, Helv. Phys. Acta **30**, 483 (1958).

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[16] R. M. Steffen, Phys. Rev. **118**, 763 (1960).

[17] B. Blake, R. Bobone, H. Frauenfelder, and H. J. Lipkin, Nuovo Cimento **25**, 942 (1962).

[18] R. A. Llewellyn and R. M. Steffen, Bull. Am. Phys. Soc. **7**, 35 (1962).

[19] A review of experiments of this type and a tabulation of results is given by R. M. Steffen and H. Frauenfelder, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1965), Chap. XXIV.G.

reason for this disagreement with the calculated parameter, it seemed of interest to reinvestigate the case of Au^{198}, using improved apparatus and taking special care in the treatment of instrumental effects.

EXPERIMENT

The apparatus used for this experiment is similar in principle to that used by Llewellyn and Steffen[18,20] (see Fig. 3). A scintillation detector is used to observe beta particles from a radioactive source. The source is located at the source point of a lens spectrometer such that the spectrometer axis makes an angle θ^* of 90° with the axis of the beta detector. From Eq. (3), it is seen that at this angle the degree of polarization $P_{\shortparallel}(\theta)$ should have its maximum value. The conversion electrons of interest are focused by the spectrometer on a thin gold scattering foil, of thickness 0.71 mg/cm², where they undergo Mott scattering. Two conversion electron detectors are located at a nominal scattering angle ψ^* of 120° to the "right" and to the "left" as viewed from the source with the beta detector "up." These detectors are used to detect the Mott scattering asymmetry δ, equal to $(N_L-N_R)/(N_L+N_R)$, where N_L and N_R are the numbers of counts to the left and right, respectively, in coincidence with beta particles in the beta detector (see Fig. 4). The asymmetry δ can be related to the state of polarization of the incoming beam according to calculations made by Sherman.[21] Sherman's calculations do not include the effect of orbital electron screening. However, at the relatively high electron energy of this transition, the effect is small, as is shown in later calculations by Lin[22] for a screened nucleus. Sherman also assumes only single scattering of the electron in the scatterer; correction for plural scattering is made according to calculations of this effect made by Wegener.[23]

The angular dependence of the Mott scattering

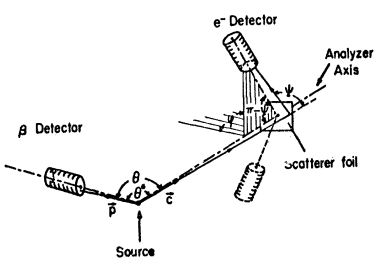

FIG. 3. Schematic diagram of the geometry of the experiment. The starred angles (θ^* and ψ^*) are the nominal instrument correlation and Mott scattering angles, respectively. In the present experiment, θ^* is chosen to be 90°, where ψ^* is 120°. The angle θ and ψ indicate some of the deviations from the nominal angles which must be taken into account in the calculation of the instrumental efficiency $R(E_{CE})$.

[20] R. A. Llewellyn and R. M. Steffen, Phys. Rev. **132**, 346 (1963).
[21] N. Sherman, Phys. Rev. **103**, 1601 (1956).
[22] Shin-R Lin, Phys. Rev. **133**, A965 (1964).
[23] H. Wegener, Z. Physik **151**, 252 (1958).

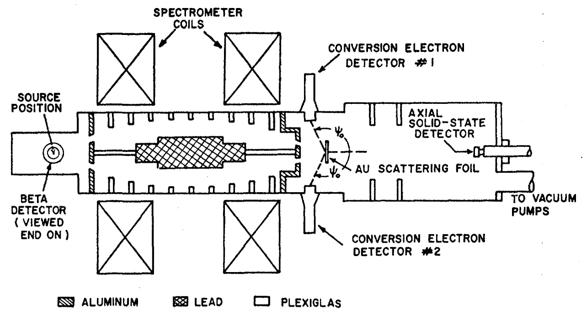

FIG. 4. Cross-sectional view of apparatus.

asymmetry and of the Coulomb elastic scattering cross section, according to the calculations of Sherman,[21] is shown in Fig. 5. From this plot it is seen that there are conflicting considerations of increasing asymmetry but decreasing cross section with increasing scattering angle. The scattering angle chosen for this experiment is a nominal 120°; however, the actual angle ψ is smeared out due to several factors, such as the spherical aberration of the spectrometer, the deviation from normal incidence of the focused electron beam on the scatterer, and the spread in angle followed by the finite size of the conversion electron detectors. The actual angles ψ for the geometry of this experiment range from 95° to 142°.

Several other factors must be taken into account which affect the relationship between the beam polarization and the observed asymmetry. These are (1) the finite solid angles of the detectors, and finite entrance angle of the spectrometer; (2) the strong dependence of the scattering parameters on scattering angle as noted above; (3) the beta-conversion electron directional correlation; (4) the relation of the rotation of the spin of an electron by the magnetic field of the spectrometer to the spherical aberration of the spectrometer; and (5) the depolarization of the beam due to scattering in the source. These are all taken into account by the numerical calculation[24] of a factor $R(E_{CE})$, according to a method similar to that outlined by Llewellyn and Steffen.[20] Thus, for a given instrument and conversion electron energy E_{CE}, the measured asymmetry is related to the polarization by

$$\delta=K_K\langle v/c\rangle R(E_{CE}). \qquad (6)$$

The quantity $\langle v/c\rangle$ is an average value which depends on the portion of the beta spectrum observed.

The coincidence-counting electronics is arranged to register coincidences between the beta detector and either of the two conversion electron (CE) detectors. The detectors themselves are pilot B plastic scintillators, two in. in diam and 0.125 in. thick, optically coupled to the photocathodes of RCA 6810A photomultiplier tubes via lucite light guides. The coincidence

[24] R. L. Rasera, Ph.D. thesis, Purdue University, 1965 (unpublished).

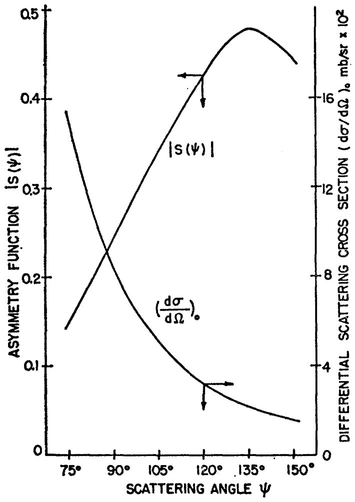

FIG. 5. Relation of the asymmetry function $S(\psi)$ and the Coulomb elastic-scattering differential cross section to the scattering angle ψ for the conditions of this experiment (328-keV electrons, scatterer $Z=79$), according to Sherman (see Ref. 21). The function $S(\psi)$ relates the transverse polarization P of an incident electron beam to the observed Mott scattering asymmetry δ observed at the angle ψ according to the relation $\delta=S(\psi)P$.

circuitry is of the "fast-slow" variety, the fast channel being built around a transistorized time-to-amplitude converter designed by Simms.[25] As used in this experiment, the coincidence resolving time 2τ was 15 nsec. The entire apparatus is controlled from a master timer which once every hour prints out the accumulated single and coincidence counts on paper tape, and rotates the beta detector through 180° about the spectrometer axis, thus reversing the function of the "left" and "right" CE detectors. This provides for the averaging of instrumental asymmetry due to source or spectrometer misalignment. As the apparatus is fully automated, around-the-clock data accumulation is feasible.

In the measurement of this kind done previously with this spectrometer,[18,20] the focusing of the spectrometer could be checked in two ways, both rather inefficient. The Mott-scattered electrons could be counted in the CE detectors; this is a very slow process due to the small percentage of the transmitted beam that is so scattered. Alternatively, the scattering tank and foil support assembly could be replaced by an accessory endplate that positions a scintillation detector at the spectrometer focus point. This is also not wholly satisfactory, due to the time consumed in such replacement, the possibility of damage to the extremely thin scattering foil, and the likelihood of misalignment of the spectrometer during removal and replacement of the assemblies. In the present experiment, these difficulties are overcome by mounting a semiconductor surface-barrier detector at the end of a long tube 1 in. in diam which can be advanced through a vacuum seal at the rear of the scattering tank to a position just behind the scattering foil, i.e., at the focus of the spectrometer. The tube itself is made the outer conductor of a coaxial line, and a length of #36 wire down the center carries the detector signal to the preamplifier. When polarization measurements are in progress, the axial detector can be withdrawn to the rear of the scattering tank. It is thus feasible with this modification to check the spectrometer focusing more often and more accurately than was previously possible.

Carrier-free Au^{198} of high specific activity was obtained from Oak Ridge National Laboratory in the form of $Au^{198}Cl_3$ in *aqua regia* solution. Sources were prepared by evaporation of the solution on insulin-treated quarter-mil Mylar backing.

Data was accumulated for twelve weeks. For six of these weeks, the experiment was run with the gold scattering foil in place, and for six more weeks with an aluminum scatterer in place of the gold. Since aluminum, with a Z of only 13, has a very small Mott scattering asymmetry, the latter measurement yields a measure of the residual instrumental asymmetry, for which the measured asymmetry δ can then be corrected.

With about 11 000 true coincidences recorded, the result for δ, corrected for the residual instrumental asymmetry, is

$$\delta=-0.044\pm0.013.$$

The value of K_K can then be calculated from Eq. (6), using known values of $\langle v/c\rangle$ and R(328 keV). In the beta detector, only those electrons with energy greater than 480 keV were accepted in order to avoid spurious coincidences of, e.g., betas in the CE detectors with gammas in the beta detector. By graphical integration of the observed beta spectrum, $\langle v/c\rangle$ is found to be 0.88. This number is not in this case very sensitive as the electrons are quite relativistic, so that the range of accepted v/c goes only from 0.86 to 0.94. The value of R(328 keV) is determined through point-by-point numerical calculation to be -0.115 ± 0.015. The error in R(328 keV) is the limit of error; that of δ above is statistical. Combining these results, then, one finds $K_K=+0.43\pm0.17$. In order to avoid confusion, it should be pointed out that a positive sign for K_K means that the conversion electron spin is parallel to the momentum of the preceding beta particle.

DISCUSSION

The experimentally obtained value for K_K may be used to obtain a value for the particle parameter $b_{1,11}(E2)$, using the results of the beta-circularly polarized gamma correlation measurements, and Eqs. (4) and (5). A weighted average of all circular polarization correlation measurements made to date[19] yields for the quantity $A_1(\beta)$ a value of $(-0.63\pm0.03)(v/c)$. Using this value and the value of the F coefficient, one finds for the K-conversion particle parameter $b_{1,11}(E2)$ a value of -1.0 ± 0.4. The calculated value for this energy given by Becker and Rose is -1.07, in good agreement with the result of the present experiment. The present measurement therefore supports the sign, and, with somewhat greater uncertainty, the magnitude of the calculated value in this case.

[25] P. C. Simms, Rev. Sci. Instr. 32, 894 (1961).

TABLE I. Results of measurements of the transverse polarization of K-conversion electrons following the beta decay of Au^{198}. Errors in the first two entries are as stated in the indicated references. The error in the present work includes the limit of error in the instrumental corrections.

	K_K	$b_{1,\text{II}}$ ($E2$)
Blake *et al.*[a]	-0.18 ± 0.07	$+0.40\pm0.16$
Llewellyn and Steffen[b]	-0.28 ± 0.04	$+0.63\pm0.10$
Present work	$+0.43\pm0.17$	$-1.0\ \pm0.4$

[a] Reference 17.
[b] Reference 18.

The two previous experiments, those of Blake *et al.*[17] and of Llewellyn and Steffen,[18] both yielded values of K_K and, consequently, of the particle parameter, of the opposite sign and of smaller magnitude than the present work (see Table I). In the former experiment, the polarization analysis was accomplished by Mott scattering through an instrument angle of 90°, with the normal to the scattering foil making a 45° angle with the nominal incident beam direction. In this arrangement, the probability for plural scattering is very high, since an individual electron may be scattered relatively easily through small angles two or more times and emerge at 90° to its incident direction. Also, in that experiment, an effort was made to cause the electron trajectory and spin rotation to vanish at the spectrometer focus by using oppositely directed currents in each coil of the lens spectrometer. Consequently, no spin rotation calculation was included in the corrections. In the latter experiment, only part of the instrumental corrections were made, and these corrections were applied in a way that does not take into account the interdependence of the spread in the angular variables and the functional dependence of the scattering parameters. Furthermore, that experiment made use of only one CE detector; the scattering asymmetry was measured by rotating the beta detector through 180° about the spectrometer axis. Instrumental asymmetry was measured by rotating the plane of the CE detector and spectrometer axes through 90° about the spectrometer axis. This causes the apparatus to measure the component of the transverse polarization $P_\perp(\theta)$ normal to the plane of the beta and conversion electron momenta, which should be very small in this case. However, in the physical operation of rotating the spectrometer main vacuum tank, and, perforce, the baffle system, the instrument alignment can very easily be changed from its original condition, rendering the subsequent measurement of instrumental asymmetry not very meaningful. The system used in the present experiment, that of two opposed CE detectors in combination with rotation of the beta detector between counting periods, provides not only for the easy detection of asymmetries due to asymmetric transmission of the spectrometer, but also the automatic averaging of such effects. The use of an aluminum scattering foil for residual instrumental asymmetry measurements involved no disturbance to the major components of the system. Finally, in the previous measurement, an error in data analysis has been found which causes a bias in the calculations in the direction of negative K_K. Although the accuracy of the result of the present experiment is not such as to preclude deviations from the theoretical particle parameter, it removes the doubt concerning the validity of the calculation of Becker and Rose that the earlier results had raised. This is as one would expect, since the same matrix elements used to calculate conversion coefficients and particle parameters of directional correlations, which have yielded adequate agreement with experiment in most cases of nonretarded $E2$ transitions.

The primary usefulness of the method herein described, in view of the uncertainty and difficulty of the experiment, is in the determination of the beta-decay coefficients $A_1(\beta)$ and thus of the combination of matrix elements therein, in cases that, although of interest, cannot be investigated using beta-gamma circular polarization correlation, for reasons such as low gamma transition energy, or large conversion coefficient. The result of the present work allows the calculated particle parameters of Becker and Rose to be used with more confidence in such cases.