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Positron-electron angular correlations in internal pair conversion

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The internal pair conversion (IPC) of transitions in Pb nuclei has been studied. Recent calculations of IPC for transitions with energies up to 2 MeV predict large differences in the shapes of the angular correlations according to their magnetic or electric character. We have measured absolute pair-conversion coefficients for $E1$ transitions in ^{206}Pb and an $M1$ transition in ^{207}Pb with uncertainties three to five times smaller than previous measurements. The measured positron-electron angular correlations are in good agreement with the predictions of the recent calculations and display the predicted differences between the electric and magnetic cases. [S0556-2813(98)50606-1]

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Internal pair conversion (IPC), whereby a photon of energy greater than 1022 keV converts into a positron-electron pair in the Coulomb field of the emitting nucleus, is a well-known process which has been studied in its own right, as well as used as a spectroscopic tool, for several decades. Recent theoretical results suggest, however, that an experimental reexamination of this phenomenon in heavy nuclei is in order. The earliest mention of IPC in the literature is by Nedelskey and Oppenheimer [1], who pointed out the expected region of validity of simple calculations of the pair production rate using the Born approximation. These approximate calculations were extended by Rose and Uhlenbeck [2], who calculated total pair-conversion coefficients, the dependence of the conversion coefficients on the positron energy and the opening-angle correlation between the positron and electron.

Early numerical calculations using Coulomb-distorted Dirac wave functions for the positron and electron were performed by Jäger and Hulme [3]. These were subsequently refined [4,5], and, most recently, Schlüter *et al.* [6] reported the results of more precise calculations of differential and total IPC coefficients using Coulomb distorted wave functions. Particular emphasis was placed on the behavior of transitions in heavy nuclei, where the effects of finite nuclear size were also treated. These calculations were later extended to describe the opening-angle dependence of IPC [7] and included the effects of nuclear alignment on the positron-electron angular correlation [8]. Significant differences between the older Born approximation results and those from the more precise methods have emerged. The absolute IPC conversion coefficients for electric and magnetic dipole conversion were found to have qualitatively different dependences on Z, the charge of the emitting nucleus. The magnetic coefficients show a dramatic rise with increasing Z above $Z=80$. In contrast, electric pair conversion generally decreases slightly in this range. In addition, the opening-angle correlations for magnetic transitions with energies up to 2 MeV, in high Z nuclei, were found to deviate strongly at large angles from those, where the Coulomb effects are small and the transition energies are high.

The most precise absolute measurements of IPC in heavy nuclei by coincident detection of both positron and electron are from Allan [9], who studied transitions in ^{205,206,207}Pb with uncertainties on the order of 20%. In that work, the measured coefficients were used to support multipolarity assignments for the different pair converting transitions. The detection efficiency, however, relied on an assumed, unmeasured, opening-angle correlation.

Angular correlation data for IPC are comparatively rare. The earliest measurement of the positron-electron angular correlation is by Devons and Lindsey [10], who studied the 6.05 MeV electric monopole transition in ^{16}O, which was later reinvestigated by Gorodetzky *et al.* [11] Warburton *et al.* [12] used a pair spectrometer and the Born approximation forms of the positron-electron angular correlation for electric and magnetic multipole radiation, to assign multipolarities for a number of transitions in light nuclei. There has also been a very recent report of a comparison between electric and magnetic transitions at high energy in Be and C [13]. In situations where strong deviations from the Born approximation are anticipated, with the exception of one recent measurement [14], such angular correlation data are unavailable.

For these reasons, we have carried out a study of IPC in heavy nuclei using the APEX spectrometer at Argonne National Laboratory [15]. Our goal was twofold. First, to improve the precision of the measured absolute pair-conversion coefficients for electric and magnetic dipole transitions in heavy nuclei, so as to check more rigorously the theory, and second, to measure the positron-electron opening-angle correlation for transitions in heavy nuclei, to test the prediction of a strong deviation from the Born approximation for magnetic transitions. To perform these tests, we have studied IPC of transitions with similar energies but different multipolarities: (1) the 1760 keV electric monopole ($E0$) transition in ^{90}Zr, (2) electric dipole ($E1$) transitions in ^{206}Pb between 1700 and 1900 keV and (3) a 1770 keV magnetic dipole

($M1$) transition in ^{207}Pb. The comparison between the results for the different cases thus minimizes systematic errors.

The APEX positron spectrometer is a solenoidal device utilizing highly segmented arrays of silicon detectors to detect positrons and electrons. Technical details of the spectrometer as well as the properties of the performance and response of the device are given in Ref. [15]. For this particular measurement, the spectrometer was augmented with two high-purity intrinsic Ge detectors; one of 70% relative peak efficiency was used for primary γ-ray detection, and a second with 25% relative peak efficiency was used for monitoring and cross checking. A pulser was used to monitor the data acquisition dead time. All events were recorded which satisfied either a hardware trigger developed from the positron-identification detectors in the spectrometer, or were downscaled samples of events triggered by the silicon and Ge detectors.

The ^{90}Y nucleus decays by β^- emission predominantly to the ^{90}Zr ground state, but also with a 0.0115% branch to the 0^+ first excited state of ^{90}Zr, which decays by an $E0$ transition via electron conversion or IPC. The two Pb isotopes are populated by electron capture (EC) decay of ^{206,207}Bi. The majority ($\approx$90%) of the ^{206}Bi decay strength goes to 5^- levels in ^{206}Pb at 3279 keV and 3403 keV. These two states have a variety of decays, of which the strongest pair producing transition is an $E1$ decay connecting the 5^- (3403 keV) and 4^+ (1684 keV) states, with a transition energy of 1719 keV. A number of other weaker $E1$ 5^--4^+ transitions also occur. Finally, the ^{207}Bi EC decay primarily feeds the $13/2^+$ (1633 keV) isomer of ^{207}Pb, but contains a 7.03% branch to the $7/2^-$ state at 2339 keV. This level decays almost exclusively by a 1770 keV $M1$ transition to the $5/2^-$ first excited state in ^{207}Pb at 569 keV [16].

The ^{90}Y and ^{207}Bi source materials were obtained from commercial suppliers. The nucleus ^{206}Bi has a rather short half-life of 6.243 d, and so was produced using the ^{206}Pb(p,n) reaction on a thick ^{206}Pb target at an incident proton energy of 11.0 MeV. This bombardment was carried out at the University of Notre Dame tandem accelerator and the ^{206}Bi which was produced was subsequently chemically separated at Argonne National Laboratory. The strengths of the radioactive sources at the beginning of the measurements were 32.5 μCi, 12.6 μCi and 4.1 μCi, for ^{90}Y, ^{206}Bi, and ^{207}Bi, respectively. The elapsed live times for the three measurements were 61.8 h, 48.6 h, and 105.4 h, respectively. In addition, a measurement of background radiation was carried out for 59.8 h. The pair detection efficiency of APEX was determined from Monte Carlo simulations using the GEANT software package [17]. These calculations have previously been demonstrated to reproduce the response of the spectrometer [15]. The efficiencies of the Ge detectors were determined using a ^{152}Eu source to measure the relative efficiency as a function of energy, and a calibrated ^{60}Co source to obtain the absolute efficiency calibration. The uncertainty in the efficiency of the Ge detector was dominated by that of the ^{60}Co activity, quoted by the manufacturer to a precision of 1.9%.

Positron-electron sum-energy spectra for the three radioactive sources studied are shown in Fig. 1. In each case the contributions to the spectra from room background have been subtracted. These amount to less than 8% of the yield in the peak sum-energy region. For the ^{90}Y and ^{207}Bi sources, the energy resolution in the sum-energy spectra is dominated by the response of the APEX silicon detectors and their associated electronics. For the ^{206}Bi case, the source was somewhat thicker and less uniform, which gives rise to energy loss straggling and consequently to a poorer overall energy resolution. The inserts in Figs. 1(b) and 1(c) show the respective gamma-ray spectra in the energy region of interest, where the gamma-ray peaks corresponding to the most prominent IPC producing transitions have been indicated.

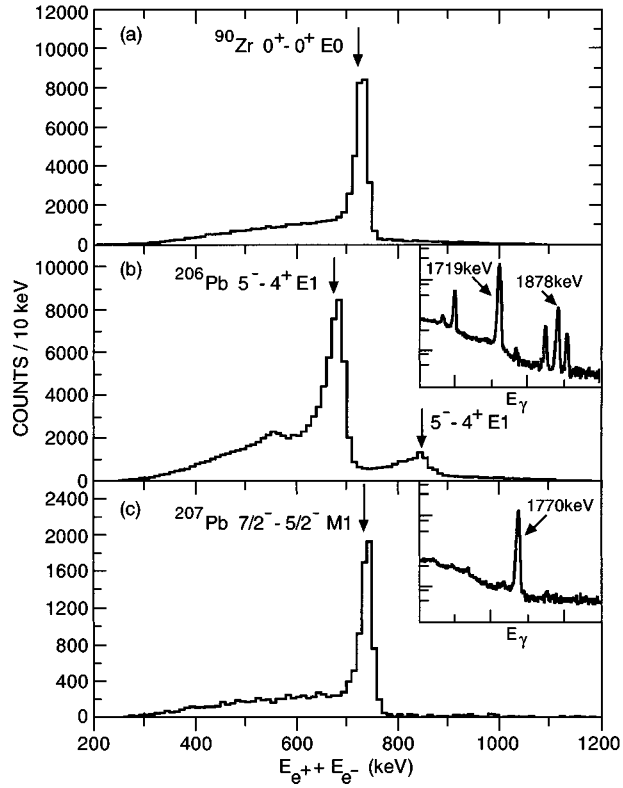

FIG. 1. Positron-electron sum energy spectra for internal pair conversion in (a) ^{90}Zr, (b) ^{206}Pb, and (c) ^{207}Pb. The inserts in (b) and (c) contain gamma-ray spectra showing the transitions producing positron-electron pairs. The vertical scales for the inserts are logarithmic.

The remaining backgrounds underneath the peak regions in Fig. 1 arise, in each case, from different processes. For ^{90}Y, there exists a broad continuum of positron-electron pairs due to coincidences of the positron from a 0^+-0^+ transition in ^{90}Zr with electrons from the β^- decay of ^{90}Y. In the case of ^{206}Bi, counts under the full energy peak arise from chance coincidences between positrons from IPC and conversion electrons produced in lower lying transitions in the decay cascade. For ^{207}Bi, a conversion electron could also, in principle, be in coincidence with a positron from the pair decay. In this case, however, in order to satisfy the sum-energy condition of $E(e^+)+E(e^-)=748$ keV the corresponding low-energy positrons are largely below our threshold of 200 keV. The effects of these different processes have been included in the Monte Carlo simulations. The contributions from these background processes in the region of the sum energy peak are estimated to be 10% to 15% of the full energy peak yield, and have been subtracted, when calculat-

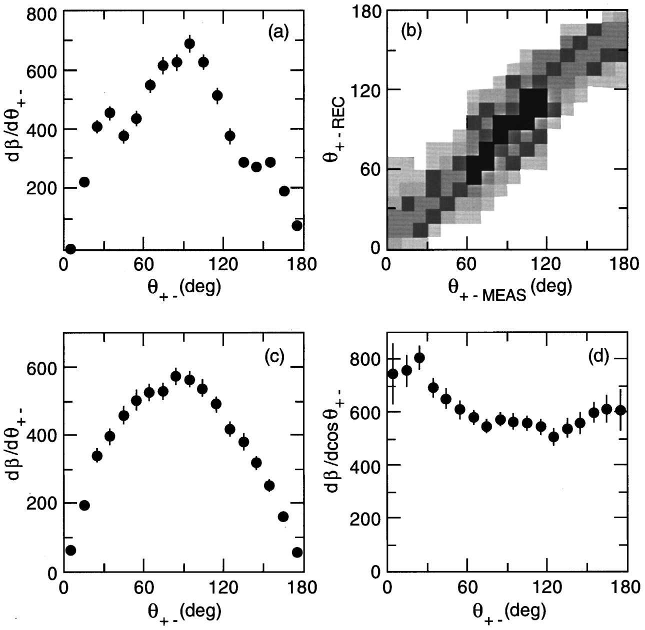

FIG. 2. Illustration of the procedure used to deduce the positron-electron opening-angle distribution for the 1770 keV $M1$ transition in ^{207}Pb. (a) Raw angular correlation, (b) response matrix for deconvolution of APEX opening angle response, obtained from Monte Carlo simulation. The X axis represents the true opening angle, and the Y coordinate the reconstructed opening angle. (c) Angular correlation $d\beta_{\pi}/d\theta_{+-}$ after deconvolution, and (d) angular correlation $d\beta_{\pi}/d\cos\theta_{+-}$.

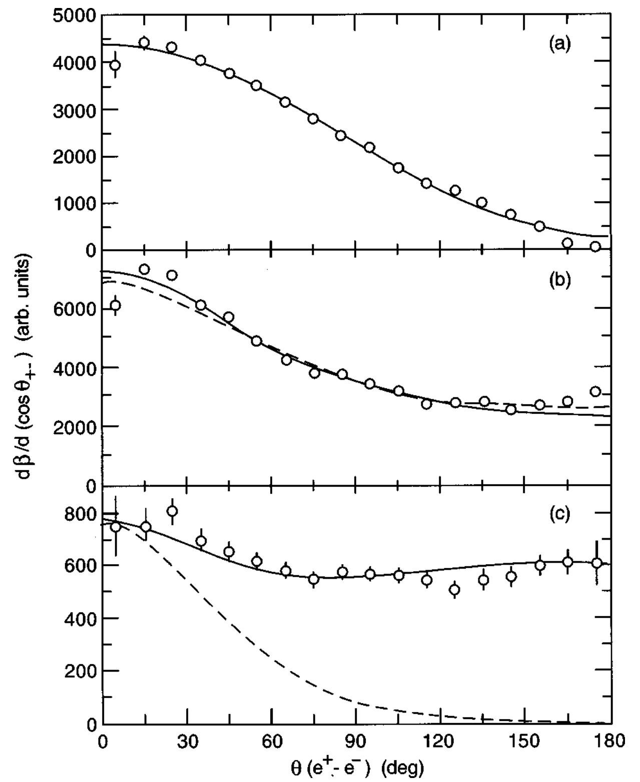

FIG. 3. Measured and calculated positron-electron angular correlations. (a) $0^+ \rightarrow 0^+$ $E0$ transition in ^{90}Zr, (b) $5^- \rightarrow 4^+$ $E1$ transition in ^{206}Pb. (c) $\frac{7}{2}^- \rightarrow \frac{5}{2}^-$ $M1$ transition in ^{207}Pb. The solid curves represent the calculations of Hofmann *et al.* and the dashed curves show the predictions of the Born approximation.

ing the absolute pair-conversion coefficients.

In order to measure the relative angles of the leptons emitted in the pair conversion process, we have exploited the transport properties of the APEX spectrometer. For each element of the silicon detector array, for a given lepton energy there are only a few trajectories by which a positron or electron can reach that element, each corresponding to a particular polar angle of emission measured relative to the solenoid axis. The spread in polar angles for paths reaching any given silicon wafer depends on the energy of the detected particle and the distance between the detector and the source, but is, in general, smaller than 20°. We have used Monte Carlo simulations to determine the average value of this emission angle for each detector element as a function of lepton energy. For each detected pair with a sum energy consistent with the full energy of the IPC transition, we have thus assigned the average value of the polar emission angle for each lepton. The azimuthal angle for each particle was then determined from the segmentation of the silicon array. Using these quantities, we calculated the experimental opening angle (θ_{+-}) for the pair.

The distortions of the opening-angle correlations due to this average treatment of the polar emission angles, as well as effects such as multiple scattering in the 1 mg/cm^2 source backing, have been studied using the Monte Carlo simulation of the response of the spectrometer [19]. As there is no unique correspondence between the true opening angles and those deduced experimentally, we have developed a response function for the apparatus which describes this transformation. This response function was obtained by simulating positron-electron pairs with sum energies equal to those under consideration with isotropic opening-angle correlations ($d\beta/d\cos\theta_{+-}$=constant). The raw data were then deconvoluted using this calculated response function, to produce a final experimental opening-angle correlation. This process is illustrated in Fig. 2, which shows opening-angle correlations for the ^{207}Pb pair transition obtained at each stage of this process, as well as a plot showing the calculated opening-angle response matrix.

We have studied the behavior of the opening-angle correlations for the three pair transitions being considered, averaged over the energy ranges of the detected positrons and electrons, between 200 keV $\leqslant E(e^+),E(e^-) \leqslant E_{\mathrm{max}}-200$ keV, where E_{max} is the maximum available lepton energy. As discussed above, the recent calculations [7] predicted that for the system under study, the opening-angle correlation for magnetic transitions is expected to deviate significantly from predictions based on the Born approximation. In the $E1$ case, the shape of the opening-angle correlation is expected to be qualitatively similar to the Born prediction, i.e., enhanced at small opening angles. Due to the relatively low charge, for the $E0$ transition in ^{90}Zr deviations from the Born approximation results are predicted to be almost negligible. Measurement of the $E0$ angular correlation thus provides a verification of the method used for extracting the angular correlation.

The positron-electron angular correlations obtained with this method are shown in Fig. 3. The solid curves represent the results of the calculations by the method of Hofmann *et al.* [7], and the dashed curves represent the results for the

TABLE I. Internal pair conversion coefficients β_π.

Transition	ω (keV)	ϵ (%)	β_π [a]	β_π [b]	$\beta_\pi(th)$ [c]
^{90}Zr($0^+ \to 0^+$) $E0$	1760	0.49	2.66(0.02)(0.19)$\times 10^{-1}$	2.96(0.01)$\times 10^{-1}$	2.78$\times 10^{-1}$
^{206}Pb($5^- \to 4^+$) $E1$	1719	0.42	3.06(0.02)(0.15)$\times 10^{-4}$	3.7(0.6)$\times 10^{-4}$	3.26$\times 10^{-4}$
^{206}Pb($5^- \to 4^+$) $E1$	1881	0.42	4.65(0.06)(0.15)$\times 10^{-4}$	4.7(1.5)$\times 10^{-4}$	4.40$\times 10^{-4}$
^{207}Pb($\frac{7}{2}^- \to \frac{5}{2}^-$) $M1$	1770	0.47	3.07(0.05)(0.18)$\times 10^{-4}$	2.5(0.5)$\times 10^{-4}$	2.73$\times 10^{-4}$

[a]Current measurement. The uncertainties are (statistical)(systematic).
[b]Results of Nessin, Kruse, and Elkund [20] ($E0$), and Allan [9] ($E1$,$M1$).
[c]Calculations of Church and Weneser [21], Wilkinson [22] ($E0$), and Schlüter, Soff, and Greiner [6] ($E1$,$M1$).

Born approximation calculations, each appropriately averaged over the lepton energy range covered in the measurement. The curves have been normalized to the data with the exception of the Born approximation result in Fig. 3(c), which is normalized to the data at small θ_{+-} so as to emphasize the difference between it and the Hofmann result. The error bars in the data reflect both statistical uncertainties, and estimated systematic errors. The systematic uncertainties which result from the deconvolution described above are difficult to estimate accurately, although prior experience with the GEANT simulation of the APEX apparatus suggests that they should not be greater than 5%. It is gratifying to observe that the agreement between the newer calculations and the data in each case is excellent. In particular, the predicted difference between the electric and magnetic angular correlations is confirmed.

Absolute total pair-conversion coefficients were obtained from the sum-energy peak yields using the measured source strengths, and efficiencies from the Monte Carlo simulations. These values are listed in Table I, together with the energy ω and the full-energy peak efficiency for each transition. The angular correlations used in the simulations are those from [7]. The table entry for the $E1$ transition in ^{206}Pb at 1881 keV represents the sum of contributions from the 1844, 1878, and 1903 keV $E1$ transitions, which are not resolved in our pair data. Here the efficiency, as well as the theoretical conversion coefficient is calculated for the average transition energy of 1881 keV. For ^{90}Zr and ^{206}Pb (1719 keV), the statistical uncertainties in the IPC coefficients are dominated by statistics in the Monte Carlo simulations. For ^{206}Pb (1881 keV) and ^{207}Pb, the statistical uncertainties in the data and the Monte Carlo calculations are comparable. The uncertainties in the source strengths are limited by the uncertainty in the strength of the ^{60}Co calibration source. For the ^{90}Y source, the strength was determined from the measured β^- yield, corrected for acceptance, and the associated uncertainty is somewhat larger. For the systematic uncertainties, we use the estimate of 5% from the GEANT Monte Carlo calculation of the pair efficiencies. In each case, we find that the pair-conversion coefficients are in good agreement with the theoretical values as well as with the results of previous measurements.

Additional consistency checks on the absolute values of the Monte Carlo simulations of the detection efficiency of the apparatus were made using data for conversion electrons from ^{207}Pb. For ^{206}Pb, the large number of conversion electron transitions and the resolution of the silicon detector array, as well as energy straggling in the source, precluded such a measurement. The electron conversion coefficients for the K and $L+M$ conversion of the 569 keV ($E2$), and the K conversion of the 1060 keV ($M4$) transition in ^{207}Pb deduced from our measurements are listed in Table II. The L and M lines for the 569 keV transition were not resolved, and their contributions are summed here. The $L+M$ conversion lines for the 1060 keV transition were beyond the spectrometer acceptance at the magnetic field setting of 300 G used in this measurement. In each case, the results are in reasonable agreement with theoretical predictions [18] and with the results of previous measurements [9].

The results of the current study, together with the work of Refs. [6–8], demonstrate that the theoretical understanding of IPC for heavy nuclei is now quite good. Our measured total pair-conversion coefficients and angular correlation data are in quite reasonable agreement with the predictions of Refs. [6–8], suggesting that the calculations are reliable even in the regime of strong vacuum polarization expected for high-Z nuclei. It is interesting to note that for Pb, the angular correlation is considerably more sensitive to the electromagnetic character of the transition than is the IPC coefficient. For example, in the Pb nuclei studied here, the measured $M1$ and $E1$ conversion coefficients are very close to each other, and still in agreement with their respective theoretical values. It is in the angular correlation that the

TABLE II. Internal conversion coefficients $\alpha_{K,L}$ for transitions in ^{207}Pb.

Transition	ω (keV)	ϵ (%)	$\alpha_{K,L}$ [a]	$\alpha_{K,L}(th)$ [b]
^{207}Pb($\frac{5}{2}^- \to \frac{1}{2}^-$) $E2$ (K)	569	23	1.46(0.04)(0.07)$\times 10^{-2}$	1.62$\times 10^{-2}$
^{207}Pb($\frac{5}{2}^- \to \frac{1}{2}^-$) $E2$ ($L+M$)	569	23	5.30(0.16)(0.27)$\times 10^{-3}$	5.66$\times 10^{-3}$
^{207}Pb($\frac{7}{2}^- \to \frac{5}{2}^-$) $M4$ (K)	1060	1.4	1.06(0.15)(0.05)$\times 10^{-1}$	1.03$\times 10^{-1}$

[a]Current measurement. The uncertainties are (statistical)(systematic).
[b]Calculations of Rösel *et al.* [18].

behavior of the two transitions becomes radically different. It would be interesting to test this sensitivity for nuclei with Z greater than 82, where the magnetic conversion process is expected to be even stronger than that observed here.

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