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Multipole character of the proposed 220 eV transition in ^{229}Pa

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Internal conversion coefficients (ICC's) have been calculated for protactinium and transition energies between 170 eV and 10 keV. The ICC's for $E1$ multipolarity show an unusual behavior, which cannot be approximated by an exponential dependence on the transition energy, whereas the ICC's for $M1$ and $E2$ multipolarities closely follow such a dependence. Using the newly calculated ICC's the unusually strong "enhancement" of a possible 220 eV $E1$ transition in ^{229}Pa proposed earlier is reduced by a factor of ~ 5, yielding an induced electric dipole moment similar to that observed in the neighboring octupole-deformed isotopes.

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An excited level was proposed by Ahmad *et al.* [1] at 220 eV in ^{229}Pa, with spin parities of $5/2^+$ and $5/2^-$ assigned to the ground state and the 220-eV state, respectively. These levels would thus form an almost degenerate parity doublet, as is characteristic for nuclei with octupole deformation, a nuclear shape that is expected theoretically in the mass region around $A=225$. Ahmad *et al.* also measured a half-life of 420±30 ns, assigned to the 220 eV level, from which they derive an $E1$ transition rate of 2.5×10^{-2} W.u. for the proposed $5/2^-\rightarrow5/2^+$ transition. This transition rate is very fast compared to the $E1$ rates usually observed between one-quasiparticle states. This led Ahmad *et al.* in a later publication [2] to propose a collective enhancement of the $E1$ transitions in octupole-deformed nuclei. This idea has turned out to be very fruitful (see, e.g., Ref. [3]), and in fact such "enhanced" $E1$ transitions are now considered as fingerprints for strong octupole correlations.

Recently Grafen *et al.* [4] have shown that part of the experimental evidence that led to the spin-parity assignment of $5/2^-$ to the proposed 220 eV level was wrong. It was also argued in this paper that the proposed enhancement of the $5/2^-\rightarrow5/2^+$ transition is much larger than expected from octupole correlations. The collective $E1$ transitions in octupole-deformed nuclei are usually interpreted as resulting from an intrinsic electric dipole moment $\mathbf{e}\cdot\mathbf{D}_0$ induced by the polarizing electric field of the nuclear octupole deformation. For the proposed 220-eV $E1$ transition in ^{229}Pa one has $B(E1,\ 5/2^-\rightarrow5/2^+)=(15/28\pi)e^2D_0^2$, and with the transition rate given by Ahmad *et al.* a value of $D_0\approx0.6$ fm is obtained. This would be the largest intrinsic electric dipole moment observed in the region of octupole deformation around $A=225$, and it would be ~5 times larger than the D_0 for the even-core nucleus ^{228}Th [3]. Such a large polarization of the nucleus ^{229}Pa, as compared to its even core, seems unusual, although it might possibly be expected on theoretical grounds [5].

Since the identification of the parity doublet in ^{229}Pa is not established experimentally, it is important to consider the experimental evidence in favor of such a doublet. In the present work we address the extraction of the $E1$ transition rate from the measured half-life. The problem here is the internal conversion rate, which dominates the transition. From the $E1$ rate quoted by Ahmad *et al.* we deduce that these authors used an internal conversion coefficient (ICC) of $\alpha_{\rm tot}(E1)\approx1600$, although it is not clear from their paper how this value was obtained.

The ICC's for very low transition energies are not available in current tabulations. In the most recent tables [6] the conversion coefficients are listed for energies above 2.2 keV. Since for $E1$ multipolarity $\alpha_{\rm tot}$ varies roughly as E_γ^{-3}, an extrapolation over three orders of magnitude is needed in the present case. Moreover, it is known that the ICC's often exhibit "strange" behavior when the transition energy approaches threshold. It is thus clear that a direct calculation of the conversion coefficients in the low-energy region is necessary to obtain reliable values for the total ICC of the 220-eV transition in ^{229}Pa. To our knowledge the internal conversion coefficients were never calculated for such low energies, except for the 77-eV $E3$ transition in ^{235}U [7,8].

The following physical assumptions were used in our calculations. Both the bound-electron and free-electron wave functions are solutions of the Dirac equation with the relativistic Hartree-Fock-Slater potential [9]. The nucleus is described by a Fermi distribution of the charge with $R=6.7$ fm. The kinetic energies of the conversion electrons were determined from the experimental binding energies [10]. Special attention was paid to correct normalizations of the wave functions for the free electrons with very low kinetic energies. The numerical accuracy of the calculated ICC's is estimated to be about 6%. In accordance with Rösel *et al.* [6], our calculation corresponds to the lowest-nonvanishing order of the perturbation theory of quantum electrodynamics.

The results for the O_4 subshell and the total ICC's for $E1$ multipolarity are shown in Fig. 1. The fine energy

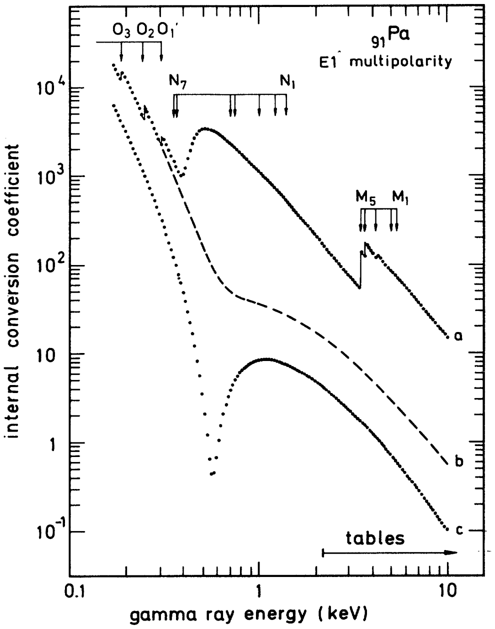

FIG. 1. Internal conversion coefficients for low-energy transitions of $E1$ multipolarity in protactinium. The points indicate the energies for which the coefficients were calculated in the present work, the horizontal line denotes the energy region covered by the tables of Rösel *et al.* [6]. Displayed are (a) the total ICC's, (b) the sum over the subshells O_2 through Q_1 playing the role of the total ICC's for γ-ray energies between 245 and 305 eV, and (c) the ICC's for the Q_4 subshell. The bump on the curve for the total ICC's at ~ 0.5 keV is due to internal conversion in the N_6 and N_7 subshells ($4f$ electrons) which is important only for low-energy $E1$ transitions [11].

mesh of our calculations enabled us to follow a complex behavior of the conversion coefficients to energies far below the 2.2 keV threshold of existing tabulations. We extended the calculations for $E1$ multipolarity, and for the M_1 through Q_1 atomic subshells, up to 10 keV to compare our values to those of Rösel *et al.* [6]. In all cases the conversion coefficients agreed within a few percent except for the N_5 subshell, where the deviation was 11%. As demonstrated in Fig. 1 for the O_4 subshell, the ICC's exhibit minima around $E_\gamma \sim 1$ keV which are most shallow for the $s_{1/2}$ subshells and sharpen with increasing angular momentum of the subshell. We verified that these resonancelike structures are due to cancellations in the leading matrix elements demonstrated earlier for $E2$ multipolarity at higher energies [12]. It is also obvious from our calculation that an extrapolation of ICC's from existing tabulations to energies below ~ 1 keV does not lead to reliable values for $E1$ multipolarity (see Fig. 1).

In the region of interest, $170 \leq E_\gamma \leq 270$ eV, the calculated total ICC's for $E1$ multipolarity vary approximately as E_γ^{-5} (to $\leq 2\%$) with proportionality constants as given in Table I. With the 420-ns half-life of the proposed 220-eV level we derive an induced electric dipole moment of $D_0 = 0.27 \pm 0.04$ fm, where the error includes uncertainties in both the half-life and the transition energy as well as numerical uncertainty of the ICC's. This value is much closer to the experimental result of 0.11 ± 0.02 fm of the ^{228}Th core nucleus than that given by Ahmad *et al.* [1].

TABLE I. Calculated ICC's for the 220±50 eV transition in ^{229}Pa.

E_γ (keV)	$E_\gamma^5 \alpha_{\mathrm{tot}}(E1)$	$E_\gamma^5 \alpha_{\mathrm{tot}}(E2)$	$E_\gamma^3 \alpha_{\mathrm{tot}}(M1)$
0.170–0.188	2.61	2.22×10^8	1.18×10^4
0.188–0.245	3.87	8.89×10^8	1.22×10^4
0.245–0.270	5.55	14.2×10^8	1.74×10^4

As pointed out by Ahmad *et al.* [1] the observed half-life is consistent with $M1$ multipolarity for the 220-eV transition. We have therefore also calculated the conversion coefficients for $M1$ and $E2$ multipolarity. In these cases the calculated ICC's closely follow a straight line in the log-log plot, even in the very-low-energy region. The total conversion coefficients are proportional to E_γ^{-3} and E_γ^{-5} for $M1$ and $E2$ multipolarity, respectively. The results of the calculation in the energy region of interest in the present work are included in Table I. For the reduced transition probability of a 220±50-eV transition one would obtain $B(M1) = (6.6 \pm 1.7) \times 10^{-3}\ (e\hbar/2Mc)^2$ and $B(E2) = (6.1 \pm 0.8) \times 10^3\ e^2$ fm^4 or $(1.2 \pm 0.3) \times 10^3\ e^2$ fm^4 for E_γ below or above the O_3 binding energy, respectively.

In summary, our calculations show that for $E1$ transitions with energies below ~ 1 keV the ICC's cannot be derived by an extrapolation from higher energies, whereas such an extrapolation yields reasonable values for $M1$ and $E2$ multipolarities, at least for heavy elements. For a possible 220-eV $E1$ transition in ^{229}Pa the half-life of 420 ns gives an enhancement of a factor of ~ 2 for the induced electric dipole moment, as compared to the ^{228}Th core nucleus, which might be expected on theoretical grounds due to the polarization of the core by the extra proton [5].

Using modern electrostatic spectrometers one should be able to examine the conversion-electron spectrum of the $^{229}\mathrm{U} \rightarrow {}^{229}\mathrm{Pa}$ decay at very low energies. An observation of the conversion electrons of the proposed 220-eV transition would not only provide uncontested evidence for its existence, but would also allow one to determine its multipolarity, even from a rough measurement of conversion-electron intensity ratios. For example, for $E_\gamma \sim 220$ eV, the $(P+Q)/(O_4+O_5+O_6)$ ICC ratio takes on values of ~ 0.3, 11.3, and 114 for $E1$, $E2$, and $M1$ multipolarity, respectively. Moreover, a precise measurement of the conversion-line intensities could serve as a test for some of the higher-order effects in the internal conversion process [8,13].

After completion of the present work we learned that Band *et al.* [14] calculated ICC's for 220-eV $E1$, $M1$, and $E3$ transitions in protactinium using several atomic models. Their total ICC's corresponding to our approach agree with our values to within 9%.

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