Parity-violation effects on the Auger-electron emission from highly charged atomic ions

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Within the framework of standard electroweak gauge theory, parity-violation effects on the Auger emission from atomic ions are examined. Highly charged ions are prime candidates due to their simple atomic structure and large electroweak charge. To be specific, the Auger decay of the $2s^2$ $J=0$ level in U^{90+} is analyzed. In QED, the polarization-asymmetry parameter is identically zero. It is found that neutral-current mixing of the $2s^2$ $J=0$ and $2s2p$ $J=0$ levels yields a polarization asymmetry of 10^{-7}.

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Parity-violating neutral-current effects, as predicted by standard electroweak gauge theory [1], have been observed in a wide variety of processes in atomic, nuclear, and particle physics [2]. The diverse measurements include: deep-inelastic νN scattering, νe scattering, W and Z masses, polarized eD scattering, and radiative transitions in heavy atoms. The accumulated data serve to test the standard model at the tree and loop levels, constrain grand unified theories, and to possibly glimpse "new physics." With the recent development of heavy-ion traps and storage rings [3], the prospects for the observation of parity-violating effects on radiative transitions in highly charged ions have been examined [4]. In this paper, we further examine parity-violating effects on Auger (radiationless) transitions in highly charged ions. In both cases, the lure of neutral-current studies with highly charged ions is due to their simple atomic structure and large electroweak charge.

Starting from the second-order perturbation-theory expression for the one Z-boson exchange between an electron and a quark, one may derive [5] an effective Hamiltonian for a zero-momentum-transfer interaction between an electron and a nucleus, given by

$$H_Z=\frac{G_F}{\sqrt{8}}Q_w\rho_{\text{nuc}}(r)\gamma^5 , \tag{1}$$

where G_F is the Fermi constant, ρ is the nuclear density, γ^5 is a Dirac matrix, and atomic units ($e=m=\hbar=1$) are used. The electroweak charge is given by

$$Q_w=Z-4Z\sin^2\theta-N , \tag{2}$$

where Z is the number of protons, N is the number of neutrons, and θ is the Weinberg angle. The effective Hamiltonian of Eq. (1) represents only the timelike component of the electron axial-vector current and quark vector-current interaction, which is by far the largest contribution to atomic parity violation [6].

As a specific example, we choose to examine the neutral-current interactions between the $2s^2$ $J_i=0$ and $2s2\bar{p}$ $J_i=0$ resonance levels of U^{90+} ($2\bar{p}=2p\,\frac{1}{2}$). In the multiconfiguration Dirac-Fock approximation [7], including Breit interaction and QED effects [8], the $2s2\bar{p}$ $J_i=0$ level lies $\varepsilon=63\,928$ eV above the U^{91+} $1s$ $J_f=\frac{1}{2}$ ionization limit, while the lower of the two $(2s^2+2\bar{p}^2)$ $J_i=0$ levels lies at $\varepsilon=63\,948$ eV. The calculated $\Delta\varepsilon=20$ eV energy separation should be accurate to ±1 eV [9]. In perturbation theory, the parity-conserving Auger decay rates for the resonance levels are given by

$$A_\alpha^{\text{PC}}=\frac{4\mathcal{N}}{p}|\langle\psi_\varepsilon(J_fjJ_i)|H_\gamma|\psi_\alpha(J_i)\rangle|^2 , \tag{3}$$

where $\mathcal{N}=1+\varepsilon/2c^2$, $p=(2\varepsilon+\varepsilon^2/c^2)^{1/2}$, (J_i,J_f) are the total angular-momentum quantum numbers of the initial and final levels, c is the speed of light, and the continuum normalization is one times a sine function. The Hamiltonian H_γ of Eq. (3) is the two-body electromagnetic interaction between electrons. The Auger rates for the $2s^2$ and $2s2\bar{p}$ $J_i=0$ levels of U^{90+} are given in Table I. The Breit interaction is seen to have a strong effect on both rates, especially the rate for the $2s2\bar{p}$ $J_i=0$ level.

In perturbation theory, the parity-violating Auger decay rates for the resonance levels are given by

$$A_\alpha^{\text{PV}}=\frac{4\mathcal{N}}{p}\left|\frac{\langle\psi_\varepsilon(J_fjJ_i)|H_\gamma|\psi_\beta(J_i)\rangle\langle\psi_\beta(J_i)|H_Z|\psi_\alpha(J_i)\rangle}{\varepsilon_\alpha-\varepsilon_\beta}\right|^2 . \tag{4}$$

From Eq. (4), the parity admixture factor is seen to be given by

$$\eta=\frac{\langle\psi_\beta(J_i)|H_Z|\psi_\alpha(J_i)\rangle}{\varepsilon_\alpha-\varepsilon_\beta} . \tag{5}$$

Upon substitution of H_Z of Eq. (1) and explicit forms for

TABLE I. Parity-conserving Auger rates for U^{90+}.

Level	Energy (eV)	Rate (Hz) Coulomb only	Rate (Hz) Coulomb and Breit
$2s^2$ $J_i=0$	63 948	7.2×10^{14}	1.1×10^{15}
$2s2\bar{p}$ $J_i=0$	63 928	1.8×10^{14}	1.0×10^{15}

the Dirac wave functions $\psi_\alpha(2s^2\ J_i=0)$ and $\psi_\beta(2s2\bar{p}\ J_i=0)$, Eq. (5) yields

$$\eta=\frac{iG_F Q_w}{\sqrt{8}\Delta\varepsilon}(\tfrac{4}{3}\pi R^3)^{-1}\int_0^R [P_{2\bar{p}}(r)Q_{2s}(r)-Q_{2\bar{p}}(r)P_{2s}(r)]dr\ , \qquad (6)$$

where R is the radius of the uranium nucleus, and (P,Q) are the reduced radial wave functions of the Dirac bispinors. We find $\eta=(3.38\times10^{-7})i$, which is in rough agreement with that found earlier [4] for the neutral-current mixing of the $1s2s\ ^1S_0$ and $1s2\bar{p}\ ^3P_0$ bound levels of U^{90+}. The parity-violating autoionizing rates for the $2s^2$ and $2s2\bar{p}\ J_i=0$ levels of U^{90+} are given in Table II. The parity-violating rates found in Table II are much smaller than the parity-conserving rates found in Table I, although the electron-quark neutral-current rates of Table II are much larger than those quoted earlier [10] for the electron-electron neutral-current interaction.

In direct analogy with the analysis of neutral currents in e^+e^- annihilation and deep inelastic scattering of charged leptons [5], parity-violation effects in Auger emission will be strongest when γ-Z interference terms can be observed. The spin angular distribution of Auger electrons is given by [11,12]

TABLE II. Parity-violating Auger rates for U^{90+}.

Level	Energy (eV)	Rate (Hz) Coulomb only	Coulomb and Breit
$2s^2\ J_i=0$	63 948	21	110
$2s2\bar{p}\ J_i=0$	63 928	82	130

$$A_\alpha(\hat{\mathbf{p}},m_s)=\frac{4\mathcal{N}}{p(2J_i+1)}\sum_{M_i}\sum_{M_f}P(J_iM_i)\times|\langle\psi_f(J_fM_f)\phi_\varepsilon^{(-)}(\hat{\mathbf{p}}m_s)|H_\gamma|\psi_\alpha(J_iM_i)+\eta\psi_\beta(J_iM_i)\rangle|^2\ , \qquad (7)$$

where (J_iM_i,J_fM_f) are the total and magnetic quantum numbers of the initial and final levels, m_s is the spin projection of the Auger electron, and $P(J_iM_i)$ are the relative populations of the magnetic sublevels. The outgoing Auger electron may be written as

$$\phi_\varepsilon^{(-)}(\hat{\mathbf{p}}m_s)=\sum_{l,m_l} i^l Y^*_{l,m_l}(\hat{\mathbf{p}})\sum_{j,m_j} C^{l\ 1/2\ j}_{m_l\ m_s\ m_j}e^{-i\delta_{l,j}}\phi_\varepsilon(jm_j)\ , \qquad (8)$$

where Y_{lm} is a spherical harmonic, $C^{l_1\ l_2\ l}_{m_1\ m_2\ m}$ is a Clebsch-Gordan coefficient, and $\delta_{l,j}$ is the phase shift of the continuum electron. Upon recoupling, the spin-angular distribution of Eq. (7) is given by

$$A_\alpha(\hat{\mathbf{p}},m_s)=\frac{4\mathcal{N}}{p(2J_j+1)}\sum_{M_i}\sum_{M_f}P(J_iM_i)\left|\sum_{l,m_l}(-i)^l Y_{l,m_l}(\hat{\mathbf{p}})\times\sum_{j,m_j}c^{l\ 1/2\ j}_{m_l\ m_s\ m_j}C^{J_f\ j\ J_i}_{M_f\ m_j\ M_i}e^{i\delta_{l,j}}\langle\psi_\varepsilon(J_fjJ_i)|H_\gamma|\psi_\alpha(J_i)+\eta\psi_\beta(J_i)\rangle\right|^2\ . \qquad (9)$$

To be specific, we again choose to examine the effects of neutral-current interactions between the $2s^2\ J_i=0$ and $2s2\bar{p}\ J_i=0$ resonance levels on the spin angular distribution of Auger electrons. Algebraic reduction of Eq. (9) yields

$$A_\alpha(\hat{\mathbf{p}},\pm\tfrac{1}{2})=\frac{4\mathcal{N}}{p}\frac{1}{8\pi}\{V_\alpha^2+\bar{\eta}^2V_\beta^2\mp2\bar{\eta}V_\alpha V_\beta\cos\theta\cos\Delta\}\ , \qquad (10)$$

where $\eta=i\bar{\eta}$, θ is the spin axis angle, and $\Delta=\delta_{1/2,1}-\delta_{1/2,0}$. The matrix elements are given by

$$V_\alpha=\langle\psi_\varepsilon(J_fjJ_i)|H_\gamma|\psi_\alpha(J_i)\rangle\ , \qquad (11)$$

which are precisely the same as those used before for A_α^{PC} of Eq. (3). The phase factor Δ may be obtained [13,14] by differencing Coulomb phase shifts for an effective charge of $q=91$ at an energy of $\varepsilon=64$ keV. We find $\cos\Delta=0.183$.

An experimental observable is the polarization-asymmetry parameter, given by

$$P^{\pm}_{\mathrm{asym}}=\frac{2\pi\int_0^{\pi/2}A(\hat{\mathbf{p}},\pm)\sin(\theta)d\theta-2\pi\int_{\pi/2}^{\pi}A(\hat{\mathbf{p}},\pm)\sin(\theta)d\theta}{2\pi\int_0^{\pi}A(\hat{\mathbf{p}},\pm)\sin(\theta)d\theta}\ . \qquad (12)$$

For $P^+_{\mathrm{asym}}>0$, there are more spin-up electrons in the top hemisphere (as defined by the spin axis) than there are in the bottom hemisphere. Reflection symmetry (parity) in the $\theta=\pi/2$ plane is violated. Substitution of $A_\alpha(\hat{\mathbf{p}},\pm1/2)$ of Eq. (10) into Eq. (12) yields

$$P^{\pm}_{\mathrm{asym}}(\alpha)=\mp\frac{\bar{\eta}_\alpha V_\alpha V_\beta\cos\Delta}{(V_\alpha^2+\bar{\eta}^2V_\beta^2)}\ . \qquad (13)$$

The polarization-asymmetry parameter $P^{+}_{\rm asym}$ for the $2s^2$ and $2s2\bar{p}\ J_i=0$ levels of U^{90+} are given in Table III. At the level of one part in ten million, there are less spin-up electrons in the top hemisphere than there are in the bottom hemisphere for Auger emission from U^{90+}. We note that the $2s^2$ and $2s2\bar{p}\ J_i=0$ levels are not complicated by further anisotropies due to collisional alignment. The total angular distribution of Auger electrons is given by

$$A_\alpha(\hat{\mathbf{p}})=\sum_{m_s} A_\alpha(\hat{\mathbf{p}},m_s)=\frac{4\mathcal{N}}{p}\frac{1}{4\pi}\{V_\alpha^2+\bar{\eta}^2V_\beta^2\}\ , \quad (14)$$

and is isotropic, while the total polarization of Auger electrons is zero.

In summary, we have calculated the order of magnitude of parity-violating effects in the Auger emission from U^{90+} by examining the γ-Z interference terms in the spin angular distribution function. For the $2s^2$ and $2s2\bar{p}\ J_i=0$ levels, the polarization-asymmetry parameter is found to be about 10^{-7}. For other atomic cases, the spin angular distribution of Auger electrons may be complicated by initial magnetic sublevel alignment. We hope this paper will stimulate further theoretical and experimental investigation into atomic parity-violating effects in electron scattering from highly charged heavy ions.

TABLE III. Polarization-asymmetry parameters for U^{90+}.

		$P^{+}_{\rm asym}$	
Level	Energy (eV)	Coulomb only	Coulomb and Breit
$2s^2\ J_i=0$	63 948	-3.1×10^{-8}	-5.8×10^{-8}
$2s2\bar{p}\ J_i=0$	63 928	-1.3×10^{-7}	-6.6×10^{-8}

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