

Parity Violation effects in highly-charged ions

I. Bednyakov, G. Plunien, G. Soff, Technische Universität Dresden
 L.N. Labzowsky, St. Petersburg State University,
 A.V. Nefiodov, St.Petersburg Nuclear Physics Institute,

Parity-nonconserving (PNC) atomic effects originate from the electroweak interaction of atomic electrons with the nucleus via Z -boson exchange. Comparing experimental results with theoretical predictions of the standard model allows to search for "new physics" beyond the standard model (e.g., a second Z -boson or new fermions) [1].

In the case of neutral atoms here is the discrepancy between theoretical and experimental results for PNC effects in the case of neutral atoms that might be explained by the uncertainties in the calculations caused by the inter-electronic interactions, correlation effects etc.

In highly-charged ions (HCI), on the other hand, the binding to the nucleus dominates by far the electron-electron interaction. The spin-independent part of an effective weak interaction Hamiltonian mediated by a Z -boson exchange is given by

$$\hat{H}_W(\mathbf{r}) = -\frac{G_F}{2\sqrt{2}} Q_W \rho_N(\mathbf{r}) \gamma_5, \quad (1)$$

where G_F is the Fermi constant, $\rho_N(r)$ is the nuclear density and γ_5 is the Dirac matrix. Due to this effective Hamiltonian states with opposite parity will be admixed. The transition amplitudes of a given atomic processes can be expressed as:

$$A = A_0 + i\eta A_1, \quad (2)$$

where A_0 denotes the amplitude of the basic process and A_1 is the amplitude being related to parity violation.

Electroweak-radiative corrections were considered both for neutral atoms (e.g. see Ref. [2]) and also for hydrogen-like ions [3]. The consideration of these radiative corrections becomes necessary because they can contribute up to 10% of the total magnitude of PNC effects.

For experiments, a promising situation occurs in He-like ions due to the near-degeneracy of two levels with opposite parities, 2^1S_0 and 2^3P_0 near $Z = 64$ (Gd^{62+}) as well as close to $Z = 92$ (U^{90+}). The situation has been analyzed in Gd^{62+} and Eu^{61+} . In particular we propose a quenching-type experiment with an interference of hyperfine- and weak-quenched transitions [4].

A typical situation for parity violation in atoms concerns the $M1$ transition with an admixture of the $E1$ transition. The one-photon hyperfine-quenched transition $2^1S_0 \rightarrow 1^1S_0$, via emission of a magnetic photon ($M1$), is due to the hyperfine mixing of the 2^1S_0 and 2^3S_1 levels. The weak interaction of electrons opens another one-photon decay channel $2^1S_0 \rightarrow 1^1S_0$, via the $E1$ emission through the mixing of the 2^1S_0 and 2^3P_1 levels by the operator \hat{H}_W . As a result, the total amplitude A in Eq. (2) appears as a mixture of the basic $M1$ amplitude $A_0 \equiv A_s$ and of the additional $E1$ amplitude $A_1 \equiv A_p$. The corresponding transitions rates are W_s and W_p , respectively. The weak mixing coefficient η is determined by

$$i\eta\Delta_0 = \langle 2^3P_0 | \hat{H}_W | 2^1S_0 \rangle, \quad (3)$$

where $\Delta_0 = E_{2^1S_0} - E_{2^3P_0}$. The theoretical predictions

| Nucl. | $W_s(\text{s}^{-1})$ | $W_p(\text{s}^{-1})$ | η |
|------------------------|----------------------|-----------------------|-----------------------|
| $^{151}_{63}\text{Eu}$ | 0.68×10^8 | 0.11×10^{14} | 0.33×10^{-6} |
| $^{155}_{64}\text{Gd}$ | 0.58×10^6 | 0.75×10^{11} | 0.91×10^{-6} |

for these quantities in europium and gadolinium are listed in the Table. Due to the admixture of states of opposite parity, in a polarized-beam experiment a small asymmetry in the number of emitted photons per direction should become visible, expressed by

$$dW(\mathbf{n}) = \frac{W_s}{4\pi} [1 + \varepsilon(\boldsymbol{\zeta} \cdot \mathbf{n})] d\Omega \quad (4)$$

where \mathbf{n} indicates the direction of the photon emission and $\boldsymbol{\zeta}$ is the unit vector in direction of the polarization of the ion. The coefficient of asymmetry is given by $\varepsilon = 3\lambda_0\eta R/(I+1)$ with $R = \sqrt{W_p/W_s}$. Here $\lambda_0 \leq 1$ denotes the degree of polarization.

The total asymmetry effect turns out to be $\varepsilon \simeq 0.37\lambda_0 \times 10^{-3}$ for Gd^{62+} , which is unusually large for parity-violation effects, but the lifetime of the 2^1S_0 level is about one order of magnitude smaller than the hyperfine-quenched 2^3P_0 lifetime. This implies a strong background in experiments with Gd^{62+} .

In Eu^{61+} the weak asymmetry effect reduces to $\varepsilon \simeq 0.11\lambda_0 \times 10^{-3}$, but the 2^1S_0 level lives significantly longer than the hyperfine-quenched 2^3P_0 level.

Since photons being observed in this experiment originate from single-photon decays of the hyperfine- and weak-quenched $F = I$ state, the success of the experiment will depend crucially on the production of a significant degree of polarization for this state of the He-ion. This is a task to be achieved experimentally in order to exploit the advantages of highly-charged ion investigations for parity-violation effects.

References

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