Parity nonconservation in dielectronic recombination in multiply charged ions

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Introduction

Successful observations of the parity nonconservation (PNC) effects in optical experiments with heavy neutral atoms have stimulated a search for the PNC effects in multiply charged ions (MCI) [1–3]. The obvious advantage of MCI is the Z^5 scaling of the PNC matrix elements, as opposed to Z^3 scaling in neutral atoms. However, this advantage is usually compensated by larger energy differences between the levels of opposite parity: the energy in MCI scales as Z^2 and *a typical PNC mixing in MCI is not larger than in neutral atoms* [4].

Sometimes levels of opposite parity in MCI are anomalously close. This leads to additional enhancement of the PNC effects [1]. One of the possibilities to study PNC mixing in He-like ions is to look for a PNC asymmetry in dielectronic recombination on an H-like ion. Here PNC interaction takes place in the intermediate doubly excited state of the He-like ion, which later decays. This process could be observed in experiments with Electron Beam Ion Trap (EBIT) devices [5].

Level crossings for $n = n' = 2$ shell

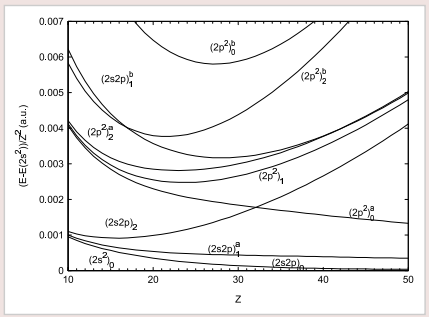

Fig.1 Relative position of the levels of the configurations $2s2p$ and $2p^2$ in respect to the level $(2s^2)_0$ for He-like ions. All energies are divided by Z^2 to account for general scaling of energies in MCI.

At the crossing between opposite-parity levels with $\Delta J = 1$ one can look for the nuclear-spin-dependent (NSD) PNC effects. The nuclear-spin-independent (NSI) PNC effects are usually larger, but they are seen when levels with $\Delta J = 0$ are mixed. There are two crossings of the levels of opposite parity with $\Delta J = 1$: for $Z \approx 17$ and for $Z \approx 42$. There are no crossings with $\Delta J = 0$, but for $Z \gtrsim 40$ levels $(2s^2)_0$ and $(2s2p)_0$ are very close.

PNC Hamiltonian

Hamiltonian of the PNC interaction includes NSI and NSD parts and in relativistic notations has the form:

$$H^{\rm PNC} = H^{\rm PNC}_{\rm NSI} + H^{\rm PNC}_{\rm NSD} = \frac{G_{\rm F}}{\sqrt{2}}\Big(-\frac{Q_{\rm W}}{2}\gamma_5 + \frac{\kappa}{I}\gamma_0\vec{\gamma}\vec{I}\Big)n(\vec{r}),$$

where $G_{\rm F} = 2.2225\times10^{-14}$ a.u. is the Fermi constant, γ_i are the Dirac matrices, $\vec{I}$ is the nuclear spin, and $n(\vec{r})$ is the nuclear density distribution. In the lowest order the standard model gives:

$$Q_{\rm W} = -N + Z(1 - 4\sin^2\theta_{\rm W}) \approx -N,$$

where N is the number of neutrons and $\theta_{\rm W}$ is the Weinberg angle.

The dominant contribution to κ comes from the anapole moment of the nucleus $\kappa_{\rm a} \sim \alpha A^{2/3}$, where $A = Z+N$ [6]. Up to now the only measurement of the NSD PNC amplitude was made by Wood *et al* for ^{133}Cs [7]:

$$\kappa(^{133}{\rm Cs}) = 0.39(6),$$

which is broadly in agreement with the theory.

PNC mixings for He-like ions

PNC Hamiltonian effectively mixes only one-electron states $ns_{1/2}$ and $\tilde{n}p_{1/2}$. For a nucleus of the radius $r_{\rm n} = 2.27\times10^{-5}A^{1/3}$ a.u. this matrix element is [8]:

$$\langle\tilde{n}p_{1/2}|H^{\rm PNC}|ns_{1/2}\rangle = -{\rm i}\frac{\sqrt{2}\,G_{\rm F}\alpha Z^4 R}{8\pi(\tilde{n}n)^{3/2}}\left(Q_W + \frac{8\gamma_{1/2}+4}{3I}(\vec{I}\cdot\vec{j})\kappa\right),$$

$$R = \frac{4\,(2Zr_{\rm n})^{2\gamma_{1/2}-2}}{\Gamma^2(2\gamma_{1/2}+1)},\quad \gamma_j = \left(\left(j+\frac{1}{2}\right)^2 - (\alpha Z)^2\right).$$

NSI part of the PNC Hamiltonian mixes states $(2s^2)_0$ and $(2s2p)_0$. The first of these states has admixtures of the configurations $2p^2_{1/2}$ and $2p^2_{3/2}$:

$$|+,0\rangle = C_{ss}|2s,2s\rangle + C_{pp}|2p_{1/2},2p_{1/2}\rangle + C_{p'p'}|2p_{3/2},2p_{3/2}\rangle,$$

and the PNC mixing is ($P = \pm$ is parity):

$$\mathrm{i}\eta_{0,0} = \frac{\langle 2s2p,-,0|H^{\rm PNC}_{\rm NSI}|2s^2,+,0\rangle}{E_{+,0}-E_{-,0}} = -{\rm i}\frac{\sqrt{2}\,G_{\rm F}\alpha Z^4 R Q_W}{64\pi(E_{+,0}-E_{-,0})}\,(C_{ss}-C_{pp})\,.$$

We calculate $\eta_{0,0}$ within Z^{-1} perturbation theory.

PNC mixing of levels with different J is caused by NSD part of the PNC Hamiltonian and for neutral atoms it scales as $Z^2R\kappa$. For the He-like ions there are two crossings between levels $(2s2p)^b_1$ and $(2p^2)^{a,b}_2$ (See Fig.1). For small Z these levels can be classified as $^1P_1(2s2p)$, $^3P_2(2p^2)$, and $^1D_2(2p^2)$, respectively. For large Z they tend to $(2s2p_{3/2})_1$, $(2p_{1/2}2p_{3/2})_2$, and $(2p^2_{3/2})_2$. In general we can write:

$$|-,1\rangle = C_{sp}|(2s,2p_{1/2})_1\rangle + C_{sp'}|(2s,2p_{3/2})_1\rangle,$$

$$|+,2\rangle = C_{pp'}|(2p_{1/2},2p_{3/2})_2\rangle + C_{p'p'}|(2p_{3/2},2p_{3/2})_2\rangle.$$

PNC matrix element between these states reads:

$$\langle -,1,F,M_F|H^{\rm PNC}_{\rm NSD}|+,2,F,M_F\rangle = \mathrm{i}\frac{\sqrt{2}}{48\pi}\,G_{\rm F}\alpha Z^4 R(2\gamma_{1/2}+1)C_{sp'}C_{pp'}A^I_F\kappa,$$

$$A^I_F \equiv (-1)^{I+F+1}\Big(15(I+1)(2I+1)/(8I)\Big)^{1/2} \times \left\{\begin{array}{ccc} F & I & 1\\ 1 & 2 & I\end{array}\right\}.$$

Numerical results for PNC mixings

We use Z^{-1} perturbation theory to calculate PNC mixings of the close levels of opposite parity for $n = n' = 2$ shell of He-like ions [9]. In the vicinity of $Z = 17$ corresponding NSD mixing is about one order of magnitude larger than NSI mixing for the same Z. At $Z = 42$ the NSD mixing also exceeds NSI mixing. Note that in general NSD mixing is approximately Z times smaller.

PNC mixing $\eta_{0,0}$ of levels $(2s^2)_0$ and $(2s2p)_0$

Z	10	17	20	30	40	42	50
$-\eta_{0,0}\times10^{11}$	0.068	0.71	1.55	16.4	108	146	501
$-\frac{\eta_{0,0}}{Z^3R}\times10^{15}$	0.651	1.28	1.64	4.31	9.44	10.5	16.8

PNC mixings $\eta^a_{1,2}$ and $\eta^b_{1,2}$ of the levels levels $(2p^2)^a_2$ and $(2p^2)^b_2$ with the level $(2s2p)^b_1$ near the crossing points $Z \approx 42$ and $Z \approx 17$.

Crossing point between $(2p^2)^a_2$ and $(2s2p)^b_1$ at $Z \approx 42$						
Z	39	40	41	42	43	45
$\eta^a_{1,2}/(A^I_F\kappa)\times10^{11}$	−47.5	−87.2	−246	626	170	88.3
Crossing point between $(2p^2)^b_2$ and $(2s2p)^b_1$ at $Z \approx 17$						

PNC asymmetry in dielectronic recombination

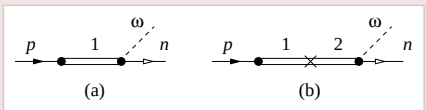

Fig.2 Diagrams for the dielectronic recombination. Initial state p corresponds to the H-like ion in the ground state and the electron with the momentum p. Intermediate states 1 and 2 correspond to the doubly excited states of the He-like ion which decay by emission of the photon ω to the final state n. The cross denotes PNC mixing of the states 1 and 2.

Dielectronic recombination of the electron on the H-like ion is described by the diagram Fig.2(a). Near the resonance corresponding cross section has the form:

$$\sigma^{\rm PC}_{\rm DR} \sim \frac{\pi}{p^2}\frac{\Gamma^{(r)}_1\Gamma^{(a)}_1}{(E-E_0)^2+\Gamma^2_1/4},$$

where $\Gamma^{(r)}_i, \Gamma^{(a)}_i, \Gamma_i$ are radiative, autoionizing and total widths of the state i. PNC interaction leads to the correction to the cross section which depends on the helicity of the electron $(\vec{\sigma}\cdot\hat{\vec{p}})$:

$$\sigma^{\rm PNC}_{\rm DR} \sim \eta_{1,2}(\vec{\sigma}\cdot\hat{\vec{p}})\sigma^{\rm PC}_{\rm DR}\sqrt{\Gamma^{(r)}_2/\Gamma^{(r)}_1}.$$

We can get additional enhancement if $\Gamma^{(r)}_2 \gg \Gamma^{(r)}_1$.

Conclusions

- PNC effects in dielectronic recombination of H-like ions are strongly enhanced because of the presence of anomalously close levels of opposite parity. In particular such levels exist for in the doubly excited configurations $n = n' = 2$.
- There are two crossing points of the levels of opposite parity with $\Delta J = 1$ where PNC effects associated with the nuclear anapole moment are strongly enhanced. These crossings take place near $Z = 17$ and $Z = 42$.
- In the vicinity of the crossing points the anapole moment contribution to the PNC effects dominates over that of the weak charge.
- Near the crossing points PNC effects strongly depend on QED corrections to energies. For example Lamb shift may make $(2s^2)_0$ and $(2s2p)_0$ cross. This will push up the NSI PNC asymmetry.

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