Parity Nonconservation Effects in the Highly Charged Ions

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The possible tests of the Standard Model in the spectra of the Highly Charged Ions via the observation of the Parity Nonconservation Effects are considered. The proposed experimental schemes, their advantages and drawbacks are discussed. The discussion is concentrated mainly on the He-like ions, where the crossing of the levels with opposite parity provides a uniquely favorable situation for the observation of the parity nonconservation.

The Parity Nonconservation (PNC) effects in atomic systems provide an unique possibility for the tests of the Standard Model (SM) in the low energy region. The experiments with colliding electron-positron beams with a center-of-mass energy as large as 100 GeV and higher can describe with high accuracy the properties of the particles, created at the resonance energies, i.e. charged and neutral vector bosons. However, the existence, e.g., one extra Z (neutral) boson which is allowed in some special versions of the SM, hardly could be observed in these experiments.

Therefore the possible discrepancy with the SM constants deduced from the high-energy physics (HEP), as large as 2.5 \( \sigma \) that was observed in the neutral Cs atomic experiments [1] was considered as the most important fundamental problem which required an urgent resolution. A dramatic situation existed while in the series of theoretical works the new effects (Breit interaction, radiative corrections) were one by one introduced into the theory and the low-energy result oscillated, correspondingly, from 2.5 \( \sigma \) to 1.0 \( \sigma \) and back. Finally these studies ended up with a reasonable compromise with the high-energy data. All the details can be found in a comprehensive review [2], the latest evaluation which confirmed this compromise arrived a bit later [3].

The Cs experiment is indirect and requires the accurate theoretical calculation for the comparison of its result with the high-energy SM predictions. This theoretical calculation is extremely difficult, since the PNC effects occurs actually inside the nucleus due to the short range of the effective weak interactions. On the other side this effect is produced entirely by the valence electrons with unclosed shells. Thus, all 55 electrons of neutral Cs atom contribute to the final result via the screening, i.e. electron correlation. The most elaborated modern methods allow for the evaluation of the electron correlation with accuracy of about 0.1 \% [3] what is comparable with the accuracy of the neutron distribution inside the nuclei also responsible for the accuracy of the answer.

Thus the theoretical accuracy is the less reliable component than the experimental one in the neutral atom PNC experiments.

This makes desirable the search for the PNC effects in the simpler atomic systems, e.g. in the few-electron highly charged ions (HCI).

An effective PNC potential of the interaction between an atomic electron and the nucleus looks like (in relativistic units \( \hbar = c = m_e = 1 \), \( m_e \) is the mass of an electron) [4]:

\[
\hat{H}_W(\vec{r}) = -\frac{G_F}{2\sqrt{2}} Q_W \gamma_5 n_N(\vec{r})
\]  

(1)

where \( G_F \) is the Fermi constant, \( G_F \approx 10^{-5} m_e^2 \), \( m_p \) is the proton mass, \( \gamma_5 \) is the Dirac matrix (pseudoscalar), \( n_N(\vec{r}) \) is the nuclear density, \( Q_W \) is the "weak charge of the nucleus",

\[
Q_W = Z(1 - 4 \sin^2 \theta_W) - N.
\]  

(2)

\( Z, N \) are the numbers of protons and neutrons in the nucleus, \( \theta_W \) is the Weinberg's angle (free parameter of SM). The HEP value for the \( \theta_W \) is defined as

\[
\sin^2 \theta_W = 0.2312
\]  

(3)

According to Eqs (2), (3) the atomic electron interacts mainly with the neutrons, so that the function \( n_N(\vec{r}) \) is defined mainly by the neutron distribution within the nucleus.

Apart from the interaction Eq (1), there is another nuclear spin-dependent type of the PNC interaction between the atomic electron and the atomic nucleus. This interaction is defined by another constant, so called anapole moment of the nucleus which characterizes the PNC effects inside the nucleus. These effects occur due to the PNC interaction between the nucleons [4]. In this paper we will concentrate on the first type of the PNC interactions defined by Eq (1).

Due to the existence of interaction Eq (1), in any atomic system a mixing of the states with opposite parity takes place. A standard example is the mixing of \( s \) and \( p \) states:

\[
\psi_s \rightarrow \psi_s + \frac{\langle p|\hat{H}_W|s\rangle}{\Delta E} \psi_p
\]  

(4)

Here \( \Delta E \) is the energy interval between the initial \( s \)-state and the \( p \)-state most close to this \( s \)-state; we assume for simplicity that there is only one such \( p \)-state.

From the mixing of states follows the mixing of the transition amplitudes: the standard example is the admixture of E1 transition amplitude to the initial M1 tran-
The order of magnitude of the PNC effects in neutral atoms follows from the estimate [4]

$$\langle |p|H_W|s\rangle^{\text{NA}} \approx G_F m_e^2 (\alpha Z)^2 Q_W \approx 10^{-6} Z^3 \text{ a.u.} \tag{8}$$

where $\alpha$ is the fine structure constant and $G_F m_e^2 \approx 10^{-11}$. From Eqs (7), (8) follow 3 ways of enhancement of the PNC effects in atomic system: I) large $Z$ value (heavy atoms); II) small $\Delta E$ values (lying levels closely of opposite parity); III) large $W^{M1}/W^{M1}$ ratio (i.e. forbidden initial magnetic transitions).

For the highly charged ions the estimate Eq (8) changes to

$$\langle |p|H_W|s\rangle^{\text{HCl}} \approx Z^2 <|p|H_W|s\rangle^{\text{NA}} \tag{9}$$

The maximum value of the "degree" of PNC achieved in neutral atoms (and, in particular, in the experiment [1]), is about $P \approx 10^{-4}$. The relation Eq (9) does not help to enhance this value in HCI, since the factor III nearly loses its importance in this case: the strongly forbidden transitions grow up very rapidly with the growth of $Z$. Contrary to this, the factor II, as we shall see below, becomes most important. The importance of this factor becomes clear when we consider the $Z$-dependence of the levels of the first excited configuration ($n = 1$, $n' = 2$, where $n$, $n'$ are the principal quantum numbers for two electrons) of He-like HCI. The picture of this dependence is given in Fig. 1, where the most accurate modern calculations [5] was used. The crossing (or near-crossing) of the levels with opposite parity occur close to $Z = 32$ (Ge), $Z = 64$ (Gd) and $Z = 92$ (U). Apart from this, the levels of the opposite parity $2^1 P_0$, $2^3 P_1$ and $2^5 S_0$ are very close to each other at $Z = 6$ (C). Though $Z$ values are integers, the accuracy of these crossings can be very high. For example, the splitting $E(2^3 P_0) - E(2^1 S_0) = 0.1081 \pm 0.0001$ eV for $Z = 64$ [5], where the inaccuracy arises due to the higher order interelectronic interaction and QED corrections, not included in the evaluation in [5]. This value should be compared to the energy interal $E(2^1 S_0) = 55866.01$ eV.

For the first time the proposal to use the crossings of the levels $2^1 S_0$ and $2^3 P_1$ for $Z$ values $Z = 6$ and close to $Z = 30$ for the PNC experiments was made in [6, 7]. The degree of the PNC was estimated as $P \approx 5 \times 10^{-14}$, where $f$ stands for the dimensionless constant, replacing the contribution of the anapole moment of the nucleus (since the total angular momenta of the admixed levels are different, only the anapole moment interaction contributes to the level mixing).

The near-degeneracy of the levels $2^3 P_0$ and $2^1 S_0$ at
$Z = 92$ (He-like uranium) was first discussed in connection with PNC effects in [8], then in [9]. In [8] the basic transition $2^3P_0 \rightarrow 1^3S_0$ was considered, which occurs as a one-photon E1M1 transition; in [9] the one-photon hyperfine-quenched $2^3S_0 \rightarrow 1^3S_0$ was chosen as a basic one. The levels $2^1S_0$ and $2^3P_0$ are mixed by the interaction Eq (1). The degree of PNC was calculated to be $P \approx 10^{-4}$ [9]. The same level mixing $2^3P_0$ and $2^1S_0$ with the basic transition $2^3S_0 \rightarrow 2^3S_1$ for $Z = 6$ was discussed in [10]. An original idea how to avoid detection of the circular polarization of X-ray photons in PNC experiment with HCI was outlined in [11]. Here it was proposed to observe the two-photon emission from the $2^3P_0$ level in He-like uranium, stimulated by the circularly polarized optical laser. The degree of the PNC effect was again $3 \cdot 10^{-4}$.

The PNC experiments with the polarized HCI beams were discussed in [12], where the crossing of $2^3S_0$ and $2^3P_0$ levels at $Z = 63,64$ ($Eu,Gd$) was under the consideration. The hyperfine quenched $2^3S_0 \rightarrow 1^3S_0$ one-photon transition was chosen as the basic one. The spacing between the $2^3S_0$, $2^3P_0$ levels is minimal for $Ge^{62+}$, but the $Eu^{61+}$ ion appeared to be most favorable candidate for the experiments. The reason was that the strong hyperfine-quenched one-photon transition $2^3P_0 \rightarrow 1^3S_0$ presents a huge background for the transition $2^3S_0 \rightarrow 1^3S_0$ since the existing detectors cannot resolve the transitions $2^3S_1 \rightarrow 1^3S_0$ and $2^3P_0 \rightarrow 1^3S_0$. However, a lifetime of $2^3P_0$ level in $Eu$, unlike the $Gd$, is smaller than the lifetime of $2^3S_0$ level. This happens because of the competition between the decay rates $W_P \equiv 2^3P_0 \rightarrow 1^3S_0 + \gamma_{E1}$ and $W_S \equiv 2^3S_0 \rightarrow 1^3S_0 + 2\gamma_{E1}$. For $Gd^{62+}$, $W_P < W_S$, but for $Eu^{61+}$, $W_P > W_S$. Thus in the beam experiment with $Eu^{61+}$ after some time delay the level $2^3P_0$ will be devastated and the background vanishes.

The possible solution of the problem of HCI (and, in particular, $Eu^{62+}$ and $Eu^{61+}$) beam polarization was proposed in [13] where the selective laser excitation scheme for the inhomogeneous population of the magnetic sublevels of hyperfine components of the electronic ground state for one-electron ions was discussed. However, the preserving of ion polarization in the magnetic system of the storage ring is not yet investigated.

There were also the proposals to use the H-like [14], B-like [15] and B-like [16] HCI for the PNC experiments. In these works the standard optical laser techniques is assumed to be used for the PNC experiments with HCI via the relativistic Doppler tuning.

Acknowledgments

This work was supported by the INTAS grant Nr 03-54-3604 and by RFBR grant Nr 03-02-17483. A.P. is also grateful to the non-profit foundation "Dynasty" (Moscow) for the support.

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