Parity nonconservation effect in the dielectronic recombination of polarized electrons with heavy He-like ions

V. A. Zaytsev\textsuperscript{1}, A. V. Maiorova\textsuperscript{1}, V. M. Shabaev\textsuperscript{1},
A. V. Volotka\textsuperscript{1,2}, S. Tashenov\textsuperscript{3}, G. Plunien\textsuperscript{2}, and Th. Stöhlker\textsuperscript{4,5,6}

\textsuperscript{1} Department of Physics, St. Petersburg State University,
Ulianovskaya 1, Petrodvorets, 198504 St. Petersburg, Russia
\textsuperscript{2} Institut für Theoretische Physik, Technische Universität Dresden,
Mommsenstraße 13, D-01062 Dresden, Germany
\textsuperscript{3} Physikalisches Institut, Universität Heidelberg, D-69120 Heidelberg, Germany
\textsuperscript{4} GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany
\textsuperscript{5} Helmholtz-Institut Jena, D-07743 Jena, Germany
\textsuperscript{6} Institut für Optik und Quantenelektronik,
Friedrich-Schiller-Universität Jena, D-07743 Jena, Germany

Abstract

We investigate the parity nonconservation (PNC) effect in the dielectronic recombination (DR) of a polarized electron with a heavy He-like ion into doubly-excited \( \left( \left( 1s^2 2p_{1/2} \right)_0 n\kappa \right)_{1/2} \) and \( \left( 1s^2 s \right)_0 n\kappa \) states of Li-like ion. We determine the nuclear charge number \( Z \) for which these opposite-parity levels are near to cross and, therefore, the PNC effect will be significantly enhanced. Calculations are performed for quantum numbers \( n \geq 4 \) and \( \kappa = \pm 1 \).

PACS numbers: 11.30.Er, 34.80.Lx
I. INTRODUCTION

Investigations of the parity nonconservation (PNC) effects in atoms play a very important role for tests of the electroweak sector of the Standard Model (SM) in the low-energy regime [1–3]. The unprecedented experimental precision for the PNC amplitude was obtained in $^{133}$Cs measurements [4, 5] and, together with recent progress in QED and atomic structure calculations (see, e.g., Refs. [6–8] and references therein), provided the most accurate to date test of the SM with atomic systems. From the theoretical side, further progress in studying the PNC effect with neutral atoms is strongly limited by the uncertainties of the electron-correlation contributions. In contrast to that, in heavy highly-charged ions the correlation effects, being suppressed by a factor $1/Z$, can be calculated by perturbation theory up to the required precision. This gives good prospects for studying the PNC effects with highly-charged ions.

PNC experiments with few-electron ions were first proposed by Gorshkov and Labzowsky in Ref. [9], where the fact that opposite-parity $2^1S_0$ and $2^3P_1$ states are near to cross for He-like ions with $Z \sim 6$ and $Z \sim 29$ was utilized. Since that work, a number of authors considered He-like ions as very promising systems for investigating the PNC effects [10–20]. This is due to the fact that the PNC effects in He-like ions can be significantly enhanced due to the near-degeneracy of some opposite-parity states. In a large number of proposals [10, 13, 15–20] the level crossing between the $2^3P_0$ and $2^1S_0$ states of He-like ions was exploited. One may expect that the addition of a highly-excited electron would not strongly change the energy difference between the corresponding levels in Li-like ions. Indeed, the opposite-parity $((1s2s)_0^0 n\kappa)_{1/2}$ and $((1s2p_{1/2})_0^0 n\kappa)_{1/2}$ states can be still made almost to cross by choosing the principal quantum number $n$ and the Dirac angular quantum number $\kappa = (-1)^{j+l+1/2}(j + 1/2)$. In this work we present such quasidegenerate levels of heavy Li-like ions and propose a scheme for observing the PNC effect in dielectronic recombination (DR) of free electrons with He-like ions into these double-excited states of Li-like ions.

In some previous proposals the dielectronic recombination was considered as a convenient probe process, which can be used to measure the parity violation effects. In Ref. [11], Pindzola studied the PNC effect on the Auger-electron emission from He-like uranium. The parity violation in dielectronic recombination of polarized electrons with H-like ions at $Z < 60$ was discussed by Gribakin et al. in Ref. [14]. In our previous work [19] we investigated the PNC effect on recombination of a polarized electron with unpolarized H-like thorium ($Z = 90$) and gadolinium ($Z = 64$) ions in the case of resonance with a doubly-excited state of the corresponding He-like ions. In the present work we investigate
the PNC effect in the process of the dielectronic recombination of polarized electrons with heavy He-like ions into the doubly-excited \(((1s2s)_{0}n\kappa)_{1/2}\) and \(((1s2p_{1/2})_{0}n\kappa)_{1/2}\) states of Li-like ions. The energy of the incident electron is considered to be tuned in resonance with one of these levels. The case of non-monoenergetic incident electron beam is also studied.

Throughout the paper relativistic units \((\hbar = c = 1)\) and Heaviside charge unit \((\alpha = e^{2}/(4\pi), e < 0)\) are used.

II. BASIC FORMALISM

We consider the process of the dielectronic recombination of an electron having asymptotic four-momentum \(p_{i} = (\varepsilon_{i}, p_{i})\) and polarization \(\mu_{i}\) with a heavy He-like ion, being originally in the ground \((1s)^{2}\) state. As a result of this non-radiative capture, one of the near-degenerate opposite-parity \(d_{1}\) or \(d_{2}\) states of the Li-like ion is formed. To simplify the derivation of formulas, we assume that these levels decay via the emission of a photon to some final state \(f\). We suppose that the incoming electron energy \(\varepsilon_{i}\) is chosen to get the resonance with one of the doubly-excited \(d_{1}\) or \(d_{2}\) states. The differential cross section of the process under consideration is defined as \([21,22]\)

\[
\frac{d\sigma_{\mu_{i}}}{d\Omega} = \frac{(2\pi)^{4}}{v_{i}} \omega^{2} \sum_{\epsilon_{f}} \sum_{M_{d_{1}}} \tau_{\gamma_{f},f,d_{1}} \frac{1}{E_{i} - E_{d_{1}} + i\Gamma_{d_{1}}/2} \langle \Psi_{d_{1}} | I | \Psi_{i} \rangle^{2}
\]

\[
+ \sum_{M_{d_{2}}} \tau_{\gamma_{f},f,d_{2}} \frac{1}{E_{i} - E_{d_{2}} + i\Gamma_{d_{2}}/2} \langle \Psi_{d_{2}} | I | \Psi_{i} \rangle^{2}
\]

where \(E_{d_{k}}, \Gamma_{d_{k}}, \) and \(M_{d_{k}}\) are the energy, the total width, and the momentum projection of the \(d_{k}\) state \((k = 1, 2)\), respectively. \(E_{i} = E_{(1s)^{2}} + \varepsilon_{i}\) is the total energy of the initial state of the system and \(v_{i}\) is the velocity of the incident electron. The outgoing photon \(\gamma_{f}\) is characterized by the energy \(\omega\) and the polarization \(\epsilon_{f}\). \(\tau_{\gamma_{f},f,d_{k}}\) is the amplitude of the radiative transition from the \(d_{k}\) state to the \(f\) state via the emission of a photon and \(I\) is the operator of the interelectronic interaction as defined in Ref. \([22]\).

As mentioned above, for heavy few-electron ions the interelectronic-interaction effects are suppressed by a factor \(1/Z\), compared to the interaction of the electrons with the Coulomb field of the nucleus. Therefore, we can generally consider the wave functions of our system in the independent-
electron approximation. With this approximation, the initial state wave function is given by

$$
\Psi_{p_i\mu_i,JM}(x_1, x_2, x_3) = A_N \sum_{\mathcal{P}} (-1)^{\mathcal{P}} \sum_{m_1m_2} C_{j_1m_1,j_2m_2}^{JM} \psi_{n_1\kappa_1m_1}(x_1) \psi_{n_2\kappa_2m_2}(x_2) \psi_{p_i\mu_i}(x_3),
$$

(2)

where \( \psi_{nkm}(x) \) is the one-electron bound-state Dirac wave function, \( \psi_{p_i\mu_i}(x) \) is the incident electron wave function, \( C_{j_1m_1,j_2m_2}^{JM} \) is the Clebsch-Gordan coefficient, \((-1)^{\mathcal{P}}\) is the parity of the permutation, \( \mathcal{P} \) is the permutation operator, and \( A_N \) is the normalization factor. From the theoretical viewpoint, it is convenient to formulate the electron capture in the ion rest frame. In this frame we can adopt that the quantization axis \((z\text{-axis})\) is directed along the incoming electron momentum \( p_i \). In this case the full expansion of the incoming electron wave function is given by (see, e.g., Refs. \([23, 24]\))

$$
\psi_{p_i\mu_i}(x) = \frac{1}{\sqrt{4\pi}} \frac{1}{\sqrt{p_i\varepsilon_i}} \sum_\kappa i^l \exp(i\Delta_\kappa) \sqrt{2l + 1} C_{i0,1/2\mu_i}^{ij\mu_i} \psi_{e_i\kappa\mu_i}(x),
$$

(3)

where \( \Delta_\kappa \) is the Coulomb phase shift, \( \psi_{e_i\kappa\mu_i}(x) \) is the partial electron wave with the Dirac quantum number \( \kappa = (-1)^{j+l+1/2}(j + 1/2) \), determined by the angular momentum \( j \) and the parity \( l \).

Neglecting the weak interaction, we can write the wave functions of the intermediate \( d \) and final \( f \) states as follows

$$
\Psi_{J,J'M'}(x_1, x_2, x_3) = A_N \sum_{\mathcal{P}} (-1)^{\mathcal{P}} \sum_{M'M_3m_3} \sum_{M_1m_1m_2} C_{j_1m_1,j_2m_2}^{JM} C_{j_1m_1,j_2m_2}^{JM'} \times \psi_{n_1\kappa_1m_1}(x_1) \psi_{n_2\kappa_2m_2}(x_2) \psi_{n_3\kappa_3m_3}(x_3).
$$

(4)

To account for the weak interaction, the intermediate \( d_1 \) and \( d_2 \) states should be considered with a small admixture of the closest-lying, opposite-parity \( d_2 \) and \( d_1 \) states, respectively. Then, the wave functions of the corresponding doubly-excited states modify as

$$
|\Psi_{d_1}\rangle \rightarrow |\Psi_{d_1}\rangle + i\xi |\Psi_{d_2}\rangle,
$$

(5)

$$
|\Psi_{d_2}\rangle \rightarrow |\Psi_{d_2}\rangle + i\xi |\Psi_{d_1}\rangle,
$$

(6)

where the admixing parameter \( i\xi = \langle \Psi_{d_2} | \sum_{i=1}^3 H_W(i) | \Psi_{d_1}\rangle / (E_{d_1} - E_{d_2}) \) is determined by the nuclear spin-independent effective Hamiltonian of weak interaction

$$
H_W = - \left( G_F / \sqrt{8} \right) Q_W \rho_N(r) \gamma_5.
$$

(7)

Here \( Q_W \approx -N + Z \left(1 - 4 \sin^2 \theta_W \right) \) denotes the weak charge of the nucleus, \( G_F \) is the Fermi constant, \( \gamma_5 \) is the Dirac matrix, and \( \rho_N \) is the nuclear weak-charge density (normalized to unity). After
substitution of the modified wave functions into Eq. (1) and summing over all decay channels, one finds

$$
\sigma_{\mu_i} = \frac{(2\pi)^3}{v_i} \sum_{M_{d1}, M_{d2}} \delta_{M_{d1}, M_{d2}} \left[ \frac{\Gamma_{d1}}{|E_i - E_{d1} + i\Gamma_{d1}/2|^2} |\langle \Psi_{d1} | I | \Psi_i \rangle|^2 + \frac{\Gamma_{d2}}{|E_i - E_{d2} + i\Gamma_{d2}/2|^2} |\langle \Psi_{d2} | I | \Psi_i \rangle|^2 
+ 2 \left( \frac{\Gamma_{d1}}{|E_i - E_{d1} + i\Gamma_{d1}/2|^2} - \frac{\Gamma_{d2}}{|E_i - E_{d2} + i\Gamma_{d2}/2|^2} \right) \Re \left( i\xi \langle \Psi_{d1} | I | \Psi_i \rangle \left( \langle \Psi_{d2} | I | \Psi_i \rangle \right)^* \right) 
+ 2 (\Gamma_{d2} - \Gamma_{d1}) \Re \left( i\xi \left( \langle \Psi_{d1} | I | \Psi_i \rangle \left( \langle \Psi_{d2} | I | \Psi_i \rangle \right)^* \right) \right) \right].
$$

(8)

In this expression the terms of order $\xi^2$ are neglected. The first and the second terms are parity conserving, while the third and the fourth terms correspond to the P-violating contributions to the cross section. The third term originates from the weak interaction in the dielectronic recombination process. The P-violation in the decay process is described by the fourth term. In the case of clearly resolved levels ($\Gamma_{d1}, \Gamma_{d2} \ll |E_{d1} - E_{d2}|$), one can consider only the resonant term in Eq. (1). For example, if the energy of the incident electron is tuned to the $d_1$ state, the total cross section takes a form

$$
\sigma_{\mu_i} = \frac{(2\pi)^3}{v_i} \frac{\Gamma_{d1}}{|E_i - E_{d1} + i\Gamma_{d1}/2|^2} \sum_{M_{d1}, M_{d2}} \delta_{M_{d1}, M_{d2}} \left[ |\langle \Psi_{d1} | I | \Psi_i \rangle|^2 + 2 \Re \left( i\xi \langle \Psi_{d1} | I | \Psi_i \rangle \left( \langle \Psi_{d2} | I | \Psi_i \rangle \right)^* \right) \right].
$$

(9)

In the case when the energy spread of the electron beam exceeds the energy spacing between the quasidegenerate states, one should integrate Eq. (8) over the incident electron energies. It can be performed analytically since the velocity $v_i$ and the DR amplitudes weakly change within the interval of the beam energy distribution. Thus, for the close lying states, one obtains

$$
\overline{\sigma}_{\mu_i} = \frac{(2\pi)^4}{v_i} \sum_{M_{d1}, M_{d2}} \delta_{M_{d1}, M_{d2}} \left[ |\langle \Psi_{d1} | I | \Psi_i \rangle|^2 + |\langle \Psi_{d2} | I | \Psi_i \rangle|^2 
+ 2 \xi (\Gamma_{d2} - \Gamma_{d1}) \Re \left( \frac{\langle \Psi_{d1} | I | \Psi_i \rangle \left( \langle \Psi_{d2} | I | \Psi_i \rangle \right)^* \right) \right].
$$

(10)

where $\overline{\sigma}_{\mu_i}$ is the integrated cross section. When the energy distribution in the beam exceeds the energy widths but is much less than the energy distance between the quasidegenerate levels, one should integrate Eq. (9). For instance, for a non-monoenergetic beam tuned to the $d_1$ state we obtain

$$
\overline{\sigma}_{\mu_i} = \frac{(2\pi)^4}{v_i} \sum_{M_{d1}, M_{d2}} \delta_{M_{d1}, M_{d2}} \left[ |\langle \Psi_{d1} | I | \Psi_i \rangle|^2 + 2 \Re \left( i\xi \langle \Psi_{d1} | I | \Psi_i \rangle \left( \langle \Psi_{d2} | I | \Psi_i \rangle \right)^* \right) \right].
$$

(11)

III. RESULTS AND DISCUSSION

As mentioned above, the enhancement of the PNC effect takes place for close-lying opposite-parity levels. In our previous work [25] we found that for Li-like ions the near degeneracy takes place for
for several doubly-excited opposite-parity \(((1s2s)_0 n\kappa)_{1/2}\) and \(((1s2p_{1/2})_0 n\kappa)_{1/2}\) states with \(4 \leq n \leq 7, \kappa = \pm 1, Z \sim 60, \text{and } Z \sim 92\). The energy difference has been evaluated as follows

\[
\Delta E = E_{((1s2p_{1/2})_0 n\kappa)_{1/2}} - E_{((1s2s)_0 n\kappa)_{1/2}} = \Delta E^{(\text{He})} + \Delta E^{(\text{Ext})},
\]

where \(\Delta E^{(\text{He})} = E_{(1s2p_{1/2})_0} - E_{(1s2s)_0}\) is the energy difference of the corresponding levels in He-like ion and \(\Delta E^{(\text{Ext})} = E_{(ns)} - E_{(ns)}\) is the difference of the one-photon exchange contributions, describing the interaction between the external \(n\kappa\) electron and the inner-shell electrons. The highly accurate values of \(\Delta E^{(\text{He})}\), including all second-order two-electron QED contributions, were taken from Ref. [26]. We also have taken into account the mixing of the close-lying \((1s2sn s)_{1/2}\) and \((1s2p_{1/2}np_{1/2})_{1/2}\) levels, as well as the \((1s2p_{1/2}ns)_{1/2}\) and \((1s2np_{1/2})_{1/2}\) levels (see Ref. [25] for details).

In the present work we consider the PNC effect in the process of the dielectronic recombination into \(d_1 = ((1s2p_{1/2})_0 n\kappa)_{1/2}\) and \(d_2 = ((1s2s)_0 n\kappa)_{1/2}\) states of Li-like ions. First, let us denote the cross sections for positive and negative helicities (spin projection onto the electron momentum direction) of the incident electron as \(\sigma_+\) and \(\sigma_-\), respectively. We also introduce designations for the cross section without the PNC effect, \(\sigma_0 = (\sigma_+ + \sigma_-)/2\), and the PNC contribution, \(\sigma_{\text{PNC}} = (\sigma_+ - \sigma_-)/2\). Deviation of \(\sigma_{\text{PNC}}\) from zero indicates the parity violation effect. Finally, one should determine the requirements on the luminosity \(L\), provided the PNC effect is measured to a relative accuracy \(\eta\) [14, 15]

\[
L > L_0 = \frac{\sigma_+ + \sigma_- + 2\sigma_b}{(\sigma_+ - \sigma_-)^2 \eta^2 T}.
\]

Here \(\sigma_b\) is the background magnitude and \(T\) is the acquisition time. In our calculations we neglect the background signal, set \(T = 2\) weeks, and \(\eta = 0.01\). In the case of non-monoenergetic incident electron beam the integrated cross sections \(\sigma_0 = (\sigma_+ + \sigma_-)/2\) and \(\sigma_{\text{PNC}} = (\sigma_+ - \sigma_-)/2\) should be used instead of \(\sigma_0\) and \(\sigma_{\text{PNC}}\). Here we denote the integrated cross sections for positive and negative helicities of the incident electron as \(\sigma_+\) and \(\sigma_-\), respectively.

In order to investigate either the levels mixed by the weak interaction are distinguished or not, we introduce the coefficient \(R = |E_{d_1} - E_{d_2}| / (\Gamma_{d_1} + \Gamma_{d_2})\). Evaluating the cross section according to Eqs. (5) and (9), it was found that the results became similar at \(R \geq 5\). Thus, levels with \(R \geq 5\) are regarded as distinguishable.

In Tables I and II we present numerical results for the most promising case of the resonance DR into the \(((1s2p_{1/2})_0 n\kappa)_{1/2}\) state at \(n, \kappa\) and \(Z\), which provide the minimum values of the luminosity \(L_0\).
Table I corresponds to the case of resolved opposite-parity states, whereas the case of unresolved states is presented in Table II. It is clearly seen from Table I, that the $R$ coefficient can be applied in order to distinguish cases of resolved and unresolved states. Indeed, at the border value ($R = 5$), $\sigma_0$ increases only by about 2% for the calculations utilizing Eq. (8) instead of Eq. (9). For other parameters $n, \kappa$ and $Z$ listed in Table I, the growth of the cross section amounts to 1% and less.

According to Tables I and II, the PNC effect seems to be most promising for the dielectronic recombination of a polarized electron with He-like uranium ($Z = 92$). When the energy of the incident electron is tuned in the resonance with the $\left[\left(\left(1s2p_{1/2}\right)_0\ n\kappa\right)_{1/2}\right]_0$ state, the ratio $\sigma_{\text{PNC}}/\sigma_0$ equals $-1.5 \times 10^{-5}$. After integration over $\varepsilon_i$ it turns into $\sigma_{\text{PNC}}/\sigma_0 = 2.5 \times 10^{-8}$. Let us compare the obtained results with similar calculations presented in Ref. [14]. In that work, the authors considered the process of the dielectronic recombination into the $(2s)^2$ and $(2s2p_{1/2})_0$ states for $Z = 48$, where the enhancement of the P-violating effect takes place due to the quasidegeneracy of these levels. The PNC asymmetry of the process considered in Ref. [14] amounted to $5 \times 10^{-9}$, while for the process considered in the present work it reaches $1.5 \times 10^{-5}$. The increase of the effect by more than three orders of magnitude is

\begin{table}[h]
\centering
\begin{tabular}{cccccccc}
\hline
$Z$ & $n\kappa$ & $\Delta E$ (eV) & $\varepsilon_i$ (keV) & $L_0$(cm$^{-2}$s$^{-1}$) & $\sigma_0$(barn) & $\Delta\sigma_0$(%) & $\sigma_{\text{PNC}}$(barn) \\
\hline
88 & 7$s$ & 3.17(29) & 19.3 & 84.76 & 1.1[30] & 3.8[2] & 0.1% & 1.2[-3] \\
90 & 5$s$ & 4.13(47) & 7.7 & 86.91 & 1.4[30] & 2.8[2] & 0.9% & 9.1[-4] \\
 & 6$s$ & 2.51(47) & 7.9 & 88.36 & 5.3[29] & 2.7[2] & 0.9% & 1.5[-3] \\
 & 7$s$ & 1.75(47) & 8.5 & 89.22 & 2.6[29] & 2.6[2] & 0.8% & 2.0[-3] \\
92 & 5$s$ & 2.97(28) & 5.0 & 91.43 & 5.1[29] & 2.5[2] & 2.1% & 1.4[-3] \\
 & 7$s$ & -1.60(28) & 7.2 & 93.86 & 1.5[29] & 2.2[2] & 1.1% & -2.4[-3] \\
\hline
\end{tabular}
\caption{Cross section of the dielectronic recombination of a polarized electron with He-like ion in the case of resolved levels ($R \geq 5$). The electron energy is tuned in resonance with the $\left(\left(1s2p_{1/2}\right)_0\ n\kappa\right)_{1/2}$ state. Parameters $n, \kappa$ and $Z$ correspond to the minimal value of luminosity $L_0$. $\Delta E = E_{\left(\left(1s2p_{1/2}\right)_0\ n\kappa\right)_{1/2}} - E_{\left((1s2s)_{0\kappa}\right)_{1/2}}$ is the energy difference and $R$ is the coefficient indicating either the states are resolved or not. $\sigma_0$ is the cross section without the PNC effect and $\sigma_{\text{PNC}}$ is the parity violating contribution. $\Delta\sigma_0$ indicates the increase of the process cross section related to the usage of Eq. (8) instead of Eq. (9). Notation: $y[x]$ represents $y \times 10^x$.}
\end{table}
TABLE II: Cross section of the dielectronic recombination of a polarized electron with He-like ion in the case of unresolved levels \((R < 5)\). The electron energy is tuned in resonance with the \(\left(\left(1s2p_{1/2}\right)_0 n\kappa\right)_{1/2}\) state. Parameters \(n, \kappa\) and \(Z\) correspond to the minimal value of luminosity \(L_0\). \(\Delta E = E_{\left(\left(1s2p_{1/2}\right)_0 n\kappa\right)_{1/2}} - E_{\left(\left(1s2s\right)_0 n\kappa\right)_{1/2}}\) is the energy difference and \(R\) is the coefficient indicating either the states are resolved or not. \(\sigma_0\) and \(\sigma\) are the cross sections corresponding to the monoenergetic and non-monoenergetic energy distribution of the incident electron beam, respectively. \(\sigma_0\) is the cross section without the PNC effect and \(\sigma_{\text{PNC}}\) is the parity violating contribution. Notation: \(y[x]\) represents \(y \times 10^x\). 

\[
\begin{array}{|c|c|c|c|c|c|c|}
\hline
Z & n\kappa & \Delta E(\text{eV}) & R & \epsilon_i(\text{keV}) & L_0(\text{cm}^{-2}\text{s}^{-1}) & \sigma_0(\text{barn}) & \sigma_{\text{PNC}}(\text{barn}) \\
\hline
62 & 7s & -0.103(64) & 2.0 & 39.56 & 3.6[29] & 1.4[3] & -4.0[-3] & 4.8[2] & 5.5[-5] \\
88 & 7p_{1/2} & -2.46(29) & 4.4 & 84.76 & 1.7[30] & 2.8[1] & -2.6[-4] & 9.6[2] & -7.0[-6] \\
90 & 6p_{1/2} & -1.26(47) & 1.1 & 88.37 & 1.0[30] & 9.6[1] & -6.2[-4] & 1.6[3] & -2.6[-5] \\
92 & 6s & -1.07(28) & 3.0 & 92.96 & 7.3[28] & 2.5[2] & -3.8[-3] & 6.8[2] & 1.7[-5] \\
6p_{1/2} & 2.38(27) & 2.0 & 92.96 & 1.3[30] & 4.3[1] & 3.6[-4] & 1.6[3] & -1.8[-5] \\
7p_{1/2} & 2.38(28) & 3.2 & 93.86 & 8.1[29] & 2.8[1] & 3.8[-4] & 1.0[3] & -4.0[-6] \\
\hline
\end{array}
\]

cause by the fact that the admixing parameter \(\xi\) for \(Z = 48\), obtained in Ref. [14], equals \(6.0 \times 10^{-9}\), whereas for Li-like uranium we get \(\xi = 4.0 \times 10^{-6}\).

In Fig. [1] \(\sigma_{\text{PNC}}\) is displayed as a function of the energy of the incident electron in the case of unresolved levels. As one can see from this figure, the PNC cross section is mainly formed by the parity violation effect in the dielectronic recombination process (third term in Eq. (8)). Nevertheless, the contribution from the subsequent radiative decay (forth term in Eq. (8)) slightly enhances \(\sigma_{\text{PNC}}\) for the energy of the incident electron tuned in resonance with \(d_2\) state. Vice versa, for the energy tuned in resonance with the \(d_1\) state a small decrease of the PNC contribution is observed. One can observe the energy of the incident electron at which \(\sigma_{\text{PNC}}\) turns to zero. It approximately corresponds to the energy just in between the quasidegenerate \(d_1\) and \(d_2\) states.

The experiment suggested in our paper involves a stored heavy ion beam intersecting with a beam of polarized electrons in an electron target or cooler. The polarized electrons can be produced with a semiconductor photocathode with circularly polarized laser light [27]. They are electrostatically
FIG. 1: PNC cross sections of the dielectronic recombination into the \( \left( \left( 1s^2p_{1/2} \right) \_0^7s \right)_{1/2} \) and \( \left( \left( 1s^27s \right)_{1/2} \right)_1 \) states of Li-like samarium \( (Z = 62) \). The difference \( E_i - E \left( \left( 1s^2p_{1/2} \right) \_0^7s \right)_{1/2} \) determines uniquely the energy of the incident electron. The Solid line corresponds to \( \sigma_{\text{PNC}} \), the dashed line is the parity-violating contribution from the dielectronic recombination, and the dotted line is the PNC contribution from the decay process multiplied by a factor of 10.

accelerated to the energies of tens of keV that are required for the experiment. The cooler with a photocathode was constructed for instance for the TSR storage ring at the MPI-K Heidelberg. Such coolers can in principle be made to produce polarized electrons and they are now under consideration for the FAIR facility and for the CRYRING at GSI / Darmstadt.

The high electron energy definition in the rest frame of the ion is required to achieve the DR resonance. The electron beam energy spread depends on the collision energy \( \varepsilon \) and the transverse \( kT_{\perp} \) and the longitudinal \( kT_{\parallel} \) temperatures of the electron beam: \( \Delta \varepsilon = \sqrt{(\ln 2kT_{\perp})^2 + 16 \ln 2 \varepsilon kT_{\parallel}} \) [28]. The
laser-produced beams of electrons are intrinsically cold and can be further cooled using an adiabatic beam expansion technique. Beams with a transverse temperature of 3.6 meV and a longitudinal temperature of 38 µeV were produced in electron cooler devices [29]. Accordingly, the energy spread of a few eV at 90 keV can be experimentally achieved at present. This means that the DR resonance structure will be integrated out. To take full advantage of the enhancement of PNC in dielectronic recombination the electron energy spread must be made smaller than 0.1 eV at 90 keV, which is nowadays not possible. Therefore further developments will be required to produce the electron beam that is cold enough. In addition, the ion beam momentum spread should be reduced below $10^{-6}$. This, however, was demonstrated at the storage ring ESR albeit with a significant reduction of the beam intensity [30].

IV. CONCLUSION

In the present work we have considered the PNC effect on the cross section of the dielectronic recombination into the $\left( (1s^2p_{1/2})_0 \, n\kappa \right)_{1/2}$ and $\left( (1s^2s)_0 \, n\kappa \right)_{1/2}$ states of heavy Li-like ions. The calculations have been performed for the parameters $n, \kappa$ and $Z$ which provide the enhancement of the P-violation effect due to quasidegeneracy of the corresponding levels. It has been found that at energies of incident electron tuned in resonance with the $\left( (1s^2p_{1/2})_0 \, n\kappa \right)_{1/2}$ state the PNC effect becomes most pronounced. The estimation of the PNC asymmetry for the most promising case of $\left( (1s^2p_{1/2})_0 \, 6s \right)_{1/2}$ and $\left( (1s^2s)_0 \, 6s \right)_{1/2}$ states for $Z = 92$ has given $-1.5 \times 10^{-5}$, which is by several orders of magnitude bigger than the result obtained for a similar process in Ref. [14].

V. ACKNOWLEDGEMENTS

Fruitful discussions with M. G. Kozlov are gratefully acknowledged. The work reported in this paper was supported by RFBR (Grants No. 12-02-31133 and 13-02-00630), by DFG, by GSI, by DAAD, and by the Ministry of Education and Science of Russian Federation (Program “Scientific and scientific-pedagogical personnel of innovative Russia”, Grant No. 8420). The work of VAZ was supported by the German-Russian Interdisciplinary Science Center (G-RISC) and by the FAIR Russia Research Center. AVM acknowledges financial support by the "Dynasty” foundation.

[1] I. B. Khriplovich, Parity Nonconservation in Atomic Phenomena (Gordon and Breach, London, 1991).
[2] I. B. Khriplovich, Phys. Scr. T112, 52 (2004).
[3] J. S. M. Ginges and V. V. Flambaum, Phys. Rep. 397, 63 (2004).
[4] C. S. Wood, S. C. Bennett, D. Cho, B. P. Masterson, J. L. Roberts, C. E. Tanner, and C. E. Wieman, Science 275, 1759 (1997).
[5] S. C. Bennett and C. E. Wieman, Phys. Rev. Lett. 82, 2484 (1999); Phys. Rev. Lett. 83, 889 (1999).
[6] V. M. Shabaev, K. Pachucki, I. I. Tupitsyn, and V. A. Yerokhin, Phys. Rev. Lett. 94, 213002 (2005); V. M. Shabaev, I. I. Tupitsyn, K. Pachucki, G. Plunien, and V. A. Yerokhin, Phys. Rev. A 72, 062105 (2005).
[7] S. G. Porsev, K. Beloy, and A. Derevianko, Phys. Rev. Lett. 102, 181601 (2009).
[8] V. A. Dzuba, J. C. Berengut, V. V. Flambaum, and B. Roberts, Phys. Rev. Lett. 109, 203003 (2012).
[9] V. G. Gorshkov and L. N. Labzowsky, Zh. Eksp. Teor. Fiz. Pis’m. JETP Lett., 19, 394 (1974); Zh. Eksp. Teor. Fiz., 69, 1141 (1975) [Sov. Phys. JETP, 42, 581 (1975)].
[10] A. Schäfer, G. Soff, P. Indelicato, B. Müller, and W. Greiner, Phys. Rev. A 40, 7362 (1989).
[11] M. S. Pindzola, Phys. Rev. A 47, 4856 (1993).
[12] R.W. Dunford, Phys. Rev. A 54, 3820 (1996).
[13] L. N. Labzowsky, A. V. Nefiodov, G. Plunien, G. Soff, R. Marrus, and D. Liesen, Phys. Rev. A 63, 054105 (2001).
[14] G. F. Gribakin, F. J. Currel, M. G. Kozlov, and A. I. Mikhailov, Phys. Rev. A 72, 032109 (2005); Phys. Rev. A 80, 049901(E) (2009); arXiv:physics/0504129 (2005).
[15] A. V. Maiorova, O. I. Pavlova, V. M. Shabaev, C. Kozhuharov, G. Plunien, and T. Stöhlker, J. Phys. B: At. Mol. Opt. Phys. 42, 205002 (2009).
[16] V. M. Shabaev, A. V. Volotka, C. Kozhuharov, G. Plunien, and T. Stöhlker, Phys. Rev. A 81, 052102 (2010).
[17] F. Ferro, A. Artemyev, T. Stöhlker, and A. Surzyukov, Phys. Rev. A 81, 062503 (2010).
[18] F. Ferro, A. Surzyukov, and T. Stöhlker, Phys. Rev. A 83, 052518 (2011).
[19] A. V. Maiorova, V. M. Shabaev, A. V. Volotka, V. A. Zaytsev, G. Plunien, and T. Stöhlker, J. Phys. B: At. Mol. Opt. Phys. 44, 225003 (2011).
[20] J. Gunst, A. Surzyukov, A. Artemyev, S. Fritzsche, S. Tashenov, A. Maiorova, V. M. Shabaev, and T. Stöhlker, Phys. Rev. A 87, 032714 (2013).
[21] V. M. Shabaev, Phys. Rev. A 50, 4521 (1994).
[22] V. M. Shabaev, Phys. Rep. 356, 119 (2002).
[23] M. E. Rose, *Elementary Theory of Angular Momentum* (Wiley, New York, 1957).

[24] J. Eichler and T. Stöhlker, Phys. Rep. 439, 1 (2007).

[25] V. A. Zaytsev, A. V. Maiorova, V. M. Shabaev, A. V. Volotka, and G. Plunien, Phys. Scr. T156, 014028 (2013).

[26] A. N. Artemyev, V. M. Shabaev, V. A. Yerokhin, G. Plunien, and G. Soff, Phys. Rev. A 71, 062104 (2005).

[27] D. T. Pierce, F. Meier, and P. Zürcher, App. Phys. Lett. 26, 670-672 (1975).

[28] A. Müller, Int. J. Mass Spectrom. 192, 9 (1999).

[29] M. Lestinsky, N. R. Badnell, D. Bernhardt, M. Grieser, J. Hoffmann, D. Lukić, A. Müller, D. A. Orlov, R. Repnow, D. W. Savin, E. W. Schmidt, M. Schnell, S. Schippers, A. Wolf, and D. Yu, Astr. J. 698, 648 (2009).

[30] M. Steck, K. Beckert, H. Eickhoff, B. Franzke, F. Nolden, H. Reich, B. Schlitt, and T. Winkler, Phys. Rev. Lett. 77, 3803 (1996).