The hyperfine quenching of polarized two-electron ions in an external magnetic field

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Abstract. The hyperfine quenching (HFQ) mechanism of metastable states in polarized He-like heavy ions is considered. The lifetime dependence of these states on the ion polarization in an external magnetic field is established. This dependence is presented for the $^2\!^3P_0$ state of the europium ($Z=63$) ion and is proposed as a method for the measurement of the ion polarization in the experiments for the search of parity violating effects.

1. Introduction

The hyperfine quenching (HFQ) in the isoelectronic sequence of He-like highly charged ions (HCI) was successfully used for the determination of the transition probabilities and the fine structure intervals in [1]-[5]. The hyperfine quenching mechanism consists of mixing of the metastable levels like $^2\!^1S_0$, $^2\!^3P_0$ etc with levels $^2\!^3S_1$, $^2\!^3P_1$ by the hyperfine interaction. Then the transitions from $^2\!^1S_0$, $^2\!^3P_0$ to the ground state become open. In [6] it was proposed to use the HFQ for observing the parity nonconservation (PNC) effect in He-like Eu. This effect consists of the mixing between $^2\!^1S_0$ and $^2\!^3P_0$ states by the PNC (weak) interaction. The choice of Eu ($Z=63$) is determined by the near-crossing of the metastable $^2\!^3P_0$ level with the opposite parity $^2\!^1S_0$ level and by the inequality $\Gamma(2^3P_0) > \Gamma(2^1S_0)$ where $\Gamma$ denotes the total width. The latter inequality allows to avoid a huge background effect in the proposed PNC experiment. The experiment assumes the employment of a polarized ion beam. The possible beam polarization method was described in [7]. In the present paper we discuss a method of measuring the beam polarization via the same HFQ mechanism in an external magnetic field. We will show that the HFQ probability in an external magnetic field depends on the beam polarization and this dependence can be measured by standard experimental HFQ techniques [1]-[5]. In the case of the $^2\!^1S_0$, $^2\!^3P_0$ states with zero total electron angular momentum the ion polarization exists as nuclear polarization. We should add that polarized ion beams can be used not only for PNC experiments but also for many other purposes, e.g. for testing the time-reversibility [8]. The values of the energies of the $^2\!^3P_0$, $^2\!^3S_1$ and $^2\!^1S_0$ states are taken from the most accurate recent calculations [9].
2. The HFQ width of the metastable level in an external magnetic field.

The decay rate for the HFQ transition $FIJ \rightarrow F'J' + \gamma$ with the admixture of the $FIJ''$ state is given

$$W_0^{HFQ}(FIJ \rightarrow F'J') = \frac{1}{\Delta E^2} \frac{1}{2F + 1} \sum_{M_F M'} \times$$

$$|\langle FM_F IJ | \hat{H}_{hf} | FM_F IJ'' \rangle |^{2}$$

Here $I,J$ are the nuclear and the total electron angular momenta of the ion, $FM_F$ is the total angular momentum and its projection. $|FM_F IJ\rangle$ is the wave function for the hyperfine structure level described by the quantum numbers $FM_F IJ$. In Eq.(1) the wave functions $|FM_F IJ\rangle$, $|F'M_F' IJ'\rangle$ correspond to the initial, final state and $|FM_F IJ''\rangle$ corresponds to the state, which is admixed to $|FM_F IJ\rangle$ by the hyperfine interaction. In case of the HFQ decay the $2^2P_0$ state, $|FM_F IJ\rangle = |FM_F 2^2P_0\rangle$, $|F'M_F' IJ'\rangle = |F'M_F' 2^1S_0\rangle$ and $|FM_F IJ''\rangle = |FM_F 2^3P_1\rangle$. The hyperfine magnetic-dipole interaction operator in Eq.(1) is denoted as $\hat{H}_{hf}$. The notation $V_{wjM}^{E(M)}$ is employed for the photon emission operator [10].

An expression for the $W_H^{HFQ}$ is given

$$W_H^{HFQ}(FIJ \rightarrow F'J') = \frac{1}{\Delta E^2} \frac{1}{2F + 1} \sum_{M_F M'} \times$$

$$2Re < FM_F IJ | \hat{H}_{hf} | FM_F IJ'' >^*< FM_F IJ | \mu \hat{H} | FM_F IJ'' >$$

$$|< FM_F IJ'' | V_{wjM}^{E(M)} | F'M_F' IJ' > |^2$$

where $\mu \hat{H}$ is the interaction of the magnetic moment of an ion with an external magnetic field.

3. The HFQ transition for the polarized ions in the presence of an external magnetic field

In case of the polarized ions, according to [7] we have

$$\sum_{M_F} n_{FM_F} M_F = F \lambda_F$$

(3)

where $n_{FM_F}$ are the occupation numbers for the Zeeman sublevels $FM_F$ and $\lambda_F$ is the ”degree of polarization” also introduced in [7].

In the quasiclassical description the degree of polarization is defined by

$$\lambda_F = \lambda(\xi \hat{h})$$

(4)

where $\lambda$ is the quasiclassical degree of polarization, $\xi$ is the unit quasiclassical polarization vector and $\hat{h} = \frac{\hat{H}}{|\hat{H}|}$.

Since the field-independent contribution $W_0^{HFQ}$ is polarization-independent we obtain the final expression for the polarized ions in the presence of an external magnetic field in the form

$$W_0^{HFQ} + W_H^{HFQ} = W_0^{HFQ}[1 + a_H(F, JJ'', I; n_1j_1l_1, n_2j_2l_2)\lambda(\xi \hat{h})]$$

(5)

where $a_H$ is some coefficient, depending on the hyperfine and Zeeman matrix elements. The indices $n_1j_1l_1$ and $n_2j_2l_2$ are the standard one-electron quantum numbers for the two-electron configuration (in our case $2^1S_0$).
4. The HFQ transition $^{2}1S_{0} \rightarrow ^{1}1S_{0}$ for the polarized ions in the presence of an external magnetic field

Evaluation of the constant $a$ for the case of $^{2}1S_{0} \rightarrow ^{1}1S_{0}$ transition in the magnetic field $H = 1T$ gives

$$a_{H} = 1.1 \times 10^{-4}$$

(6)

The smallness of this coefficient is connected with the smallness of the Zeeman matrix elements compared to the $hfs$ matrix element in HCI.

There are methods of the ion beam polarization measurement where the polarization effect is larger than in Eq.(6) [11], [12]. However, our proposal has some advantage since it can be performed within the same PNC experiment. The polarization can be observed from the difference between two signals with the opposite directions of the magnetic field

$$dW^{HFQ} = 2\lambda a_{H} W_{0}^{HFQ}$$

(7)

where $dW^{HFQ}$ is the signal difference. Another possibility is switching off the magnetic field. The signal then is

$$dW^{HFQ} = \lambda a_{H} W_{0}^{HFQ}$$

(8)

For $^{2}1S_{0} \rightarrow ^{1}1S_{0}$ transition the two-photon decay is dominant. However it does not change the value of the effect (Eq.(6)) but influences only the statistics of the experiment. We assume that this statistics is enough for the observation of the polarization effect.

5. Summary

We have proposed a method for measuring heavy ion beam polarization in the HFQ transitions in $He$-like HCI. The method consists of the observation of the asymmetry of the HFQ photon emission with respect to the external magnetic field. The same HFQ transitions were discussed earlier in the context of the possible observation of the PNC effects. The accuracy necessary for the measurement of the degree of polarization $\lambda$ does not exceed the accuracy achieved in the modern HFQ transition measurements.

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6. References

[1] Marrus R, Simionovici A, Indelicato P, Dietrich D D, Charles P, Briand J P, Finlayson K, Bosch F, Liesen D and Parente F 1989 Phys. Rev. Lett. 63 502
[2] Dunford R W, Liu C J, Last J, Berrah-Memsur N, Vondrasek R, Churah D A and Curtis L J 1991 Phys. Rev. A 44 764
[3] Indelicato P, Birkett B B, Briand J P, Charles P, Dietrich D D, Marrus R and Simionovici A 1992 Phys. Rev. Lett. 68 1307
[4] Birkett B B, Briand J P, Charles P, Dietrich D D, Finlayson K, Indelicato P, Liesen D, Marrus R and Simionovici A 1993 Phys. Rev. Lett. A 47 R2454
[5] Simionovici A, Birkett B B, Briand J P, Charles P, Dietrich D D, Finlayson K, Indelicato P, Liesen D and Marrus R 1993 Phys. Rev. A 48 1695
[6] Labzowsky L N, Nefiodov A V, Plunien G, Soff G, Marrus R and Liesen D 2001 Phys. Rev. A 63 054105
[7] Prozorov A, Labzowsky L, Liesen D and Bosch F 2003 Phys. Lett. B 574 180
[8] Khriplovich I B 1998 Phys. Lett. B 444 98; 2000 Hyperfine Interact. 127 365
[9] Artemyev A N, Shabaev V M, Yerokhin V A, Plunien G and Soff G 2005 Phys. Rev. A 71 062103
[10] Labzowsky L, Klimchitskaya G and Dmitriev Yu 1993 Relativistic Effects in the Spectra of Atomic System, IOP Publishing, Bristol and Philadelphia
[11] Surzhykov A, Fritzsche S, Stöhlker Th and Tashenov S 2005 Phys. Rev. Lett. 94 203202

[12] Tashenov S, Stöhlker Th, Banas D, Beckert K, Beller P, Beyer H F, Bosch F, Fritzsche S, Gumberidze A, Hagmann S, Kozhuharov C, Krinds T, Liesen D, Nolden F, Protic D, Sierpowski D, Spillmann U, Steck M and Surzhykov A 2006 Phys. Rev. Lett. 97 223202