Angle-resolved x-ray spectroscopic scheme to determine overlapping hyperfine splittings in highly charged helium-like ions

Z. W. Wu, A. V. Volotka, A. Surzhykov and S. Fritzsche

Introduction.—Hyperfine splitting of energy levels occurs primarily due to the interaction of bound electrons with the magnetic (dipole) field of nucleus. The strength of this nuclear magnetic field increases rapidly with the magnetic field of nucleus. The strength of the nuclear magnetization distribution is substantially reduced.

An angle-resolved x-ray spectroscopic scheme is presented for determining the hyperfine splitting of highly charged ions. For helium-like ions, in particular, we propose to measure either the angular distribution or polarization of the 1s2p 3P1, F → 1s2 1S0, Ff emission following the stimulated decay of the initial 1s2s 1S0, F level. It is found that both the angular and polarization characteristics of the emitted x-ray photons strongly depends on the (relative) splitting of the partially overlapping hyperfine 1s2p 3P1, F resonances and may thus help resolve their hyperfine structure. The proposed scheme is feasible with present-day photon detectors and allows a measurement of the hyperfine splitting of helium-like ions with a relative accuracy of about 10^{-4}.

PACS numbers: 32.10.Fn, 31.10.+z, 32.30.Rj, 32.70.-n

Z. W. Wu, A. V. Volotka, A. Surzhykov and S. Fritzsche

1Helmholtz-Institut Jena, D-07743 Jena, Germany
2Key Laboratory of Atomic and Molecular Physics & Functional Materials of Gansu Province, College of Physics and Electronic Engineering, Northwest Normal University, Lanzhou 730070, P.R. China
3Department of Physics, St. Petersburg State University, 198504 St. Petersburg, Russia
4Physikalisch-Technische Bundesanstalt, D-38116 Braunschweig, Germany
5Technische Universität Braunschweig, D-38106 Braunschweig, Germany
6Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena, D-07743 Jena, Germany

(Dated: March 26, 2018)

An angle-resolved x-ray spectroscopic scheme is presented for determining the hyperfine splitting of highly charged ions. For helium-like ions, in particular, we propose to measure either the angular distribution or polarization of the 1s2p 3P1, F → 1s2 1S0, Ff emission following the stimulated decay of the initial 1s2s 1S0, F level. It is found that both the angular and polarization characteristics of the emitted x-ray photons strongly depends on the (relative) splitting of the partially overlapping hyperfine 1s2p 3P1, F resonances and may thus help resolve their hyperfine structure. The proposed scheme is feasible with present-day photon detectors and allows a measurement of the hyperfine splitting of helium-like ions with a relative accuracy of about 10^{-4}.

PACS numbers: 32.10.Fn, 31.10.+z, 32.30.Rj, 32.70.-n

Introduction.—Hyperfine splitting of energy levels occurs primarily due to the interaction of bound electrons with the magnetic (dipole) field of nucleus. The strength of this nuclear magnetic field increases rapidly with the nuclear charge and reaches about 10^{9} T at the surface of 209Bi. For this reason, the study of the hyperfine splitting in highly charged ions has attracted much recent attention from both theory and experiment, and aims to probe bound-state QED at extreme electric and magnetic fields. In the past, various high-precision measurements on the hyperfine splitting in hydrogen-like ions were performed [1-4] and thus stimulated a good deal of theoretical developments, see review [5] and references therein. Due to recent advances in experiment, moreover, the accuracy of the (measured) hyperfine splitting in 209Bi^{82+} was improved by almost one order of magnitude and meanwhile reached the level of about 10^{-5} [6]. Until now, however, further theoretical progress has been restricted by the lack of knowledge of the natural magnetization distribution. In Ref. [7], it was therefore proposed to consider the specific difference of the hyperfine splitting in different electronic configurations, e.g., the difference between the ground-state hyperfine splitting in hydrogen- and lithium-like ions of the same isotope, for which the uncertainty due to the nuclear magnetization distribution is substantially reduced.

Besides ground-state hyperfine splitting in hydrogen-like ions, until now only a very few measurements have been made for lithium- and beryllium-like praseodymium ions [8] and lithium-like bismuth ions [9]. Recently, the LiBELLE collaboration presented a new high-precision measurement of the ground-state hyperfine splitting in 209Bi^{81+} ion [10]. The specific difference between the hyperfine splitting in hydrogen- and lithium-like bismuth ions, determined in this measurement, yields 7σ disagreement when compared with the corresponding theoretical values [11]. In order to resolve this discrepancy, additional measurements of the hyperfine splitting with different electronic configurations are highly desirable.

Helium-like ions are another alternative that may serve for the same purpose. Apart from the hyperfine quenching (cf. the review by Johnson [12]), however, to the best of our knowledge there are no experimental studies on the hyperfine structure of such ions. In contrast to hydrogen- and lithium-like ions, there is no hyperfine splitting in the 1s2 1S0, Ff ground level of helium-like ions. As for the excited levels 1s2p 3P1, F (and 1s2s 3S1, F^{'}) for which the natural linewidth is comparable in magnitude or even larger than the corresponding hyperfine splitting, they can therefore not be resolved by conventional fluorescence spectroscopy. For the 1s2p 3P1, F levels, for example, the natural linewidth goes rapidly from 0.10 eV for 71Ga^{29+} to 12.75 eV for 209Bi^{81+}, while the hyperfine splitting just increases from 0.11 eV to 5.35 eV. Moreover, the transition energies of the (partially) overlapping 1s2p 3P1, F levels to the ground state are quite large and thus less suitable for precision measurements.

In this contribution, we propose a novel scheme for resolving the hyperfine splitting in highly charged helium-like ions by measuring the angular distribution and angle-resolved polarization of the emitted fluorescence photons. As an example, we shall predict and analyze the angular distribution and angle-resolved polarization of the 1s2s 1S0, Ff + γ_2 photons emitted in the two-step radiative decay

\[ 1s2s \, ^1S_0, F_f + \gamma_2 \rightarrow 1s2p \, ^3P_1, F_f + \gamma_2 \quad (1) \]

of helium-like ions, from which we aim to determine the
FIG. 1: (Color online) Schema (left panel) and geometry (right panel) for measuring the two-step radiative decay (1) of helium-like $^{71}\text{Ga}^{29+}$ ions. While the first-step decay is stimulated by laser photons $\gamma_1$ with energy $h\omega_1$, the fast subsequent spontaneous decay to the $1s^21S_0, F_f$ ground level gives rise to an emission of the $\gamma_2$ fluorescence photons. As distinguished in black solid and gray dashed lines, the angular distribution and polarization of the $\gamma_2$ photons depend sensitively on the hyperfine constant of the intermediate levels.

hyperfine splitting of the intermediate $1s2p^3P_{1}, F$ levels. Fig. 1 displays the (involved) fine-structure levels of helium-like $^{71}\text{Ga}^{29+}$ ions and their hyperfine splittings (left panel). In this scheme, the ions first decay from the initial $1s2s^1S_0, F_i$ level to the intermediate $1s2p^3P_{1}, F$ levels under a stimulation by incident laser photons $\gamma_1$. Subsequently, fast spontaneous decay of the $1s2p^3P_{1}, F$ levels into the ground level $1s^21S_0, F_f$ occurs with an emission of the $\gamma_2$ photons. The angular distribution and polarization of the emitted $\gamma_2$ photons are then measured as functions of the photon energy $h\omega_1$. The obtained $\gamma_2$ angular distribution and polarization are expected to be sensitive to the $1s2p^3P_{1}, F$ hyperfine splittings due to their different populations following the first-step stimulated decay, as shown in the right panel of Fig. 1.

It is well known, both experimentally [13] and theoretically [14, 15], that the angular distribution and polarization of $K\alpha_1$ photons in helium-like ions are often affected by the hyperfine admixture of different fine-structure levels, which may alter the branching ratios between different hyperfine sublevels. In the proposed scheme, the hyperfine levels can be populated in a controlled manner by just tuning the photon energy $h\omega_1$ of the incident laser over the resonance of the first-step decay. By analyzing the angular distribution or linear polarization of the emitted $\gamma_2$ fluorescence photons, one can restore the created population. Below, we will demonstrate that the angular distribution and polarization of the $\gamma_2$ photons depend sensitively on the hyperfine splitting, as shown in the right panel of Fig. 1. The obtained results suggest that an angle- or polarization-resolved measurement of the $1s2p^3P_{1}, F \rightarrow 1s^21S_0, F_f$ emission line may provide an experimental determination on the splitting of the partially overlapping hyperfine levels with a relative accuracy of about $10^{-4}$.

Theoretical background.—To understand how the splitting of overlapping hyperfine levels affect the fluorescence emission of helium-like ions, let us start from a theoretical analysis of the photon angular distribution and linear polarization. Our theory is developed within the framework of density matrix and second-order perturbation theory. For the two-step decay process (1), if the geometry in Fig. 1 is adopted, the second-order transition amplitudes can be expressed in the form [14]

$$M_{M_{f}, M_{i}}^{\lambda_1, \lambda_2}(h\omega_1) = \sum_{FM} \sum_{p_1, L_1, M_{L_1}} \sum_{p_2, L_2, M_{L_2}} i^{-L_1 - L_2} (i\lambda_1)_{P_1} (i\lambda_2)_{P_2} \delta_{\lambda_1, M_{L_1}} D_{M_{L_1}M_{L_2}}^{L_1L_2} \langle \varphi, \theta, 0 | L_1, L_2 \rangle^{1/2} | F_i, F_f \rangle^{-1/2} (-1)^{F_i - F_f} \times \langle F_f M_f, L_2 M_{L_2} | FM \rangle \langle FM, L_1 M_{L_1} | F_i M_i \rangle \left\langle \sum_m \alpha_m a^{P_2}_{L_2} (r_m) \right\rangle \left\langle F_f \left| \sum_m \alpha_m a^{P_1}_{L_1} (r_m) \right| F_i \right\rangle \frac{E_{F_i} - E_F - h\omega_1 + i\Gamma_F/2}{E_{F_i} - E_F - h\omega_1 + i\Gamma_F/2}. \quad (2)$$

Here, $\delta_{\lambda_1, M_{L_1}}$ denotes a Kronecker delta function, $[a, b] \equiv (2a + 1)(2b + 1)$, and the standard notations for the Wigner $D$-functions and the Clebsch-Gordan coefficients have been employed. Moreover, the individual photons $\gamma_{1,2}$ are characterized in terms of their helicity $\lambda$ and multipolarities $pL$, with $p = 0$ for magnetic multipoles and $p = 1$ for electric ones. $E_F$ and $\Gamma_F$ represent, respectively, the energy and natural linewidth of the hyperfine level $|F\rangle \equiv |\alpha J I F\rangle$ with (total) angular momentum $F$, nuclear spin $I$, angular momentum $J$ of the electronic state, and all additional quantum numbers $\alpha$ that are needed for its unique specification. It should be noted that, we here neglect the linewidth $\Gamma_{F_i}$ of the initial level in the denominator as it is much smaller than the linewidth $\Gamma_F$ of the intermediate levels. The hyperfine transition amplitudes $\langle F'\left| \sum_m \alpha_m a^{P_2}_{L_2} (r_m) \right| F \rangle$ can be obtained from the corresponding fine-structure transition amplitudes by representing the $IJ$ coupled atomic basis states in their product basis. From the hyperfine transition amplitudes, we can easily determine the decay rate of excited hyperfine-resolved levels and their natural linewidths. The transition amplitudes of the $1s2s^1S_0 \rightarrow 1s2p^3P_{1}$ and $1s2p^3P_{1} \rightarrow 1s^21S_0$ are here evaluated within the framework of perturbation theory and by including the first-order interelectronic-interaction correction, see Ref. [17] for details. For the case of the transi-
The anisotropy and polarization sensitivity coefficients \( \frac{d\beta}{d\Omega} \) together with the transition energies (eV) of both the 1s2s^1S_0 \rightarrow 1s2p^3P_1 and 1s2p^3P_1 \rightarrow 1s^21S_0 lines taken from Ref. \[22\]. The anisotropy and polarization constants are estimated by employing the nuclear single-particle model \[22\]. The obtained hyperfine constants are in fair agreement with previously published values \[15, 20\].

Apart from the hyperfine transition amplitudes and natural linewidths \( \Gamma_F \), we still need to know the hyperfine structure energies in order to compute the second-order transition amplitudes \[22\]. Since the electric-quadrupole hyperfine interactions are negligibly small throughout the helium-like isoelectronic sequence when compared to the nuclear magnetic-dipole interaction, they will not be considered here. The magnetic-dipole hyperfine splitting of a fine-structure level \( \alpha J \) can be expressed as

\[
\Delta E_{\alpha JIF} = A_J [F(F+1) - I(I+1) - J(J+1)]/2
\]

in terms of the hyperfine constant \( A_J \). With this notation, \( E_F = E_{\alpha J} + \Delta E_{\alpha JIF} \), where \( E_{\alpha J} \) is the energy of the corresponding fine-structure level. As seen from Eq. (3), the hyperfine splitting can be easily obtained once the hyperfine constant is determined. The hyperfine constant of the 1s2p^3P_1 level is evaluated in the intermediate coupling scheme of mixing 1s2p^3P_1 and 1s2p^1P_1 levels as in Ref. \[21\], while the remaining interelectronic-interaction corrections are accounted for by a local screening potential. The effect of nuclear magnetization distribution is calculated by employing the nuclear single-particle model \[22\]. The obtained hyperfine constants are in fair agreement with the results from Ref. \[22\]. In addition, we also estimate the one-electron QED corrections — self energy and vacuum polarization — to the hyperfine constant \( A_J \). These corrections contribute, for instance, about 0.5% for \( ^{209}\text{Bi}^{81+} \) ions.

As a first attempt on this kind of studies, the incident stimulating laser is assumed to be unpolarized for simplicity. In this case, the density matrix of the emitted \( \gamma_2 \) photons can be expressed in terms of the second-order amplitudes \[22\] as follow,

\[
\rho_{\lambda_1\lambda_2}^{\gamma_2} = \langle k_2, \lambda_2; \rho^{\gamma_2} | k_2, \lambda_2 \rangle
\]

\[
= \frac{1}{2|F_1|} \sum_{M_1,M_2} \sum_{\lambda_1 = \pm 1} \mathcal{M}_{M_1,M_2}^{\lambda_1,\lambda_2}(\hbar\omega_1) \mathcal{M}_{M_1,M_2}^{\lambda_1,\lambda_2^*}(\hbar\omega_1) .
\]

Once we obtain the density matrix \[4\], the angular distribution and polarization of the \( \gamma_2 \) photons can be given in terms of its matrix elements. If, for instance, the polarization of the \( \gamma_2 \) photons remains unobserved, the \( \gamma_2 \) angular distribution follows simply from the trace of Eq. (4).

\[
\frac{d\sigma}{d\Omega} = \rho_{\lambda_1\lambda_2}^{\gamma_2} + \rho_{\lambda_2\lambda_1}^{\gamma_2} - \frac{\sigma_0}{4\pi}[1 + \beta P_2(\cos \theta)] .
\]

As the \( \gamma_1 \) photons are unpolarized, the angular distribution \[4\] is azimuthally symmetric and thus independent of the angle \( \varphi \). For this reason, it is parameterized by a single, so-called anisotropy parameter \( \beta \) within the E1 approximation, as shown in the second equality. Moreover, the linear polarization \( P_1 \) can be given as follows,

\[
P_1 = (\rho_{\lambda_1\lambda_2}^{\gamma_2} + \rho_{\lambda_2\lambda_1}^{\gamma_2})/(\rho_{\lambda_1\lambda_2}^{\gamma_2} + \rho_{\lambda_2\lambda_1}^{\gamma_2}) .
\]

We are now ready to study the angular distribution and linear polarization of the emitted \( \gamma_2 \) photons.

**Results and discussion.** — Table I lists the calculated hyperfine constant and linewidth of the 1s2p^3P_1 level, together with the transition energies of the 1s2s^1S_0 \rightarrow 1s2p^3P_1 and 1s2p^3P_1 \rightarrow 1s^21S_0 lines from Ref. \[22\] for helium-like \( ^{71}\text{Ga}^{29+}, ^{141}\text{Pr}^{57+} \) and \( ^{209}\text{Bi}^{81+} \) ions. These data are used for the evaluation of the second-order transition amplitudes and, further, to analyze the angular distribution and linear polarization of the emitted \( \gamma_2 \) photons. Fig. 2 displays the anisotropy parameter \( \beta \) and the linear polarization \( P_1 \) of the 1s2p^3P_1, \( F = 1/2, 3/2, 5/2 \) \( \rightarrow \) 1s^21S_0, \( F = 3/2 \) fluorescence photons of helium-like \( ^{71}\text{Ga}^{29+} \) ions as functions of the photon energy \( \hbar\omega_1 \). The linear polarization \( P_1 \) is presented for the \( \gamma_2 \) photons that are emitted perpendicular to the incident \( \gamma_1 \) photons, i.e., at \( \theta = 90^\circ \). The parameter \( P_1 = (I_{0\perp} - I_{90\perp})/(I_{0\perp} + I_{90\perp}) \) characterizes the intensities of the emitted \( \gamma_2 \) photons linearly polarized in parallel \( (I_{0\perp}) \) or perpendicular \( (I_{90\perp}) \) to the reaction plane defined by the propagation directions of the \( \gamma_1 \) and \( \gamma_2 \) photons. Results are shown for the calculated hyperfine constant \( A_J = 0.0274 \) eV and also for two assumed values, 0.8\( A_J \) and 1.2\( A_J \), which differ by just 20%.

As can be seen from the figure, both the \( \gamma_2 \) anisotropy and linear polarization appear to be rather sensitive with regard to the photon energy \( \hbar\omega_1 \) for any given hyperfine constant of the 1s2p^3P_1, F levels. Typically, the \( \gamma_2 \) photons have the smallest anisotropy and polarization near the resonance energy \( \hbar\omega_1 \approx 0.173 \) eV, but both become more and more anisotropic or (linearly) polarized when the photon energy \( \hbar\omega_1 \) is tuned away from the resonance.

### Table I: Table of isotopes with nuclear spin I and magnetic moment \( \mu_I \) in units of the nuclear magneton \( \mu_N \) considered in this work \[22\].

| Isotope     | Spin | Magnetic moment | Hyperfine constant | Linewidth | Transition energies |
|-------------|------|----------------|-------------------|-----------|-------------------|
|             | \( \lambda \) | \( \mu_I \) | \( A_J (2\ \text{eV}) \) | \( \Gamma_F (2\ \text{eV}) \) | \( \Delta \) |
| \( ^{141}\text{Pr}^{57+} \) | 5/2 | +4.2754 | 0.2530 | 2.9551 | 12.461 |
| \( ^{209}\text{Bi}^{81+} \) | 9/2 | +4.1103 | 0.5349 | 12.7539 | 63.961 | 76131.359 -0.291 -0.369 |

\( \gamma_2 \) lines from Ref. \[25\] for \( \gamma_1 \) lines from Ref. \[22\].
obtained strong angular and polarization dependence of sensitivity coefficients are also given in Table I. The γ dependence arises from the interplay of the lifetime and linewidths are comparable in magnitude. For both ions, the corresponding linear polarization still depend on the 1, 2, 3, 4, and high-...ions, moreover, the corresponding minimum intensities are also determined in a similar way to be 3, 4, and 5, respectively. For such low laser intensities, the resulting

This dependence arises from the finite linewidths of the overlapping resonances 1s2p 3P1, F = 1/2, 3/2, 5/2, which lead to a coherent population of them during the first-step stimulated decay and, ultimately, affects the angular and polarization behaviors of the emitted γ photons. Moreover, both the anisotropy parameter and linear polarization depend strongly on the hyperfine constant of the 1s2p 3P1 level, especially, if the γ photon energy is close to the resonance, say, hω1 ≃ 0.173 eV. The linear polarization P1, for instance, changes from −0.39 for A J = 0.0274 eV to −0.51 for 0.8 A J at this resonance energy. In order to further analyze this dependence quantitatively, two sensitivity coefficients dP1/ dA J and dP1/ dP1 are introduced. These coefficients reach their respective maximum at the resonance energy, which are listed in Table I. From these coefficients, it is quite easy to see how a change in the hyperfine constant A J will affect the γ anisotropy or polarization, i.e., if A J is modified by, say, 20%, β will change by 23.6% while P1 by 27.2%, as shown in Fig. 2.

Besides the low-Z 71Ga29+ ions, we also consider medium- and high-Z ions such as 141Pr57+ and 209Bi81+. For these ions, the corresponding γ anisotropy and linear polarization still depend on the 1s2p 3P1, F hyperfine splittings and also on the photon energy hω1, as shown in Fig. 3 although this dependence is slightly reduced when compared to the case of 71Ga29+. In practice, this dependence arises from the interplay of the lifetime and splitting of the hyperfine levels that contribute to the γ emission, and it becomes strongest when the splitting and linewidths are comparable in magnitude. For both 141Pr57+ and 209Bi81+ ions, moreover, the corresponding sensitivity coefficients are also given in Table II.

The obtained strong angular and polarization dependence of the emitted γ photons on the hyperfine constant is therefore expected to help determine the hyperfine splitting of highly charged helium-like ions.

**Experimental feasibility.**—The proposed scheme is feasible with present-day experimental facilities, such as, heavy-ion storage rings or electron-beam ion traps. The initial 1s2s 1S0 level can be populated quite selectively via K-shell ionization of lithium-like projectiles in relativistic collisions with gas target at the experimental storage ring. Alternatively, it can also be populated via the prompt 2s2p 1P1 → 1s2s 1S0 decay following the resonant electron capture of hydrogen-like ions into the 2s2p 1P1 resonance. Due to the high selectivity on the production of the 1s2s 1S0 level, as demonstrated in these experiments, the influence of neighboring levels on its subsequent decay can be ignored.

The 1s2s 1S0, F1 level of helium-like ions is known to decay primarily into the 1s2 1S0, F1 ground level via two-photon (2E1) emission. Since we wish to study the effect of the 1s2p 3P1, F hyperfine splitting upon the angular distribution and linear polarization of the emitted γ photons, cf. Fig. 1 our aim is to make the 1s2s 1S0, F1 → 1s2p 3P1, F transition strong enough to compete with the 2E1 decay and thus to populate the 1s2p 3P1, F levels. For this aim, this transition is supposed to be stimulated by the incident laser photons γ1 with suitable intensity and tunable energy hω1. For 71Ga29+ ions, for example, we obtain the required minimum laser intensity 3.2 × 105 W/cm2 by using Eq. (35) in Ref. 31. For both 141Pr57+ and 209Bi81+ ions, in addition, the corresponding minimum intensities are also determined in a similar way to be 3.0 × 105 W/cm2 and 3.6 × 1011 W/cm2, respectively.

![Fig. 2](image_url) Anisotropy parameter β (left panel) and degree of linear polarization P1 (right panel) of the hyperfine 1s2p 3P1, F = 1/2, 3/2, 5/2 → 1s2 1S0, F1 = 3/2 fluorescence emission from helium-like 71Ga29+ ions as functions of photon energy hω1 of the incident photons γ1. Results are shown for the calculated hyperfine constant A J = 0.0274 eV (black solid lines) as listed in Table I as well as for two assumed values, 0.8 A J (red dash-dotted lines) and 1.2 A J (blue dash-dot-dotted lines), which differ by just 20%.

![Fig. 3](image_url) The same as in Fig. 2 but for 141Pr57+ (left panel) and 209Bi81+ (right panel).
Stark effect on the energy levels of ions is negligibly small and hence can be ignored. These intensities are easily accessible with present-day laser sources from near-infrared to extreme-ultraviolet photon energy regions. Since the linewidth of laser radiations in this energy range is much smaller than the natural linewidth of the levels involved, the incident stimulating laser photons $\gamma$ can be treated to be monochromatic.

Finally, let us discuss the measurement of the angular distribution and linear polarization of the emitted $\gamma_2$ fluorescence photons. The angular distribution can be accurately measured by an array of highly efficient solid-state Ge(i) detectors placed at different angles, while the polarization can be determined by means of two-dimensional position-sensitive x-ray detectors and Compton scattering technique. Moreover, due to recent progress in the channel-cut silicon crystal polarimetry technique the polarization purity of x-ray photons have been measured with an unprecedented level of accuracy, $\sim 10^{-10}$. Since the required emission flux of the $\gamma_2$ photons for achieving such a high accuracy is mainly restricted by the amount of the production of helium-like ions, we may thus expect an experimental uncertainty of about $10^{-4}$ in measuring the anisotropy parameter $\beta$ and the polarization $P_1$. This uncertainty allows to determine the hyperfine constant on a level of accuracy $7 \times 10^{-5}$ for $^{71}$Ga$^{29+}$ and of $3 \times 10^{-4}$ for $^{208}$Bi$^{81+}$, which would be well below the level of the contributing QED effects.

In summary, the angular distribution and linear polarization of x-ray photons emitted in a two-step radiative decay of highly charged helium-like ions have been studied with the aim to pursue a scheme for determining their hyperfine splitting. For the particular process $\Pi$, it is found that the angular and polarization behaviors of the $\gamma_2$ photons depend strongly on the hyperfine splitting of the 1$S2p^3P_1$, $F$ levels. This dependence will allow a determination on the hyperfine splitting of helium-like ions with an accuracy of about $10^{-4}$, together with the hyperfine structures of hydrogen- and lithium-like ions which could serve as a probe of QED in strong electromagnetic field generated by heavy nucleons.

We are grateful to S. Trotsenko and B. Marx for very helpful discussions on the production of highly charged ion beam and high-precision x-ray polarization measurement, respectively. This work has been supported by the BMBF (Grant No. 05P15SJFAA) and the NSFC (Grant Nos. 11464042 and U1332206).

[1] I. Klaft et al., Phys. Rev. Lett. 73, 2425 (1994).
[2] J. R. Crespo López-Urrutia et al., Phys. Rev. Lett. 77, 826 (1996); Phys. Rev. A 57, 879 (1998).
[3] P. Seelig et al., Phys. Rev. Lett. 81, 4824 (1998).
[4] P. Beiersdorfer et al., Phys. Rev. A 64, 032506 (2001).
[5] A. V. Volotka et al., Ann. Phys. (Berlin) 525, 636 (2013).
[6] J. Ullmann et al., J. Phys. B 48, 144022 (2015).
[7] V. M. Shabaev et al., Phys. Rev. Lett. 86, 3959 (2001).
[8] P. Beiersdorfer, E. Träbert, G. V. Brown, J. Clementson, D. B. Thorn, M. H. Chen, K. T. Cheng, and J. Sapirstein, Phys. Rev. Lett. 112, 233003 (2014).
[9] M. Lochmann et al., Phys. Rev. A 90, 030501(R) (2014).
[10] J. Ullmann et al., Nat. Commun. 8, 15484 (2017).
[11] A. V. Volotka et al., Phys. Rev. Lett. 108, 073001 (2012).
[12] W. R. Johnson, Can. J. Phys. 89, 429 (2011).
[13] J. R. Henderson et al., Phys. Rev. Lett. 65, 705 (1990).
[14] Z. W. Wu, A. Surzhykov, and S. Fritzsche, Phys. Rev. A 89, 022513 (2014).
[15] A. Surzhykov, Y. Litvinov, Th. Stöhlker, and S. Fritzsche, Phys. Rev. A 87, 052507 (2013).
[16] Z. W. Wu, A. V. Volotka, A. Surzhykov, C. Z. Dong, and S. Fritzsche, Phys. Rev. A 93, 063413 (2016).
[17] P. Indelicato, V. M. Shabaev, and A. V. Volotka, Phys. Rev. A 69, 062506 (2004).
[18] G. W. F. Drake, Phys. Rev. A 19, 1387 (1979).
[19] W. R. Johnson, D. R. Plante, and J. Sapirstein, Adv. At., Mol., Opt. Phys. 35, 255 (1995).
[20] V. Yu. Andreev, L. N. Labzowsky, and G. Plunien, Phys. Rev. A 79, 032515 (2009).
[21] A. V. Volotka, V. M. Shabaev, G. Plunien, G. Soff, and V. A. Yerokhin, Can. J. Phys. 80, 1263 (2002).
[22] V. M. Shabaev, M. Tomaselli, T. Kühl, A. N. Artemyev, and V. A. Yerokhin, Phys. Rev. A 56, 252 (1997).
[23] W. R. Johnson, K. T. Cheng, and D. R. Plante, Phys. Rev. A 55, 2728 (1997).
[24] N. J. Stone, At. Data Nucl. Data Tables 75, 75 (2005).
[25] A. N. Artemyev, V. M. Shabaev, V. A. Yerokhin, G. Plunien, and G. Soff, Phys. Rev. A 71, 062104 (2005).
[26] S. Fritzsche, P. Indelicato, and Th. Stöhlker, J. Phys. B 38, S707 (2005).
[27] J. Rzadkiewicz et al., Phys. Rev. A 74, 012511 (2006).
[28] S. Trotsenko et al., Phys. Rev. Lett. 104, 033001 (2010).
[29] P. H. Mokler et al., Phys. Rev. Lett. 65, 3108 (1990).
[30] A. V. Volotka, A. Surzhykov, V. M. Shabaev, and G. Plunien, Phys. Rev. A 83, 062508 (2011).
[31] F. Ferro, A. Surzhykov, and Th. Stöhlker, Phys. Rev. A 83, 052518 (2011).
[32] S. Tashenov et al., Phys. Rev. Lett. 97, 223202 (2006); 107, 173201 (2011).
[33] G. Weber et al., Phys. Rev. Lett. 105, 243002 (2010).
[34] B. Marx et al., Phys. Rev. Lett. 110, 254801 (2013).