01 Nov 2006

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Recommended Citation

A. S. Surzhykov et al., "K α_1 Radiation from Heavy, Heliumlike Ions Produced in Relativistic Collisions," *Physical Review A - Atomic, Molecular, and Optical Physics*, vol. 74, no. 5, pp. 052710-1-052710-5, American Physical Society (APS), Nov 2006.
The definitive version is available at https://doi.org/10.1103/PhysRevA.74.052710

$K\alpha_1$ radiation from heavy, heliumlike ions produced in relativistic collisions

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(Received 10 April 2006; revised manuscript received 25 September 2006; published 15 November 2006)

Bound-state transitions in few-electron, heavy ions following radiative electron capture are studied within the framework of the density matrix theory and the multiconfiguration Dirac-Fock approach. Special attention is paid to the $K\alpha_1$ $(1s_{1/2}2p_{3/2}\ ^{1,3}P_{J=1,2} \to 1s_{1/2}^2\ ^1S_{J=0})$ radiative decay of heliumlike uranium U^{90+} projectiles. This decay has recently been observed at the GSI facility in Darmstadt, giving rise to a surprisingly *isotropic* angular distribution, which is inconsistent with previous experiments and calculations based on a "one-particle" model. We show that the unexpected isotropy essentially results from the mutual cancellation of the angular distributions of the $^1P_1 \to {}^1S_0$ electric dipole and $^3P_2 \to {}^1S_0$ magnetic quadrupole transitions, both of which contribute to the $K\alpha_1$ radiation. Detailed computations on the anisotropy of the $K\alpha_1$ radiation have been carried out for a wide range of projectile energies and are compared to available experimental data.

DOI: 10.1103/PhysRevA.74.052710 PACS number(s): 34.70.+e, 31.30.Jv

I. INTRODUCTION

During the last two decades, collisions of highly charged, heavy ions with atoms and free electrons have been studied intensively both at ion storage rings [1–3] and at electron beam ion traps [4,5]. In these collision studies, special interest has been devoted to the production of excited ionic states and on the measurement of their subsequent radiative decay. Indeed, the analysis of the bound-state transitions in high-Z ions plays a key role in our understanding of electron-electron and electron-photon interactions in the presence of strong fields, including important information about the relativistic and quantum electrodynamic effects in few-electron systems [1,3,6–9]. In addition to accurate studies of transition energies and probabilities for highly charged ions, measurements of the angular distributions of characteristic x-ray photons provide an important route to learn more about the structure and dynamics of high-Z ions.

A great advantage of angle-resolved x-ray studies is that they are often much more sensitive to the magnetic and retardation effects than the analysis of the total (i.e., integrated over the angles) rates. Within the last years, a new generation of experiments has been performed at the GSI storage ring to explore the angular distributions of the characteristic photon emission from heavy, few-electron ions [1,10–13]. In these experiments, the excited ionic states are produced by means of radiative capture of a free (or quasifree) electron by heavy projectiles. Examples include the radiative electron capture (REC) into the $2p_{3/2}$ state of (initially) bare and $1s_{1/2}2p_{3/2}\ ^{1,3}P_{J=1,2}$ states of (initially) hydrogenlike uranium ions as well as their subsequent Lyman-α_1 $(2p_{3/2} \to 1s_{1/2})$ and $K\alpha_1$ $(^{1,3}P_{1,2} \to {}^1S_0)$ radiative decays. A rather surprising result of these studies is an *even qualitatively* different angular behavior of the x-ray emission from the (finally) hydrogenlike as opposed to heliumlike ions: while the Lyman-α_1 radiation exhibited a strong angular dependence, the $K\alpha_1$ decay gave rise to almost an isotropic emission pattern [11,12]. In order to understand the unexpected discrepancy between the emission patterns of the Lyman-α_1 and $K\alpha_1$ radiation, a more detailed theoretical analysis is required: it includes a careful treatment of the two-step capture-and-decay process using the density matrix formalism to describe the the formation of the excited states, and it also includes the electronic correlations; the latter select the "fast" fine-structure subcomponents of the $K\alpha_1$ transitions in conjunction with the radiation field.

Within the density matrix approach, described in previous papers [14,15], the angular distribution of the characteristic radiation is entirely governed by a set of so-called anisotropy parameters which reflect the population transfer mechanism for the excited ionic states as well as the electronic structure of the ion. Below, we first derive the expressions for the anisotropy parameters of the Lyman-α_1 decay in hydrogenlike and $K\alpha_1$ decay in heliumlike ions. These expressions, which take into account both the many-electron effects and higher-order multipoles of the radiation field, are then used to calculate the photon emission from the hydrogenlike U^{91+} and heliumlike U^{90+} uranium projectiles for a wide range of collision energies. The isotropic $K\alpha_1$ $(1s_{1/2}2p_{3/2}\ ^{1,3}P_{1,2} \to 1s_{1/2}^2\ ^1S_0)$ radiation is found to arises essentially due to a mutual compensation of the two strongly anisotropic $^1P_1 \to {}^1S_0$ electric dipole $(E1)$ and $^3P_2 \to {}^1S_0$ magnetic quadrupole $(M2)$ transitions. These transitions, up to now, have not been resolved experimentally. As a consequence, the individual contributions of the two unresolved j sublevels to the observed $K\alpha_1$ radiation may vary as a function of the observation angle and lead to the unexpected isotropic pattern, which is in sharp contrast to the Lyman-α_1 case [16].

II. THEORETICAL BACKGROUND

In the theoretical investigations of x-ray emission from heavy, few-electron ions, the formation of the excited states and their subsequent decay can be treated independently as these states represent well isolated resonances with a natural widths much smaller than the energy splitting between the levels of the same symmetry (see, e.g., Refs. [3,17–19]). In the first step, therefore, an excited level of the projectiles can be formed either by electron capture, collisional excitation or inner-shell ionization processes. Since in ion-atom collisions at storage rings the ion momentum determines the only preferred direction of the overall system, the resulting ion may appear to be *aligned* along this direction. The unequal population of the ionic sublevels with the different modulus of magnetic quantum number $|M_J|$ (the alignment), is usually described in terms of the so-called alignment parameters $\mathcal{A}_k(J) \equiv \mathcal{A}_{k0}(T_p, Z; J)$. Within the density matrix approach [14,17,20,21], the alignment parameters can be directly related to the (partial) cross sections $\sigma_{|JM\rangle}$ for the population of the different ionic sublevels $|\alpha JM\rangle$. For example, the alignment of the $1s_{1/2}2p_{3/2}\ ^{1,3}P_J$ levels of the heliumlike ion is characterized by a second-rank parameter both for $J=1$

$$\mathcal{A}_2(J=1) = \sqrt{2}\frac{\sigma_{|1,\pm1\rangle} - \sigma_{|1,0\rangle}}{\sigma_{|1,0\rangle} + 2\sigma_{|1,\pm1\rangle}} \tag{1}$$

and for $J=2$

$$\mathcal{A}_2(J=2) = -\sqrt{\frac{10}{7}}\frac{\sigma_{|2,0\rangle} + \sigma_{|2,\pm1\rangle} - 2\sigma_{|2,\pm2\rangle}}{\sigma_{|2,0\rangle} + 2\sigma_{|2,\pm1\rangle} + 2\sigma_{|2,\pm2\rangle}}. \tag{2}$$

Apart from the parameter $\mathcal{A}_2(J=2)$, the alignment of the $^3P_2$ level is also described by the fourth-rank parameter $\mathcal{A}_4(J=2)$. For REC into fast, high-Z projectiles, however, theoretical calculations [15] show that the parameter $\mathcal{A}_4(J=2)$ is very small and, hence, can be neglected in the following analysis of the angular distribution of the characteristic $K\alpha_1$ radiation.

The alignment parameters $\mathcal{A}_k(J)$ describe the magnetic sublevel population of the excited projectile ions following the capture of an electron in ion-atom collision. The subsequent decay of these ions may lead to the emission of one (or several) photons, until the ground state is reached. Of course, the angular as well as the polarization properties of this characteristic radiation are closely related to the alignment parameters $\mathcal{A}_k(J)$. For instance, the angular distribution of the Lyman-α_1 decay in hydrogenlike ions is given in the projectile frame (i.e., in the rest frame of the ion) by [20,22]

$$W_{\mathrm{Ly}\alpha_1}(\theta) \sim 1 + \beta_2^{\mathrm{eff}} P_2(\cos\theta), \tag{3}$$

where θ is the angle between the directions of the decay photon and the ion beam, while the β_2^{eff} denotes the "effective" anisotropy parameter [15,16]

$$\beta_2^{\mathrm{eff}}(2p_{3/2} \to 1s_{1/2}) = \alpha\mathcal{A}_2(J=3/2) f(E1, M2). \tag{4}$$

Apart from the alignment $\mathcal{A}_2$ and a factor $\alpha=1/2$, this anisotropy parameter also depends on the structure function $f(E1, M2)$ which describes the multipole mixing between the electric dipole and magnetic quadrupole transitions [15]. For the hydrogenlike uranium ion, this multipole mixing leads to a 30% enhancement of the anisotropy of the Lyman-α_1 radiation.

Equations (3) and (4) describe the angular distribution of the Lyman-α_1 decay in hydrogenlike ions. For the nonzero alignment $\mathcal{A}_2(J=3/2)$ of the excited $2p_{3/2}$ state this angular distribution appears to be strongly anisotropic [12,15]. A similar anisotropic behavior can be expected for both, the $^1P_1 \to {}^1S_0$ electric dipole ($E1$) and $^3P_2 \to {}^1S_0$ magnetic quadrupole ($M2$), radiative transitions in the heliumlike ions whose emission patterns again follow Eq. (3) but with the anisotropy parameters

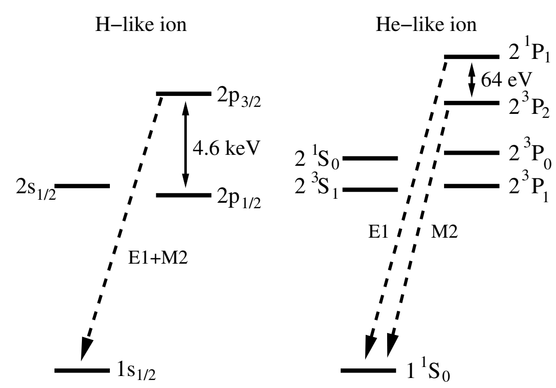

FIG. 1. Lyman-α_1 ($2p_{3/2} \to 1s_{1/2}$) and $K\alpha_1$ ($^{1,3}P_{1,2} \to 1\ ^1S_0$) decay in the hydrogen- and helium-like uranium ions.

$$\beta_2(^1P_1 \to {}^1S_0) = \frac{1}{\sqrt{2}}\mathcal{A}_2(J=1) \tag{5}$$

and

$$\beta_2(^3P_2 \to {}^1S_0) = -\sqrt{\frac{5}{14}}\mathcal{A}_2(J=2), \tag{6}$$

respectively [15]. In contrast to the Lyman-α_1 decay, however, these anisotropy parameters do not depend on the (ratios of the) bound-bound transition amplitudes since no multipole mixing can occur for the cases of the $^1P_1 \to {}^1S_0$ and $^3P_2 \to {}^1S_0$ decay paths (see Fig. 1).

If the fine-structure components of the $K\alpha_1$ radiation were resolved experimentally, their anisotropic behavior (5) and (6) could be studied and could provide information on the (individual) anisotropy parameters β_2. However, since the splitting between the $^1P_1$ and $^3P_2$ levels is below the energy resolution of available x-ray detectors, only an incoherent superposition of the $^1P_1 \to {}^1S_0$ and the $^3P_2 \to {}^1S_0$ radiation has been observed in the current experiments. Therefore, the angular distribution of the overall $K\alpha_1$ radiation is completely determined by the angular distributions of the electric dipole $^1P_1 \to {}^1S_0$ *and* magnetic quadrupole $^3P_2 \to {}^1S_0$ transitions, taken with nonstatistical weights as determined by the excitation (formation) mechanism of the two excited $P_{1,2}$ levels

$$W_{K\alpha_1}(\theta) = N_{J=1}W_{E1}(\theta) + N_{J=2}W_{M2}(\theta) \sim 1 + \beta_2^{\mathrm{eff}}(^{1,3}P_{J=1,2} \to {}^1S_0)P_2(\cos\theta). \tag{7}$$

That is, the angular dependence of the $K\alpha_1$ radiation of heliumlike ions follows the typical $\sim 1 + \beta\, P_2(\cos\theta)$ shape, but with an overall anisotropy parameter

$$\beta_2^{\rm eff}(^{1,3}P_{1,2} \to {}^1S_0) = N_{J=1}\mathcal{A}_2(J=1)\frac{1}{\sqrt{2}} - N_{J=2}\mathcal{A}_2(J=2)\sqrt{\frac{5}{14}} \quad (8)$$

which depends on both, the alignment parameters $\mathcal{A}_2(J=1)$ and $\mathcal{A}_2(J=2)$ of the $^1P_1$ and $^3P_2$ states and the weight factors $N_{J=1}$ and $N_{J=2}$, respectively. These weights describe the contribution of the individual $^1P_1 \to {}^1S_0$ and $^3P_2 \to {}^1S_0$ transitions to the overall $K\alpha_1$ and are given by the (relative) population of the $^{1,3}P_{1,2}$ levels.

III. RESULTS

As seen from Eqs. (7) and (8), any analysis of the angular distribution of the $K\alpha_1$ radiation can be traced back to computations of the alignment as well as the relative populations of the $^{1,3}P_{1,2}$ excited ionic states. For REC by high-Z ions, however, the alignment parameters $\mathcal{A}_2(J=1,2)$ and the weights $N_{J=1,2}$ are determined not only by the direct electron capture into the particular states but also by the cascade feeding from the high-lying levels. In the present work, calculations for both of these (population) mechanisms were performed by using the multiconfiguration Dirac-Fock (MCDF) approach [14,15] for the bound ionic states and by adopting the impulse approximation for the electron capture process. Within such an approximation, which is appropriate for the relativistic collisions of heavy, high-Z ions with low-Z atoms [23], a loosely bound target electron can be considered as (quasi)free. The sublevel capture rates and, hence, the alignment parameters are evaluated first for the radiative recombination (RR) of a free electron with well defined asymptotic momentum **p** and subsequently convoluted with the momentum distribution of the electrons in the target atom [1,23,24]. In addition to the MCDF and impulse approximations, moreover, it is assumed that no further ion-atom collisions can alter the magnetic sublevel population subsequent to the REC. This assumption is well justified for current experiments at the storage ring in Darmstadt which are carried out in the single-collision regime [12].

After this brief discussion of our theoretical model (for further details see Refs. [14,15]), we are now ready to present the calculations for the angular distribution of the $K\alpha_1$ radiation from the heliumlike uranium ions following REC. As mentioned above, these calculations require knowledge on both the alignment parameters and the relative populations of the $^{1,3}P_{1,2}$ states. For the parameters $\mathcal{A}_2(J=1)$ and $\mathcal{A}_2(J=2)$, the MCDF calculations predict that the direct electron capture results in a strong alignment of the $1s_{1/2}2p_{3/2}$ excited states, which is is almost -0.56 and -0.66 for $J=1$ and $J=2$ at the projectile energy $T_p=10$ MeV/u and slightly decreases to -0.37 and -0.44 for higher energies (for further details see Ref. [15]). We take cascade feeding from higher-lying levels into account according to the procedure outlined in Ref. [12], as already done in our previous study [16]. A considerable reduction due to cascades is found for the alignment. For instance, the subsequent decay of the levels with $n \leqslant 6$ decreases the (absolute value) of the alignment $\mathcal{A}_2(J=1,2)$ and, hence, the anisotropy $\beta_2(^{1,3}P_{1,2} \to {}^1S_0)$ parameters by about 40–50% for the collision energies in the range 10 MeV/$u \leqslant T_p \leqslant 400$ MeV/u (see Fig. 2).

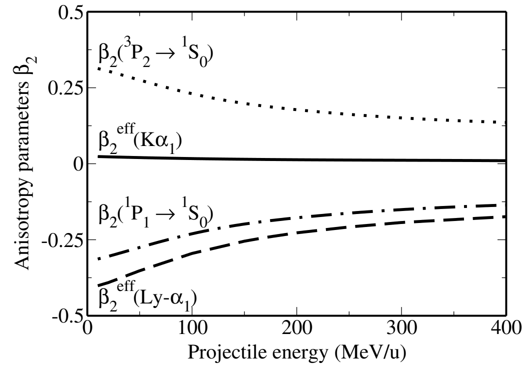

FIG. 2. Anisotropy parameters of the Lyman-α_1 (dashed line) and $K\alpha_1$ (solid line) radiation following REC into excited states of (initially) bare and hydrogenlike uranium ions, correspondingly. In addition to the theoretical calculations for the $K\alpha_1$ decay, we also present the anisotropy parameters (5) and (6) of its fine-structure $^1P_1 \to {}^1S_0$ (dash-dotted line) and $^3P_2 \to {}^1S_0$ (dotted line) components. All results include the feeding transitions from the higher excited states.

In contrast to the alignment, the relative populations of the $^{1,3}P_{1,2}$ excited ionic states are less affected by the cascade contributions. For heliumlike uranium ions U^{90+}, for instance, the cascade feeding basically preserves the statistical ratio $(N_{J=1}/N_{J=2})_{\rm REC}=3/5$ of the level populations as it arises from the direct electron capture [14]. For the full analysis of the $K\alpha_1$ emission pattern, however, this ratio should also account for possible depopulation mechanisms, since the decay of the $^{1,3}P_{1,2}$ levels may proceed not only through the $^{1,3}P_{1,2} \to {}^1S_0$ transitions but also through competitive channels. For instance, due to a significant contribution from the $1s_{1/2}2p_{3/2}\ {}^3P_2 \to 1s_{1/2}2s_{1/2}\ {}^3S_1$ decay, only about 70% of the population of the $^3P_2$ state contributes to the $K\alpha_1$ transition. This branching ratio implies that the weights of the $^1P_1 \to {}^1S_0$ and $^3P_2 \to {}^1S_0$ fine-structure components in the $K\alpha_1$ transition are almost equal: $N_{J=1}/N_{J=2} \approx 6/7$. In Fig. 2, we apply this ratio together with the alignment parameters $\mathcal{A}_2(J=1,2)$ to calculate the effective anisotropy parameter (8) for the $K\alpha_1$ radiation from heliumlike uranium ions. As seen from this figure, the parameter $\beta_2^{\rm eff}$ is almost energy independent and does not exceed 0.03 over the entire range of projectile energies calculated here. In fact, such a behaviour is quite different from what is known for hydrogenlike ions for which a strong anisotropy arises for the subsequent Lyman-α_1 radiation following REC. For these ions, a variation of the parameter $\beta_2^{\rm eff}(2p_{3/2} \to 1s_{1/2})$ from roughly -0.4 for the projectile energy $T_p=10$ MeV/u to -0.17 for $T_p=400$ MeV/u has been predicted theoretically within the exact relativistic approximation [17] and confirmed in experiments [12].

The different (energy) dependence of the anisotropy parameters (4) and (8), depicted in Fig. 2, results in qualitatively different emission patterns of the Lyman-α_1 and $K\alpha_1$ radiation following the electron capture by heavy uranium ions. In particular, the large negative parameter $\beta_2^{\rm eff}(2p_{3/2} \to 1s_{1/2})$ leads to a strong angular dependence of

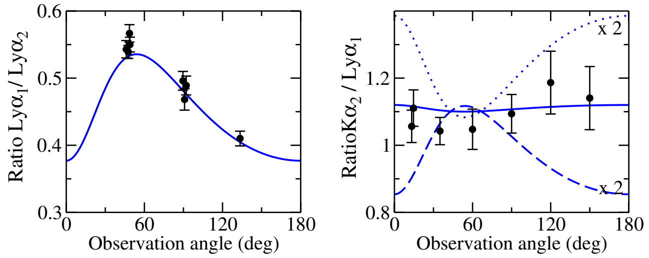

FIG. 3. (Color online) Angular distributions of the Lyman-α_1 (left panel) and $K\alpha_1$ (right panel) radiation following REC into excited states of (initially) bare and hydrogenlike uranium ions with energy $T_p = 220$ MeV/u [12,13]. Apart from the experimental (solid points) and theoretical (solid line) results for the $K\alpha_1$ emission we also present the angular distributions of its individual $^1P_1 \to {}^1S_0$ (dashed line) and $^3P_2 \to {}^1S_0$ (dotted line) components, multiplied by a factor 2. All data are normalized with respect to the intensity of the isotropic Lyman-α_2 radiation following the capture into bare U^{92+} ions.

the Lyman-α_1 radiation (see the left panel of Fig. 3) whose anisotropy is only slightly decreased if one proceeds towards higher collision energies. The $K\alpha_1$ radiation from heliumlike uranium projectiles, in contrast, appears to be almost isotropic since the modulus of the averaged $\beta_2^{\rm eff}({}^{1,3}P_{1,2} \to {}^1S_0)$ parameter is less than 0.03 within the energy range $10 \leqslant T_p \leqslant 400$ MeV/u. As seen from the right panel of Fig. 3, such a (nearly) isotropic behavior of the $K\alpha_1$ radiation is observed even though the individual $1s_{1/2}2p_{3/2}\,{}^1P_1 \to 1s_{1/2}^2\,{}^1S_0$ (dashed line) and $1s_{1/2}2p_{3/2}\,{}^3P_2 \to 1s_{1/2}^2\,{}^1S_0$ (dotted line) components of this line are strongly anisotropic. The angular distributions of these transitions were calculated for REC into hydrogenlike uranium ions U^{91+} at an energy of $T_p = 220$ MeV/u and compared with experimental data [12,13]. The data were taken at the internal target of the ESR storage ring for initially bare and H-like uranium projectiles colliding with N_2 molecules. For a detailed description of the experimental technique used we refer to Ref. [12] and just mention here that for consistency reasons the angular distribution of the $K\alpha_1$ radiation was normalized to the Lyman-α_2 intensities measured for bare ions in a subsequent run. As observed in Fig. 3, the experimental data and the theoretical findings are, reassuringly, in excellent agreement for *both* the initially bare and the H-like projectiles.

If we compare the (different) angular behavior of the $K\alpha_1$ and the Lyman-α_1 radiation, the following question arises naturally: Is the (nearly complete) cancellation of the anisotropy of the $J=1$ and $J=2$ lines decay lines *accidental* for heliumlike uranium, or does it follow a more general principle? To address this questions, let us again consider Eq. (8) for the effective anisotropy parameter of the $K\alpha_1$ decay. Apart from the alignment $\mathcal{A}_2(J=1,2)$ of the two lines of interest, the effective anisotropy of the $K\alpha_1$ radiation of course depends also on the relative population and the branching fractions of the $J=1$ and $J=2$ excited states which can be treated together a the effective "weights" of the two $K\alpha_1$ components. Following the REC into initially hydrogenlike uranium, for example, these weights are almost equal $N_{J=1}/N_{J=2} \approx 0.85$ for the two upper $J=1,2$ levels, leading to a final cancellation of the anisotropy. As mentioned before, however, the ratio $N_{J=1}/N_{J=2}$ accounts for the direct as well as the cascade population mechanisms of the $1s_{1/2}2p_{3/2}\,{}^{1,3}P_{1,2}$ states and, hence, may vary significantly for collision processes other than REC. In addition to the population mechanisms, the effective parameter $\beta_2^{\rm eff}({}^{1,3}P_{1,2} \to {}^1S_0)$ critically depends on the $E1$ decay into the $1s_{1/2}2s_{1/2}\,{}^3S_1$ level. The strong enhancement of this competitive decay branch with increasing charge implies that only about 70% of the population of the triplet $2^3P_{J=2}$ state contributes to the $K\alpha_1$ decay for heliumlike ions U^{90+}, while the same contribution is 79% for heliumlike gold Au^{79+} and even 89% for xenon Xe^{52+} projectiles [25]. This increase of the $1s_{1/2}2p_{3/2}\,{}^3P_2 - 1s_{1/2}^2\,1\,{}^1S_0$ ($M2$) branching fraction then results in the weight ratios: $(N_{J=1}/N_{J=2})_{\rm Au} \approx 0.75$ and $(N_{J=1}/N_{J=2})_{\rm Xe} \approx 0.67$ and, hence, in a remarkable enhancement of the anisotropy of the $K\alpha_1$ radiation in going from high-Z to medium-Z heliumlike ions, following an initial population of the levels due to REC. In order to illustrate such a Z dependence, we display in Fig. 4 the anisotropy parameter (8) for the heliumlike xenon Xe^{52+}, gold Au^{77+}, and uranium U^{90+} ions. As seen from this figure, the strongest effect on the anisotropy parameters can be observed for low collision energies, where the parameter $\beta_2^{\rm eff}({}^{1,3}P_{1,2} \to {}^1S_0)$ increases by more than a factor of 2 if the decay of heliumlike xenon Xe^{52+} ions is compared to those for uranium U^{90+} projectiles. For the projectile energy $T_p = 10$ MeV/u, for example, the anisotropy of the $K\alpha_1$ radiation in heliumlike xenon ions is $\beta_2^{\rm eff} \approx 0.065$ and could possibly be detected using presently available x-ray detectors.

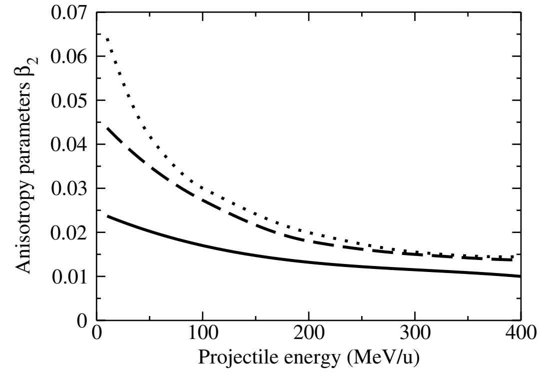

FIG. 4. Anisotropy parameters of the $K\alpha_1$ radiation following REC into the $1s_{1/2}2p_{3/2}\,{}^{1,3}P_{J=1,2}$ levels of the (finally) heliumlike xenon Xe^{52+} (dotted line), gold Au^{77+} (dashed line), and uranium U^{90+} (solid line) ions. All results include the feeding transitions from the higher excited states.

As seen from Fig. 4 and our discussion above, therefore, the observed isotropy of the $K\alpha_1$ radiation from heliumlike uranium ions (and following REC) is indeed rather accidental and will not necessarily be found for other ions or population mechanisms. Note, however, that a *partial* cancellation of the anisotropy of the $K\alpha_1$ radiation always occurs owing to the relative strength of its $E1$ and $M2$ fine-structure components. This reduction in the anisotropy, which has to be taken into account for the analysis of the experimental data, can be described on the basis of the general formulas as obtained in the present paper.

IV. CONCLUSIONS

In conclusion, we have studied the radiative capture-and-decay processes involving excited states of heavy, few-electron ions. Emphasis has been placed especially on the Lyman-α_1 and $K\alpha_1$ x-ray emissions following REC into (initially) bare U^{92+} and hydrogenlike U^{91+} uranium projectiles. We have shown that the angular distributions of these two radiative transitions behave in qualitatively different ways owing to the coupling of the electrons to the radiation field and to each other. The strong anisotropy of the Lyman-α_1 transition in a one-electron system following capture, which is enhanced by $E1$-$M2$ mixing [15,16], is contrasted by an unexpected "$E1$-$M2$ cancellation" between $^1P_1 \rightarrow {}^1S_0$ ($E1$) and $^3P_2 \rightarrow {}^1S_0$ ($M2$) decays in the case of an intermediate heliumlike state. Besides the potential relevance of unexpected angular distributions in few-electron systems for other processes involving, e.g., dielectronic recombination, inner-shell ionization and excitation, we note that our results may also affect the interpretation of experimental $K\alpha_1$ line centroid data as given in literature for ions at high Z (see, e.g., Refs. [26,27]). Obviously, our study suggests that the line centroids not only depend on the relative population of the two unresolved j levels but may vary additionally as a function of the observation angle.

ACKNOWLEDGMENTS

Elucidating discussions with P. H. Mokler are gratefully acknowledged. The work of U.D.J. was supported by DFG (Heisenberg program). S.F. acknowledges support by BMBF and GSI (Project No. KS-FRT).

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