Angular Distribution Studies for the Time Reversed Photoionization Process: The Identification of Spin-Flip Transitions

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Introduction: Photoionization is one of the most important interaction processes between radiation and matter [1,2]. We have previously shown that for high-Z ions photoionization is studied best via its inverse reaction, the radiative electron capture (REC) [3,4,5] in energetic ion-atom collisions. For very high-*Z* systems, relativistic effects become important and require an exact theoretical treatment adopting relativistic electron wave functions and the inclusion of retardation, i.e. of all multipole orders of the photon field [6,7]. Already in the nonrelativistic regime of low-*Z* ions, an admixture of quadrupole contributions to the dominant dipole term has been identified. For the quantitative assessment of relativistic effects in high-*Z* ions, angular distributions are a very sensitive probe. In direct photoionization the retardation leads to a strong forward peaking of the photoelectron angular distribution, and electron correlations in multielectron atoms cannot unambiguously be separated from relativistic effects. The inverse reaction lends itself to a more critical test. For REC into the *K* shell of bare nonrelativistic ions, this is due to the cancellation between the effects of retardation on the one hand and the Lorentz transformation into the laboratory system on the other hand [8,9] and, moreover, to the absence of electron correlations. As a result, all deviations from a $\sin^2\theta$ distribution provide a direct measure of relativistic effects. Surprisingly, these deviations, turn out to be rather unimportant at ion energies up to 300 MeV/u and nuclear charges up to *Z*=50 or 70 [10]. However, at the same collision energy and *Z*=92, a significant cross section at forward angles has been predicted for REC into the *K* shell [4,7,10] and shown to be a unique signature of spin-flip transitions.

Identification of spin-flip transitions: Here, we report the first experimental study of a complete photon angular distribution for radiative electron capture into the *K* shell of a bare high-*Z* ion (uranium, Z=92). Our measurement, conducted at the intenal target of the ESR [11], encompass laboratory observation angles from near 0^O to 150^O, permitting to identify spin-flip contributions that lead to photon emission at 0^O. Photon emission at 0^O is forbidden by angular momentum conservation unless a magnetic spin-flip transition accounts for the spin of the emitted photon [10,12]. Furthermore, we deduce the electron angular distribution following photoionization of hydrogenlike uranium. This process is at present not accessible in the direct channel due to the lack of the necessary luminosity. The derivation of the electron angular distribution is greatly facilitated by the simultaneous observation of $\boldsymbol{Ly\alpha_2}$+(***M1***) radiation in the same spectra, as these transitions are isotropic in the emitter frame.

In Fig. 1, the measured differential cross sections for REC into the *K* shell of U^{92+} are presented as a function of the laboratory observation angle (solid triangles) and compared with predictions based on rigorous relativistic calculations [7,10]. To facilitate a comparison of experimental and theoretical cross sections, the measured angular distribution was normalized to the theoretical prediction at 90^O.

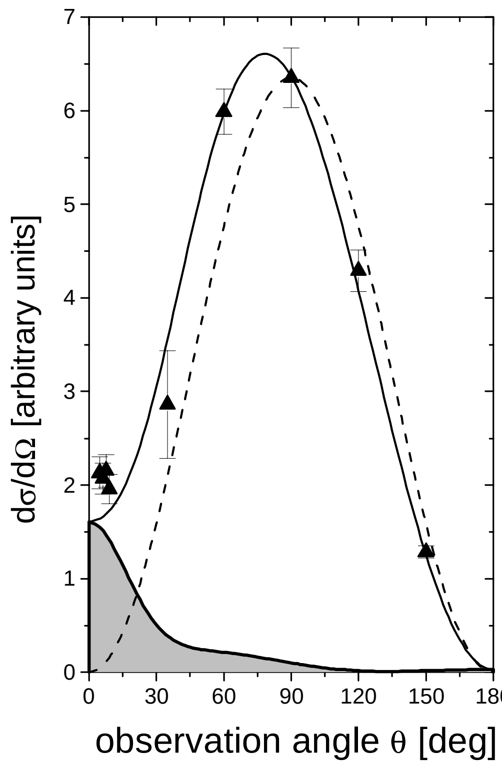

Fig. 1: *Angular distribution for REC into the K shell of bare uranium (solid triangles) as a function of the observation angle θ. For details see text.*

As seen in the figure, good agreement is obtained between the experimental data and the rigorous relativistic calculations. In order to elucidate the necessity of a complete relativistic treatment for high-Z projectiles, the figure also includes the $\sin^2\theta$ distribution following from a nonrelativistic treatment which incorporates the full retardation as well as the Lorentz transformation to the laboratory frame. Obviously, the experimental data deviate considerably from symmetry around 90^O. Most importantly, the large cross section observed close to 0^O is at variance with the assumption of a spinless electron or a passive electron spin. Rather, in a complete relativistic treatment, the interaction of the electron magnetic moment with the magnetic field produced by the fast moving projectile gives rise to spin-flip transitions which compensate the angular momentum carried away by the photon. Therefore, our measurement close to 0^O provides an unambiguous identification of spin-flip transitions occurring in relativistic ion-atom collisions. This effect, predicted recently [4,7,10], has not been confirmed experimentally up to now. For example, for the case of $Xe^{54+} \rightarrow$ Be collisions at 197 MeV/u [14], no relativistic effects were observed and the measured *K*-REC angular distribution could be well reproduced by the nonrelativistic theory. It should also be mentioned that in the relativistic Sauter approximation [15], in which the matrix element of the photoelectric effect is treated in the lowest order of $\alpha \boldsymbol{Z}$ (α is the fine-structure constant) spin-flip contributions at forward angles do not occur. Hence, the present results indicate that higher orders in αZ (automatically contained in the exact wave functions) are needed.

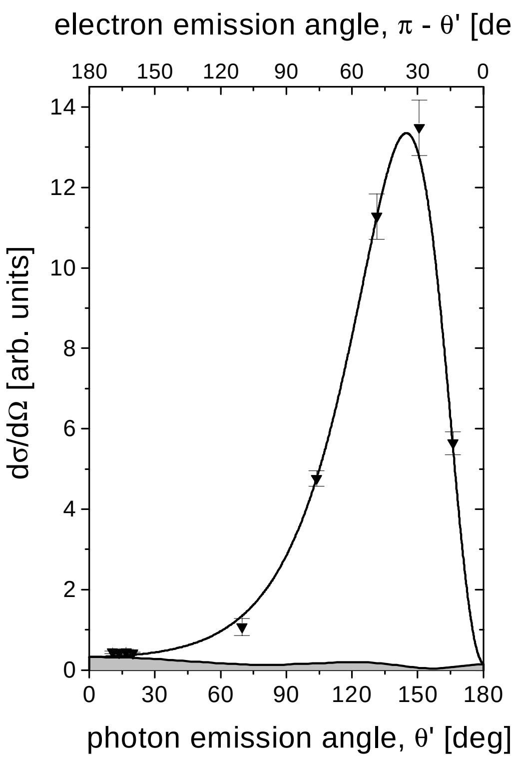

Fig. 2: *K-REC angular distribution (projectile frame) as a function of the emission angle θ' (bottom x-axis). The x-axis at the top refers to the corresponding electron angular distribution for photoionization of U^{91+} (photon energy 272 keV) obtained by interchanging θ' by π- θ' (see text).*

Photoionization: In order to elucidate the physics of the REC process and its relation to photoionization in more detail, we normalize the measured K-REC x-ray yield directly to the intensity of the simultaneously observed $\boldsymbol{Ly}$-$\boldsymbol{\alpha_2}$+$\boldsymbol{M1}$ line. By applying this technique of normalization, we obtain the REC angular distribution in the emitter frame. This requires only the Lorentz transformation (see e.g. Ref. [9]) of the observation angle. In Fig. 2, the result for this ratio is depicted as a function of the emission angle in the emitter frame (cf. the x-axis at the bottom) along with the corresponding prediction by the rigorous relativistic theory. As can be observed in the figure, both the experimental and the theoretical angular distributions exhibit a pronounced backward shift, since the strong retardation effect (equivalently, the contribution of high multipole orders) is no longer cancelled by the Lorentz transformation to the observer system. The maximum of the distribution is now localized close to 150^{O} and the cross section decreases drastically by more than a factor of 40 when going to 0^{O}. Here, indeed the occurrence of spin-flip transitions (compare shaded area in Fig. 2) appears to be a tiny effect with an almost isotropic distribution. This is in obvious contrast to the distribution in the laboratory frame, where the Lorentz transformation not only compensates retardation but also amplifies the relative weight of the spin-flip transitions close to 0^{O} by more than an order of magnitude with respect to the maximum of the distribution

From the experimental REC distribution in the emitter frame, the corresponding angular distribution for photoionization can also be derived by simply replacing the REC angle θ' with θ' since the directions of the photon and the electron are interchanged. Therefore, the upper abscissa in Fig. 2 refers to the electron angular distribution for photoionization of hydrogenlike uranium at the corresponding photon energy of 272 keV. We note, that contrary to conventional photoionization studies for high-***Z*** elements where scattering inside the solid targets leads to a considerable broadening of the photoelectron emission angle [16], no such effects have to be considered here. The features of the figure illustrates the potential of REC experiments for precision studies of the photoionization process. In particular, it reveals the origin of the observed spin-flip transitions as events related to large-angle backward scattering photoionization, i.e. events where the momentum transfer to the nucleus is largest.

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