Study of Electron Bremsstrahlung in Strong Coulomb Fields at the ESR Storage Ring

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Electron bremsstrahlung has been investigated for collisions of 223.2 MeV/amu He-like uranium ions with N_2 and Ar gaseous targets. The doubly differential cross-sections for bremsstrahlung are compared to the predictions of relativistic first order Born calculations (Bethe-Heitler formula with Elwert correction factor) and to the calculations based on the exact wave-functions for electrons moving in the external point-Coulomb potential of the projectile. Whereas the "exact" calculations give an improved agreement with experimental data, as compared to the Bethe-Heitler theory, in particular at the end-point region of the bremsstrahlung spectra, discrepancies still remain at lower photon energies.

1. Introduction

In relativistic atomic collisions the x-ray emission due to charge changing and excitation processes is accompanied by continuum radiation originating from electron bremsstrahlung. For low-Z systems the bremsstrahlung cross-sections are generally predicted with success by the Coulomb modified relativistic Born approximation (for a review see eg. [1]). However, for highly charged high-Z systems this process occurs in the presence of strong Coulomb fields, thus requiring theoretical description which goes beyond first order Born approximation [2]. Up to now very few experimental investigations have been reported for bremsstrahlung production in relativistic ion-atom collisions involving very-heavy highly-charged ions [3]. These studies demonstrated that the experimental data for doubly differential bremsstrahlung cross-sections for heavy ion impact are significantly underestimated by the Born approximation calculations even if Coulomb distortion effects are taken into account in an approximate way (Born-Elwert formula).

We report here on the recent experimental results for electron bremsstrahlung in collisions of He-like uranium with light gaseous targets at relativistic energies. Such systems provide a unique possibility to study bremsstrahlung in the domain of strong Coulomb fields while simultaneously screening effects play a negligible role. Furthermore, the gaseous targets used in the present experiments reduce significantly the background associated with secondary electron bremsstrahlung as compared to solid-target measurements. The experimental results for the doubly differential bremsstrahlung cross-sections are compared to "exact" numerical calculations of Pratt *et al.* [2] and to calculations based on the Born approximation (Bethe-Heitler formula with Elwert correction factor).

2. Experimental method and data analysis

The measurements were performed at the internal gas-target of the ESR storage ring facility at GSI-Darmstadt. The detailed description of the experiment can be found elsewhere [4]. The absolute cross-sections for bremsstrahlung were determined by normalizing the bremsstrahlung intensity to that of the radiative electron capture to the L-shell of the projectile (L-REC) observed at 132°. The theoretical L-REC cross-sections used for the normalization purpose were obtained from rigorous relativistic calculations [6]. The latter are known to describe very well the available experimental data for REC into high-Z projectiles. In particular, it has been demonstrated that this model yields good quantitative agreement with experimental sub-shell resolved angular distributions of L-REC for He-like uranium [5].

Simultaneously, the measured spectra were corrected for efficiency of the x-ray detectors, background radiation, as well as for the x-rays associated with radiative electron capture to L- and higher shells. The latter correction is essential in order to determine the overall shape of bremsstrahlung spectrum since REC into the M-, and higher shells partially overlaps with the end-point region of the primary bremsstrahlung. For this purpose, the spectra taken in coincidence with down-charged uranium ions were subtracted from the corresponding single spectra. We estimate that the overall uncertainty of the doubly differential cross sections does not exceed 30%.

For $U^{90+} \rightarrow N_2$, Ar collisions bremsstrahlung occurs in the inverse scattering kinematics, i.e. the bound target electrons are inelastically scattered from the nucleus of the projectile giving rise to the emission of bremsstrahlung. In order to compare the experimental results with theoretical calculations (which are conventionally given in the rest frame of the scattering center), the latter have to be transformed to the laboratory reference frame (see e.g. [6]). In addition, we

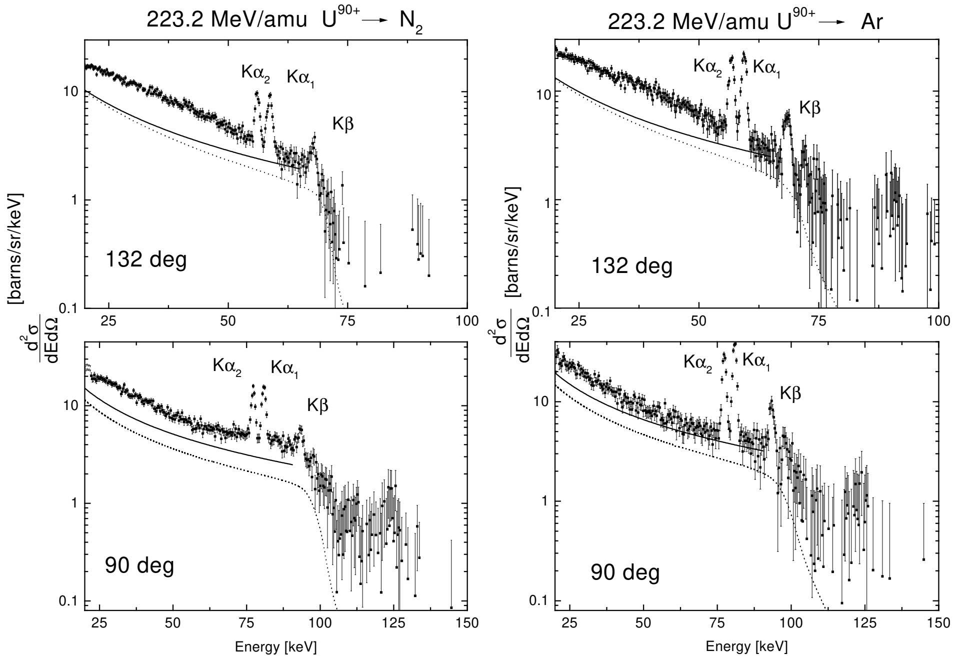

Figure 1. Doubly differential cross-sections for bremsstrahlung in collisions of 223.2 MeV/amu U^{90+} with N_2 (left), and Ar (right) at observation angles $\Theta = 132°$ and $\Theta = 90°$, respectively. The experimental data are compared to the Bethe-Heitler-Elwert model taking into account the Doppler broadening and the electron momentum distribution of the target atom (dotted line), and to the "exact" point-Coulomb field calculations (solid line).

assume that the loosely bound target electrons can be treated as free particles, in high-energy collision. The initial electron momentum distribution of the target electron is, however, taken into account by folding the theoretical cross-sections with the Compton profile of the target electrons.

3. Results and discussion

In figure 1 the doubly differential cross-sections are shown for bremsstrahlung in collisions of U^{90+} with N_2 and Ar target electrons at observation angles 132° and 90°, respectively. The experimental data are compared to the predictions of the relativistic Born approximation calculations with Elwert correction factor, and to the rigorous relativistic calculations. The latter were obtained using relativistic independent particle approximation which takes into account the exact scattering electron wave-functions in a static potential, and include the lowest non-zero term in the interaction between the emitted photon field with the electron [2]. It is evident that both models underestimate the experimental data for photon energies up to the vicinity of the end-point of the bremsstrahlung spectra. It should be recognized that for He-like projectiles an additional x-ray continuum associated with the excitation process to the $2S_0$ state of the projectile contributes to the observed x-ray spectra. The characteristic Kα and Kβ radiation seen in Fig. 1 is due to the Coulomb excitation to the P states of U^{90+}. In contrast, the collisionally excited $2S$ states, decay by succesive emission of two-photons (2E1) which is manifested as an x-ray continuum stretching from photon energy equal zero to approximately the energy of the Kα_2 transition in U^{90+}. This de-excitation mode can alter slightly the shape of the observed x-ray continua. However, the end-point energy region of bremsstrahlung is not affected by the two-photon transitions, while simultaneously, here the systematic uncertainties of the absolute experimental cross sections are smallest. This energy domain is in particular sensitive to the final state Coulomb interaction, since high energy x-rays originate from collisions where final kinetic electron energy is small as compared to the electron-nucleus interaction. For these photon energies the calculations based on the Born-approximation generally fail to predict the experimental data. This failure is connected to the fact that Born approximation utilizes a power expansion in series of $Z\alpha/\beta_f$ (Z is here the charge of the scattering center, α is fine structure constant and β_f is final electron velocity in units of the speed of the light). It is apparent from Fig. 1 that rigorous calculations lead to a better agreement with experimental data for doubly differential bremsstrahlung cross-sections at the end-point energy region. This demonstrates the importance of rigorous non-perturbative treatment of the electron – electromagnetic field interaction for bremsstrahlung in the domain of strong Coulomb potentials.

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