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Fine-structure effect in the relativistic $(e,2e)$ process

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Using a transversely polarized electron beam a relativistic $(e,2e)$ experiment has been performed to look for a spin-up–spin-down asymmetry in the electron-impact ionization process caused by the fine-structure effect. An incident energy of 300 keV, coplanar asymmetric kinematics, and the $2p_{3/2}$ shell of uranium $(Z=92)$ have been used. We found clear evidence for the fine-structure effect in the relativistic regime and a qualitative agreement with theoretical results of the relativistic distorted-wave Born approximation, including a change of sign in the angular distribution of the asymmetry near the Bethe ridge. [S1050-2947(98)50710-X]

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Kinematically complete electron-electron coincidence [or $(e,2e)$] experiments have proved to be a valuable method of investigating the dynamics of electron-impact ionization of atoms [1,2]. $(e,2e)$ experiments with polarized electrons are a further step towards the ideal of a quantum mechanically complete analysis of the elementary process of electron-impact ionization. Recently, two types of $(e,2e)$ experiments using transversely polarized electron beams and unpolarized targets have been carried out to measure spin asymmetries. In the first type, spin-up–spin-down asymmetries have been measured which are caused by spin-dependent forces, i.e., by the spin-orbit interaction of the continuum electrons moving with relativistic energies in the Coulomb field of the atomic nucleus [3,4]. In experiments of the second type done at nonrelativistic energies [5,6] the spin asymmetries are interpreted in terms of the so-called fine-structure effect first discussed by Hanne [7] for the case of electron-impact ionization of states with nonzero orbital angular momentum. Here the asymmetries are caused by the Coulomb interaction, within the system and the exchange interaction even if spin-dependent forces on the continuum electrons are of minor importance.

A simple model of the fine-structure effect is presented in the papers of Madison *et al.* [8] and Jones *et al.* [9] for the nonrelativistic regime. An essence of these arguments is given by Keller *et al.* [10] as follows: If a fine-structure multiplet is experimentally resolved (i.e., if the total angular momentum J is known) in an ionization experiment using an electron beam polarized perpendicular to the scattering plane, then, assuming approximate validity of LS coupling for the initial target state, the possibility of exchange scattering of the spin parallel electrons yields an asymmetry in the differential cross section. This effect is due to an interference: while (in absence of spin-orbit coupling leading to spin-flip transitions) the spin singlet direct and exchange amplitudes do not interfere because the incident electron can be identified in the final channel if a spin measurement is carried out, the spin triplet amplitudes do interfere because of the possibility of spin-exchange scattering. Due to conservation of total angular momentum, this effect may also be interpreted in terms of an orientation of the spectator ion in the final state.

For atoms of high atomic number the LS coupling scheme is clearly invalid. Therefore the question arises whether the fine-structure effect does exist if relativistic electrons ionize inner shells of atoms of high atomic numbers and how to separate it from asymmetries caused by spin-dependent forces. This gave us the motivation to start the present work in the course of which relativistic calculations have become available showing considerable asymmetries attributed to the relativistic fine-structure effect. A first calculation was based on the semirelativistic Coulomb-Born approximation of Jakubassa-Amundsen [11]. In a basic paper of Keller *et al.* [10] a theory of $(e,2e)$ processes with spin-polarized relativistic electrons has been worked out using the fully relativistic distorted-wave Born approximation (RDWBA). Details of the RDWBA, which is a first-order theory using exact eigenstates of the Dirac equation with an effective atomic potential for all electron wave functions, are outlined in Keller *et al.* [12].

We report here on an $(e,2e)$ experiment with a transversely polarized primary beam designed to look for the fine-structure effect in the relativistic energy regime and on an inner shell of an atom of high atomic number. We used a primary energy of 300 keV and the $2p_{3/2}$ state of the L shell of uranium $(Z=92)$. In general, the asymmetry caused by the spin-orbit interaction of the continuum electrons may appear simultaneously with that of the fine-structure effect. Since for the present we are interested in measuring the fine-structure effect exclusively we chose kinematical conditions in a way that the asymmetry coming from the continuum electrons is expected to be as small as possible. To achieve this our considerations were as follows. In an $(e,2e)$ experiment with coplanar asymmetric kinematics (Ehrhardt geometry) where the fast outgoing electrons are detected at a small scattering angle the angular distribution of the slow outgoing electrons consists, in general, of a binary peak and a recoil peak. The recoil peak cannot be explained unless an electron-nucleus interaction is taken into account. Consequently, in this region a spin-orbit interaction of the continuum electrons must contribute, and a spin asymmetry is to be expected. The binary peak, however, has a large contribution from a direct binary collision between the incoming electron and the atomic electron, with the nucleus in the role of a ‘‘spectator,’’ and the spin-orbit interaction will be weak. Indeed, we could show in a former $(e,2e)$ experiment on the K shell of silver [3] that the relating asymmetry in the binary peak is close to zero, whereas in the recoil region a distinct asym-

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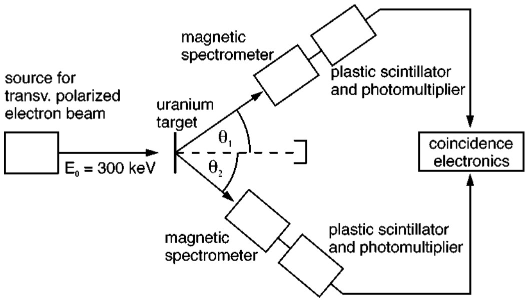

FIG. 1. Sketch of the coplanar electron-electron coincidence experiment. The spin direction of the primary electron beam (300 keV) is perpendicular to the scattering plane.

metry was found. (Asymmetries due to the fine-structure effect vanish for K-shell ionization because of the absence of the orbital angular momentum in the s state.) Therefore we started our search for the relativistic fine-structure effect in the binary region of the angular distribution of the $(e,2e)$-process. To confirm this feature of a small influence of the spin-orbit coupling of the continuum electrons we have repeated the former $(e,2e)$ experiment in the binary peak of the K shell of silver [3] with kinematical parameters similar to those in the present measurement of uranium. Due to the smaller radius of the K-shell orbital of silver the spin-orbit interaction of the continuum electrons should be about a factor of 3 stronger compared to the $2p_{3/2}$ orbital of uranium. Nevertheless we got only asymmetries between 0% and 3%, indicating that any larger asymmetry observed under comparable kinematical conditions cannot be explained by continuum spin-orbit coupling.

A sketch of the experimental arrangement is shown in Fig. 1. The source for the polarized electron beam used the photoemission of electrons from a strained GaAs crystal irradiated by circularly polarized light of a laser diode (the source is described in principle elsewhere [13], but was at that time operated merely with a conventional GaAsP crystal). After deflection by a 90° cylindrical deflector, the extracted electrons are transversely polarized. Reversal of the polarization of the electron beam can easily be realized by inverting the helicity of the laser light. The source is installed in a high-voltage terminal of a 300-kV accelerator tube and produces a continuous transversely polarized beam with a degree of polarization in the range of 60–65 %. The polarization was measured by a Mott analyzer put into the beam line in front of the entrance of the scattering chamber. In the Mott analyzer the electrons scattered through 120° by a gold foil were detected by a pair of ion-implanted silicon detectors. The primary beam was focused to a 1-mm-diam spot on the target foil placed at the center of a vacuum chamber. As the target we used uranium foil with a thickness of 60 μg/cm^2. We performed the measurement on the $2p_{3/2}$ shell (E_{bind}=17.2 keV), as the energy distance to the $2p_{1/2}$ shell is 3.8 keV and therefore best to separate. (We could not separate the $2p_{1/2}$ from the $2s_{1/2}$ shell because of the difference of the binding energy of 0.8 keV only.) Each of the two electron detector systems consists of a magnetic spectrometer for the energy analysis combined with a plastic scintillation detector. Each magnet is a doubly focusing homogeneous sector field shaped by an iron core. The fast signals from the detectors were fed into a time-to-amplitude converter via constant fraction discriminators. The quantity measured directly is the counting rate of the true coincidences alternately for spin-up and spin-down electrons of the primary beam. The spin asymmetry is defined as the relative cross-section difference

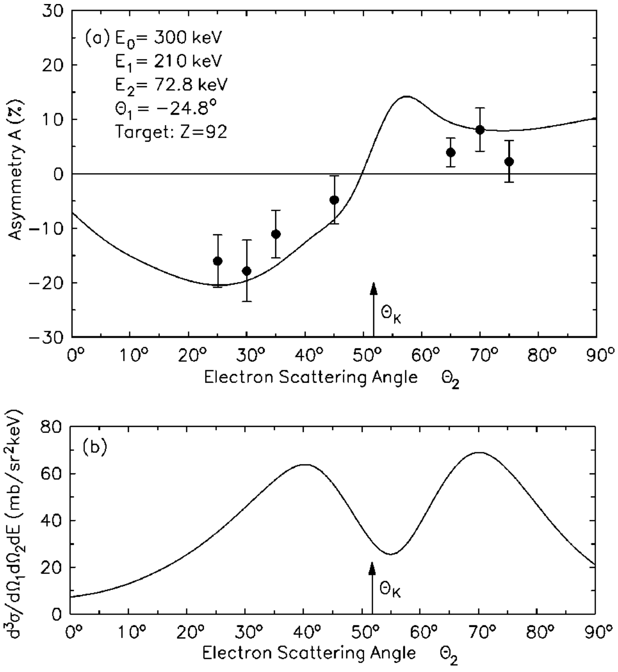

FIG. 2. (a) Spin-up–spin-down asymmetry A of the triply differential cross section for electron-impact ionization of the $2p_{3/2}$ state of the L shell of uranium as a function of the scattering angle Θ_2 of the outgoing slow electrons of energy E_2=72.8 keV. The primary electron energy amounted to E_0=300 keV. The outgoing fast electrons of E_1=210 keV were observed at an angle of Θ_1= −24.8°. Θ_K is the direction of the momentum-transfer vector. The error bars represent the standard deviations only; the systematic error of asymmetry scale was estimated to be ±2%. The solid line is a theoretical prediction of the relativistic distorted-wave Born approximation of Keller *et al.* [10]. (b) Angular distribution of the triply differential cross section calculated according to the relativistic distorted-wave Born approximation for an unpolarized beam. The plot displays only the binary region; the region of the recoil peak is not shown.

$$A=\frac{d^3\sigma^{\uparrow}-d^3\sigma^{\downarrow}}{d^3\sigma^{\uparrow}+d^3\sigma^{\downarrow}}, \tag{1}$$

where $d^3\sigma^{\uparrow}$ and $d^3\sigma^{\downarrow}$ are the triply differential ionization cross sections for impinging electrons with spin up and spin down perpendicular to the scattering plane. We got the asymmetry A as the ratio

$$A=\frac{N}{P}, \tag{2}$$

where P is the polarization of the beam, and for spin-up and spin-down counting rates $N^{\uparrow}$ and $N^{\downarrow}$, respectively,

$$N=\frac{N^{\uparrow}-N^{\downarrow}}{N^{\uparrow}+N^{\downarrow}}. \tag{3}$$

We chose the following parameters for the measurement: The polarized electron beam of $E_0=300$ keV impinges on the uranium target. In coplanar asymmetric geometry the outgoing fast electrons of $E_1=210$ keV are observed at a fixed scattering angle of $\Theta_1=-24.8°$ with respect to the primary beam direction. The detector for the coincident slow electrons was adjusted to an energy of $E_2=72.8$ keV in order to select $(e,2e)$ processes from the $2p_{3/2}$ shell.

The result of the measurement of the spin asymmetry A as a function of the scattering angle of the outgoing slow electrons is shown in Fig. 2(a) (full circles). The error bars are the standard deviations. The solid line is a theoretical prediction of the relativistic distorted-wave Born approximation of Keller *et al.* [10], where one can also find plots for the $2s_{1/2}$ and the $2p_{1/2}$ states under similar kinematical conditions. To visualize the angular distribution of the triply differential cross section in the binary peak we show in Fig. 2(b) the corresponding result of the RDWBA calculation, averaged over spin degrees of freedom. The experiment shows large asymmetries (up to 18%), which, according to the argument given above, cannot be explained in terms of spin-orbit coupling of the continuum electrons. In view of the fact that in this energy domain there are no known mechanisms other than spin-orbit coupling and possibly the fine-structure effect that could lead to spin asymmetries, we conclude that our experiment clearly evidences the existence of the fine-structure effect in relativistic $(e,2e)$ collisions. In particular, the characteristic change of sign of the asymmetry near the so-called Bethe ridge (ion recoil momentum $\mathbf{k}_{ion}=0$) could be confirmed. It appears for relativistic as well as for nonrelativistic primary energies. Our interpretation is confirmed by the reasonable agreement between the experimental data and the calculated RDWBA results, which include just the two mechanisms mentioned above. It is interesting to note that a plane-wave calculation leads to a vanishing asymmetry [14,10]. This theoretical result gives a hint that the interaction between the continuum electrons and the Coulomb field of the atom has to be present also in the binary peak region in order to produce the fine-structure effect.

For the present high energies the active electrons are well decoupled from the spectator target electrons. Therefore no exchange between the continuum electrons and the target atom is included for the incoming and outgoing elastic channels in the RDWBA calculations of the relativistic fine-structure effect [10,12]. Compared to this a calculation of the asymmetry for lower incident energies done by Dorn *et al.* [15] includes the exchange between each outgoing electron and the remaining target electrons. There it turned out, that this exchange mechanism could be the major factor under particular kinematical conditions. In view of this fact the asymmetry measured in the present experiment can be regarded to be due to a more basic scattering mechanism since there is only the exchange between the two active electrons involved.

In forthcoming measurements we plan to go over to the recoil region. Here, in addition to the fine-structure effect a substantial asymmetry due to the spin-orbit coupling of the continuum electrons is to be expected. Interference effects may produce a rich structure of the resulting asymmetry [10]. Another interesting task would be to link up with the work of Prinz and Keller [4]. Particularly, in the binary region they observed a small asymmetry in an inclusive measurement on the L shell of gold, in contrast to comparatively large asymmetry values predicted by their theoretical investigations for the $2p$ subshells. This phenomenon is supposed to be due to the averaging over the different fine-structure levels [4]. It will be interesting to confirm this feature experimentally by carrying out inclusive and exclusive measurements under the same kinematical conditions.

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