Spin-Orbit Interaction of the Continuum Electrons in Relativistic $(e, 2e)$ Measurements

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Using a transversely polarized electron beam a relativistic $(e, 2e)$ experiment has been performed to look for a spin up-down asymmetry in the electron-impact ionization process caused by the spin-orbit interaction of the continuum electrons in the Coulomb field of the atomic nucleus. An incident energy of 300 keV, coplanar asymmetric kinematics, and the K shell of silver ($Z = 47$) have been used. We found a distinct spin asymmetry in the recoil peak (up to 16%), whereas in the binary peak the asymmetry is close to zero. This feature is confirmed by theoretical calculations, but quantitatively the agreement is poor.

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The study of the dynamics of electron-impact ionization of atoms by electron-electron coincidence [or $(e, 2e)$] experiments has proved to be a valuable method of investigating the physics of ionization processes [1,2]. The application of spin-polarized electron beams allows for an even more severe test of theory, and recently results have been reported for low energies. In these nonrelativistic $(e, 2e)$ experiments spin-dependent asymmetries have been studied which are due to the exchange interaction [3] and to the so-called fine-structure effect [4,5].

In this Letter we report on a relativistic $(e, 2e)$ experiment with a transversely polarized electron beam designed to look for a spin asymmetry caused by the spin-orbit interaction of the *continuum* electrons in the Coulomb field of the atomic nucleus. The spin-orbit interaction arises from the interaction of the magnetic moment of the electrons with the magnetic field felt in the rest frame of the electrons because of their motion in the Coulomb field of the target nucleus (Mott scattering). As a result, a spin up-down asymmetry is to be expected in the triply differential cross section of electron-impact ionization. In particular, we were interested in investigating the angular distribution in view of the question whether the asymmetry is larger within the region of the so-called recoil peak than the asymmetry within the binary peak. Our assumption is based on the following intuitive argument. As the binary peak 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," the spin-orbit interaction will be weak. The recoil peak, however, cannot be explained unless an electron-nucleus interaction is taken into account. Consequently, here a spin-orbit interaction must contribute, and a spin asymmetry is to be expected.

A sketch of the experimental arrangement is shown in Fig. 1. The source for the polarized electron beam (described in detail elsewhere [6]) used the photoemission of electrons from a GaAsP crystal irradiated by circularly polarized light of a helium-neon laser. After being deflected by a 90° cylindrical deflector, the extracted electrons are transversely polarized. The spin flip of the electron beam can be easily realized by reversing 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 polarization degree in the range 35%–40%. The degree of spin 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 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 silver foil with a thickness of 50 $\mu g/cm^2$, for which plural scattering was found to be small in previous cross section measurements. Each of the two electron detector systems consisted of a magnetic spectrometer for the energy analysis combined with a plastic scintillation detector. Each magnet is a doubly focusing homogenous 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

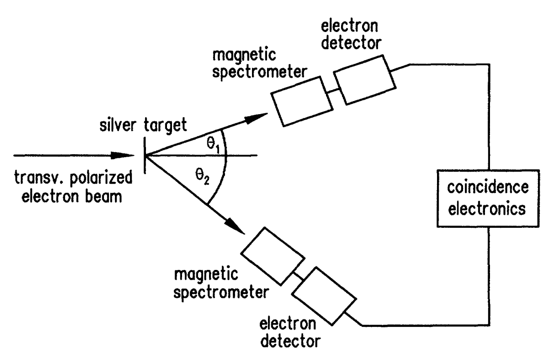

FIG. 1. Sketch of the coplanar electron-electron coincidence experiment. The spin direction of the primary electron beam (300 keV) is perpendicular to the scattering plane.

spin asymmetry is defined as the relative cross section difference

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

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

$$A = \frac{N}{P}, \quad (2)$$

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

$$N = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}. \quad (3)$$

Because theoretical predictions [7,8] of A—which were stimulated only by our experiment—were not available until the end of the present measurements, we had used the following arguments to choose suitable atomic numbers of the target nucleus and kinematical conditions. Since the spin-orbit interaction the continuum electrons experience will increase with the strength of the electric field in which they are moving, the resulting spin up-down asymmetry is expected to increase with the atomic number Z of the target nucleus. The triply differential cross section, however, decreases with increasing Z. Balancing asymmetry to be expected against cross section we chose the K shell of silver ($Z = 47$).

We used coplanar asymmetric kinematics (fast outgoing electron is detected under a small scattering angle with regard to the primary beam) where the angular distribution of the coincident slow outgoing electrons consists of a binary peak and a distinct recoil peak. As already shown in a previous measurement [9], for our relativistic primary energies the recoil peak is relativistically transformed into the forward direction, whereas for nonrelativistic energies it appears in the backward direction [1,2].

We chose the following parameters for our measurement: A primary electron beam of $E_0 = 300$ keV transversely polarized with the spin perpendicular to the reaction plane impinges onto a silver target. The outgoing fast electrons of $E_1 = 200$ keV are observed at a fixed scattering angle of $-10°$ with respect to the primary beam direction. The detector for the coincident slow electrons was adjusted to an energy of 74.5 keV in order to select $(e, 2e)$ processes from the K shell ($E_{\text{bind}} = 25.5$ keV). The results 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). To visualize the angular positions of the recoil and the binary peak, Fig. 2(b) shows the measured relative triply differential cross section (averaged over the spin directions of the primary beam).

Comparing the angular dependence of the asymmetry with the pertinent cross section, the intuitive physical picture described above is confirmed. Whereas in the recoil peak the spin-orbit interaction of the continuum electrons generate a distinct asymmetry up to 16%, the asymmetry in the binary peak is close to zero. This is, to our knowledge, the first direct evidence for the influence of spin-orbit coupling of the continuum electrons on the process of electron-impact ionization. (No evidence of continuum spin-orbit effects in excitation could be found in the experiment of Furst *et al.* [10].)

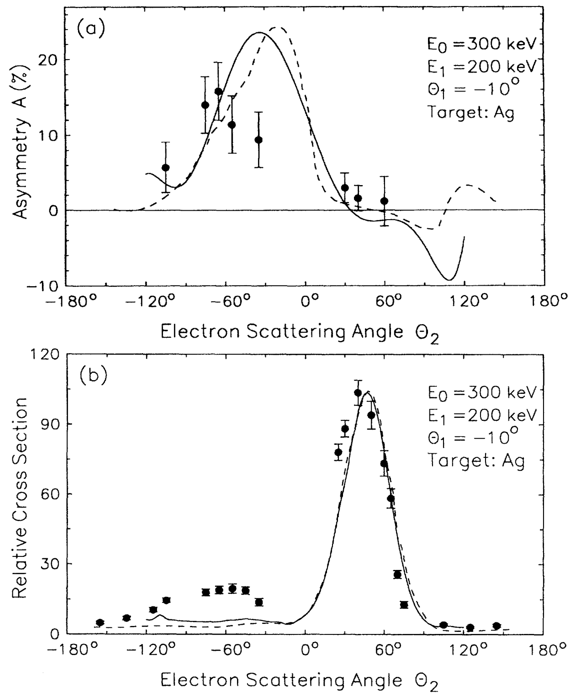

FIG. 2. (a) Spin up-down asymmetry A of the triply differential cross section for electron-impact ionization of the K shell of silver as a function of the scattering angle Θ_2 of the outgoing slow electrons of energy $E_2 = 74.5$ keV. The primary electron energy amounted to $E_0 = 300$ keV. The outgoing fast electrons of $E_1 = 200$ keV were observed at an angle of $\Theta_1 = -10°$. The error bars represent the standard deviations only; the systematic error of the asymmetry scale was estimated to be $\pm 2\%$. The dashed and solid lines are calculations of Jakubassa-Amundsen [7] and of Tenzer and Grün [8], respectively. (b) Measured (full circles) relative triply differential cross section averaged over the spin directions of the primary beam. The dashed and solid lines are calculations of Jakubassa-Amundsen [7] and of Tenzer and Grün [8], respectively, normalized to the measurement in the maximum of the binary peak.

The dashed and solid lines in Fig. 2(a) are theoretical predictions of Jakubassa-Amundsen [7] and of Tenzer and Grün [8], respectively. In both calculations the process is treated in lowest order perturbation theory. The designations, however, used by the authors differ as follows: Jakubassa-Amundsen [7] calls her calculation a first-order Coulomb Born approximation since it is a first-order treatment of the electron-electron interaction, whereas for the electron-nucleus interaction of the continuum electrons nonrelativistic Coulomb waves multiplied by a free Dirac spinor are used. Tenzer and Grün [8] call their calculation a second-order perturbation theory since in the expansion of the S matrix the leading term is of second order in the electromagnetic coupling constant. For the continuum electrons likewise nonrelativistic Coulomb waves multiplied by a free Dirac spinor are used. For the bound state of the atomic electron Jakubassa-Amundsen uses a semirelativistic Darwin function, whereas Tenzer and Grün use a hydrogenic $1s$ Dirac wave function. Exchange and spin-flip processes are accounted for in both calculations. The differences between the results of the two calculations are presumed to be partly due to numerical inaccuracies.

Qualitatively, both calculated curves of Fig. 2(a) follow the tendency of the measured asymmetry; quantitatively, however, strong discrepancies occur. The latter is not surprising if one compares [Fig. 2(b)] the measured relative triply differential cross sections with the calculations of Jakubassa-Amundsen [7] and of Tenzer and Grün [8] (normalized to the measurement in the maximum of the binary peak). The predicted ratio of the recoil to the binary peak intensities is too low. This is in accordance with the result of a former absolute measurement [9], where the recoil peak is strongly underestimated by the Coulomb Born approximation.

The theory, so far predicting the absolute cross section of asymmetric relativistic $(e, 2e)$ measurements best, is a relativistic distorted wave Born approximation [11,12]. Therefore calculations of the asymmetry according to this approximation are highly desirable. This approximation allows for elastic (Mott) scattering of the incident and outgoing electrons in the field of the atom. It would be interesting to analyze theoretically the contribution of the incoming and the fast and slow outgoing electrons to the spin asymmetry.

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