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LETTER TO THE EDITOR

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LETTER TO THE EDITOR

Observation of continuum spin–orbit coupling in L-shell ionization of gold by polarized relativistic electrons

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Abstract. The spin asymmetry associated with the ionization of the L shell of gold by 300 keV electrons polarized perpendicular to the scattering plane has been measured in an (e, 2e) coincidence experiment carried out in coplanar asymmetric geometry. The agreement with theoretical results obtained in the relativistic distorted wave Born approximation is favourable.

(e, 2e) experiments with polarized electrons represent an important step towards the ideal of a quantum mechanically complete analysis of the elementary process of electron impact ionization. The first studies of this type have delivered insights into the ratio of triplet- and singlet scattering ionization of the 2s electron of lithium (Baum *et al* 1992), demonstrated the importance of continuum spin–orbit coupling in the K-shell ionization of silver (Prinz *et al* 1995) and shown that the fine structure effect (Jones *et al* 1994) leads to sizeable spin effects in the ionization of the fine structure split magnetic sublevels of the 5p state of xenon (Guo *et al* 1996, Hanne 1996). These findings show that spin sensitive (e, 2e) experiments probe a number of different physical mechanisms and their interplay, that are difficult to discriminate otherwise: exchange scattering, spin–orbit coupling of both bound and continuum states, and orbital orientation and alignment.

It is currently a matter of debate to what extent relativistic effects have to be taken into account in the theoretical interpretation of the non-relativistic fine structure effect (Madison *et al* 1996). Therefore, it is quite natural to ask whether effects of the fine structure type do exist in systems where all energy scales are relativistic from the outset, so that it is clear that only fully relativistic theoretical models will be adequate for the interpretation of the experimental data. In this contribution, we will study the importance of continuum spin–orbit coupling in the ionization of the L shell of gold. Apart from being of considerable interest in its own right, such a study is an indispensable prerequisite for the investigation of the fine structure effect in a relativistic setting.

The experimental arrangement used in the present measurement has been described elsewhere (Prinz 1994, Prinz *et al* 1995), so only a brief outline of the setup and procedures will be given here. Polarized electrons were produced in a GaAsP source (Mergl *et al* 1991), deflected electrostatically through 90° to render the spin orientation perpendicular

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to the scattering plane, and accelerated to 300 keV kinetic energy using a high-voltage cascade generator. The resulting continuous electron beam with a degree of polarization P of 35–40% was directed onto a 50 μg cm^{-2} gold-foil target. The two outgoing electrons resulting from electron impact single ionization events were detected in coincidence using magnetic spectrometers in combination with plastic scintillator detectors. The quantities measured were the count rates $N_\pm$ of true coincidences for the two opposite orientations (plus or minus) of the beam polarization. In terms of these observables, the spin up–down asymmetry A is given by

$$A := \frac{1}{P}\frac{N_+ - N_-}{N_+ + N_-} = \frac{\mathrm{d}^3\sigma(+) - \mathrm{d}^3\sigma(-)}{\mathrm{d}^3\sigma(+) + \mathrm{d}^3\sigma(-)} \tag{1}$$

where $\mathrm{d}^3\sigma(\pm)$ is the triply differential cross section for a given incident electron spin orientation. Substantial sampling times ($\sim$ 200 h per data point) were required to obtain statistically significant results for the asymmetry A. The major source of systematic error is the uncertainty associated with the determination of P (less than 2%).

The experiment was carried out in coplanar asymmetric geometry. Fast outgoing electrons of 200 ± 5.7 keV kinetic energy were detected at $\Theta_1 = -10^\circ$, while the second detector sampled electrons of 86.9 ± 2.9 keV. The energy width of the detectors chosen represent a compromise between the necessities of separating the L shell from higher shells, and covering the ionization events from all magnetic substates of the L shell (the relevant binding energies are 14.3, 13.7, and 11.9 keV, respectively). Corresponding theoretical calculations were carried out using the relativistic distorted wave Born (DWBA) code described in Keller *et al* (1994, 1996), which includes exactly all spin–orbit couplings that occur in the pertinent first-order matrix elements. Triply differential cross sections were calculated for ionization of the individual magnetic sublevels and for the same energy of the fast outgoing electron, i.e. here the different level binding energies were balanced by different secondary electron kinetic energies. The results were added incoherently to give the subshell averaged cross sections and asymmetries sought. Tests using simpler theoretical models showed that the explicit convolution of theoretical data with the experimental energy and angle acceptance functions leads to results in complete agreement with those obtained from the above procedure.

In figure 1 we compare the experimental and theoretical relative triply differential cross section determined along with the asymmetries. All major features of the experimental data, notably the asymmetric shape of the main ('binary') maximum (which is due to the superposition of the binary maxima of the subshell ionization cross sections that take their maxima at different angles), the double-peak structure around $\Theta_2 = -60^\circ$ and the ratios of the peaks, are reasonably well reproduced by the calculation, indicating that the relativistic DWBA is an adequate starting point for the analysis of this experiment.

The results of the measurement of the spin asymmetry, (1), are depicted in figure 2. Comparison with figure 1 shows that both measured and calculated asymmetries are very small in the region of the main maximum, while larger spin effects are associated with the broad structure in the region $-120^\circ \leqslant \Theta_2 \leqslant -30^\circ$. Again the calculation reproduces the experimental data quite well. These results resemble closely those found for K-shell ionization of silver (Prinz *et al* 1995). The interpretation then proposed (and subsequently underpinned by theoretical analysis (Keller *et al* 1996)) pointed out that the main maximum is commonly associated with binary electron–electron collisions where the nucleus acts only as a spectator (hence the name 'binary peak'). In contrast, the region of the secondary structure can only be accessed if the nucleus takes up considerable momentum. This requires strong electron–

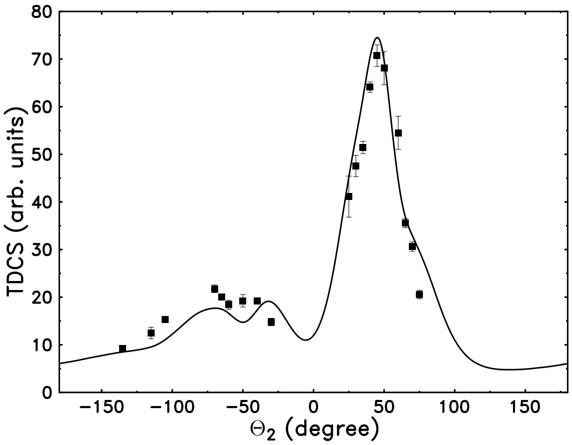

Figure 1. Relative triply differential cross section for electron impact ionization of the *L* shell of gold, as a function of the observation angle Θ_2 of the slow outgoing electron. Impact energy 300 keV, fast outgoing electron energy 200 keV, $\Theta_1 = -10°$. Symbols: experiment (error bars indicate statistical error), full curve: relativistic DWBA calculation, normalized to give best visual fit to the experimental data.

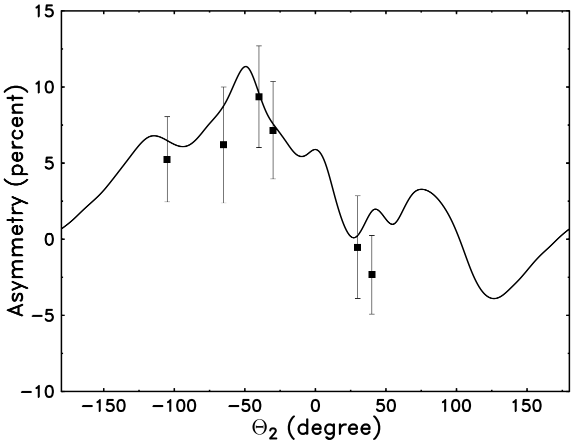

Figure 2. Spin up-down asymmetry (as given by equation (1)) of the triply differential cross section for the kinematics of figure 1. Symbols: experiment (error bars indicate statistical error), full curve: result of relativistic DWBA calculation, averaged over subshells.

nucleus interactions which lead to substantial spin–orbit coupling of the continuum electrons.

The same argument suggests itself in the present case. To confirm this interpretation, we compare the calculated total asymmetry with the corresponding results for the individual magnetic sublevels (figure 3). The numerical data give strong evidence that the subshell averaged asymmetry is dominated by the contribution of the $2s_{1/2}$ state, while the p state asymmetries appear to cancel out almost completely. In fact the large $2p_{1/2}$ and $2p_{3/2}$ state asymmetries are quite similar in shape except for an overall (negative) factor. As was observed earlier (Keller *et al* 1996) in the relativistic regime this pattern is characteristic for the presence of the fine structure

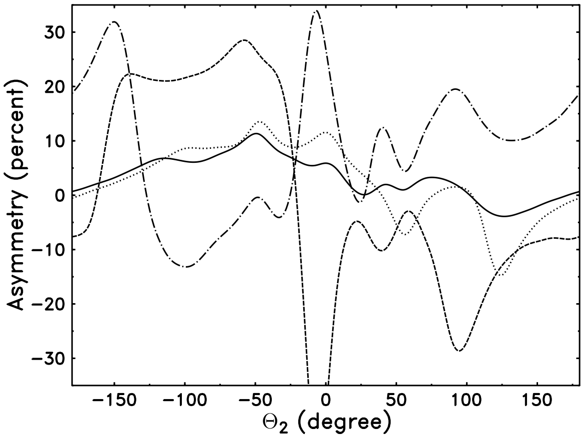

Figure 3. Results of relativistic DWBA calculations for spin up–down asymmetries for the kinematics of figure 1. Full curve: asymmetry, averaged over subshells, chain curve: asymmetry for $2p_{3/2}$ state ionization, broken curve: asymmetry for $2p_{1/2}$ state ionization, dotted curve: asymmetry for $2s_{1/2}$ state ionization.

effect, which indeed vanishes if the two levels are not discriminated in the experiment (Jones *et al* 1994). The apparent dominance of the $2s_{1/2}$ contribution in the subshell averaged asymmetry can then naturally be explained by invoking the above argument: in contrast to the p states, the wavefunction of this state is concentrated around the nucleus, so that, in a semiclassical picture, smaller impact parameters are relevant for the ionization process. Hence the continuum electron states which make dominant contributions to ionization of the $2s_{1/2}$ state are more strongly affected by spin–orbit coupling effects.

These results have several consequences for both theory and experiment. The observation that the relativistic DWBA approach adequately describes spin–orbit coupling in the elementary process of L-shell ionization suggests the application of this model to the non-relativistic problem studied by Guo *et al* (1996) and Hanne (1996) in order to help to clarify the issue of relativistic effects in these experiments. In fact, the present data suggest that in the binary region, continuum spin–orbit coupling plays no significant role in L shell ionization. Therefore, it may well be possible to demonstrate the fine structure effect in a relativistic (e, 2e) experiment. Work in these directions is in progress.

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