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Spin asymmetry in electron impact ionization of caesium

G Baum, B Granitza†, L Grau, B Leuer, W Raith, K Rott, M Tondera and B Witthuhn

Fakultät für Physik, Universität Bielefeld, D-4800 Bielefeld 1, Federal Republic of Germany

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Abstract. We measured the total ionization asymmetry A in dependence on the incident electron energy E. Here 'total' refers to integration over all emission angles and energy partitions of the outgoing electrons. From a threshold value of $A = 0.125$ the $A(E)$ curve rises smoothly toward a broad maximum of $A_{max} = 0.31$ at $E_{max} = 8.3$ eV. The fall-off towards higher energies is quite similar to that of the other one-electron atoms. However, it shows a structure which can be explained by contributions from autoionizing P states. Bartschat has made a theoretical estimate of $A(E)$ for various atoms. At low energies the agreement with our data is satisfactory, at higher energies the experimental A values are considerably smaller than the theoretical ones. In the threshold region measurements were performed with small electron energy width (0.1 eV). No structure in the $A(E)$ curve was found. The slope at threshold was determined as $dA/dE = (0.136 \pm 0.005)\ eV^{-1}$.

1. Introduction

The spin asymmetry A is determined according to

$$A = \frac{1}{P_e P_a} \frac{N^{\downarrow\uparrow} - N^{\uparrow\uparrow}}{N^{\downarrow\uparrow} + N^{\uparrow\uparrow}} \tag{1}$$

where $N^{\downarrow\uparrow}$ and $N^{\uparrow\uparrow}$ are the ion signals obtained with antiparallel and parallel beam polarizations, respectively, in the two beams. P_e is the electron polarization and P_a is the atomic polarization referring to the spin-polarized valence electron of the Cs atom. The nuclear polarization of the Cs atom is irrelevant here.

Up to now spin-asymmetry measurements in total ionization have been made for the one-electron atoms H, Li, Na, K and the two-electron atom He(2^3S) (references in table 1). Common to all results is

$$A \geq 0 \tag{2}$$

at all energies. The investigated atoms differ distinctly in their $A(E)$ curves: The slope of $A(E)$ at threshold is nearly zero for Li, Na and K, slightly positive for He(2^3S), significantly positive for H; only for K is the shape of $A(E)$ irregular exhibiting a minimum between threshold and maximum. Therefore, one reason for studying Cs was to find out whether a trend exists which leads to very different $A(E)$ curves for the heavy alkali atoms.

† Present address: School of Physical Sciences, The Flinders University of South Australia, Bedford Park SA 5042, Australia.

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Table 1. Comparison of A for different atoms.

Atom	A at E_1	A_{max} at E_{max}	E_{max}/E_1
H[a]	0.43 ± 0.04	0.49 ± 0.04	1.26
He(2^3S)[b]	0.34 ± 0.03	0.42 ± 0.01	1.54
Li[c]	0.43 ± 0.01	0.49 ± 0.01	1.77
Na[c]	0.45 ± 0.03	0.46 ± 0.02	1.55
K[c]	0.25 ± 0.02	0.28 ± 0.01	3.46
Cs[d]	0.13 ± 0.01	0.31 ± 0.01	2.26

[a] Fletcher *et al* (1985).
[b] Baum *et al* (1989).
[c] Baum *et al* (1985).
[d] This work.

2. Experiment

In a crossed-beam arrangement (figure 1) we intersected a polarized electron beam from a GaAs source with a polarized Cs atomic beam. The caesium atomic beam had a spin polarization close to unity and was produced by employing a recirculating oven and optical pumping with two laser diodes (Baum *et al* 1991).

The electron current in the interaction region was typically 0.1 μA, the electron polarization $P_e \approx 0.3$. For the first measurements extended over a wide energy range, the energy width of the electron beam, emitted from the cathode with $\Delta E \approx 0.45$ eV, was not reduced by the 180° spherical monochromator. Later, for the measurements in the threshold region, the monochromator was tuned to reduce the energy width to $\Delta E \approx 0.1$ eV. This value was calculated from the voltage settings and is consistent with results of retarding-potential measurements.

The electron polarization was determined with a small-size retarding-field Mott polarimeter (Rott 1991). The polarimeter was constructed by slightly modifying a

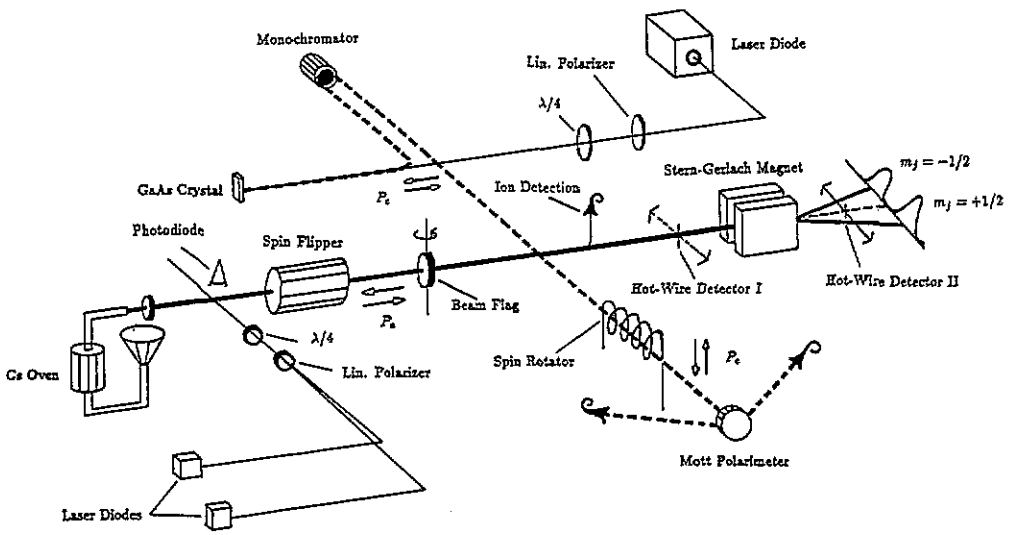

Figure 1. Experimental arrangement.

design of Gellrich and Kessler (1991). By using a thick thorium foil we obtained an analysing power of $S_{\text{eff}} = 0.4$ at 45 keV electron scattering energy.

The atomic beam had a density of 10^9 atoms/cm^3 and a diameter of about 0.5 cm in the interaction region. The atomic polarization P_a was measured with an analysing Stern–Gerlach magnet, as described earlier (Baum *et al* 1991), yielding values of $P_a > 0.9$. To guide the atomic spins, a magnetic field of about 5×10^{-6} T, collinear with the atomic beam, was present in the interaction region.

The produced ions were extracted from the interaction region with a small electric field of about 0.5 V cm^{-1} oriented in the atomic beam direction. After passage through a grid the ions were deflected in a cylindrical condenser and directed towards a Channeltron multiplier for detection. On the first plateau of the total ionization cross section ($E \approx 10$ eV) the ion counting rate was typically 5000 s^{-1}. For obtaining the spin asymmetry according to equation (1) ion rates were observed at each energy with parallel and antiparallel spin orientations of the two beams. The orientations were changed by using the spin flipper in the atomic beam line. Measurements were also made with different settings of the quarter-wave plates which determine the circular light polarization for the electron source, as well as those for the optical pumping of the atomic beam. Above 20 eV background events contributed appreciably to the rate. They were measured separately (atomic beam flag closed) and subtracted accordingly. The data accumulation time for one data point was typically 600 to 1000 s.

3. Results

Figure 2 shows measured A values over a wide range of E/E_I where E_I is the ionization energy. In the threshold region ($1 < E/E_I < 2$) we plotted every third of our closely

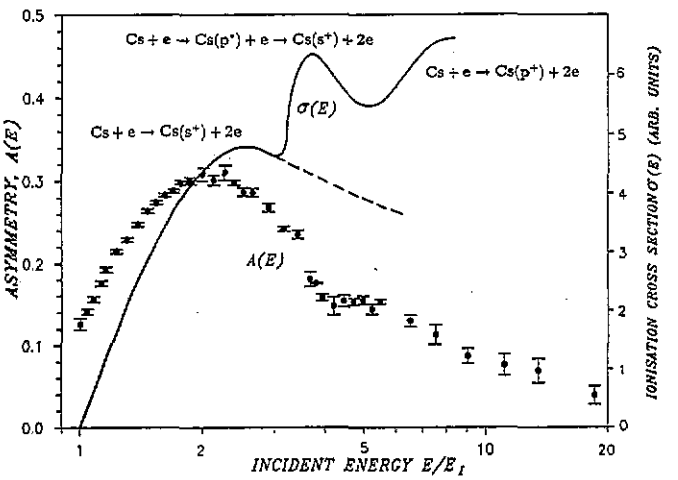

Figure 2. Ionization asymmetry A (our data points/left scale) and ionization cross section σ (full curve/right scale) in their dependence on the incident-electron energy E (in units of E_I(Cs) = 3.89 eV). The cross section information was taken from Zapasochnyi and Aleksakhin (1969). The broken curve indicates the part of the cross section which is due to direct s electron ionization. The superscripts have the following meaning: *, electron excitation; +, electron vacancy.

spaced high-resolution data points which are discussed in detail later on. The fall-off on the high-energy side of the maximum has two causes. Firstly, this shows the expected general behaviour of $A(E)$ for the ionization of the polarized s electrons. Secondly, events from the ionization of the unpolarized p electrons, which sets in at about 17 eV, also contribute to the fall-off. Furthermore, around 15 eV autoionization from excited P states causes a peak in the cross section curve (cf figure 2) and is thought to be responsible for the shoulder in the $A(E)$ curve.

There are no theoretical predictions for $A(E)$ of Cs available yet. In table 1 we list the values of the asymmetry at threshold and at the maximum for all the atoms studied thus far. Only for He(2^3S) and Cs do the threshold values lie substantially below the maximum.

The value of A is directly related to the ratio r of singlet to triplet cross section by

$$\sigma^{\uparrow\uparrow}=\sigma_T \qquad \sigma^{\downarrow\uparrow}=\tfrac{1}{2}\sigma_S+\tfrac{1}{2}\sigma_T$$

$$A=\frac{\sigma_S-\sigma_T}{\sigma_S+3\sigma_T} \qquad r=\frac{\sigma_S}{\sigma_T}=\frac{1+3A}{1-A}.$$

Consequently, $A=1$ corresponds to pure singlet scattering and $A=-\frac{1}{3}$ to pure triplet scattering. The observed threshold value of $A=0.13$ leads to $r=1.60$, giving evidence for a strong triplet component right at threshold. The positive slope of $A(E)$ near threshold is interesting as it shows a decrease of triplet scattering with increasing energy. This behaviour was also observed in He(2^3S) (Baum *et al* 1989) and discussed in more detail there. The distorted-wave Born approximation (DWBA) of Bartschat (1990) for He(2^3S) gives a positive slope of $A(E)$ near threshold. However, from the calculation one cannot extract which mechanisms are responsible for this behaviour (Bartschat 1992). For Cs the region of positive slope is quite extended in energy (3 eV).

In figure 3 we show Bartschat's calculations for Li and K. Since these and also his results for He(2^3S) and Na all lie very close together, it can be expected that the same 'maximum interference' distorted-wave Born approximation (DWBA) would yield a

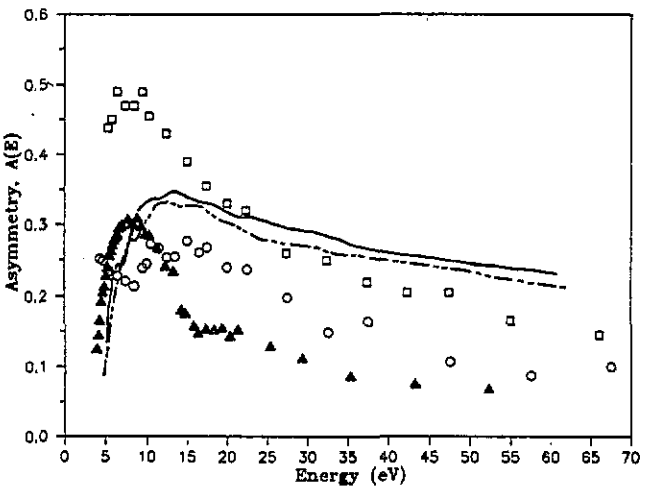

Figure 3. Ionization asymmetry A against electron energy E (linear scale). The upper curve gives the theoretical results of Bartschat (1990) for Li, the lower curve, for K. The symbols refer to experimental results: Li, open squares; K, triangles; Cs, full triangles (Baum *et al* 1985 for Li and K, this work for Cs).

similar $A(E)$ curve for Cs, not taking spin-orbit coupling and autoionization effects into account. Figure 3 also shows the experimental results for Li, K and Cs. For Li (as well as for H, Na and He(^{3}S), not shown in figure 3) the experimental A-values at threshold and around the maximum of $A(E)$ are significantly higher than the theoretical results and the slope of the fall-off towards higher energies is steeper. For K, the experimental data show an irregular energy dependence, whereas the shape of the $A(E)$ curve for Cs does not follow this trend and is more similar to those of the other atoms studied. Since for Cs the p-electron ionization contributes on the high-energy side of the maximum, a more rapid decrease of $A(E)$ than predicted by theory is not surprising.

The $A(E)$ data obtained with $\Delta E \approx 0.1$ eV are shown in figure 4. The data points lie on a smooth curve. They do not exhibit 'undulations' as predicted by Temkin (1966, 1982) and possibly seen in $A(E)$ for atomic hydrogen (Guo *et al* 1990). Kelley *et al* (1983) performed high-resolution measurements on Na and did not see any structure either.

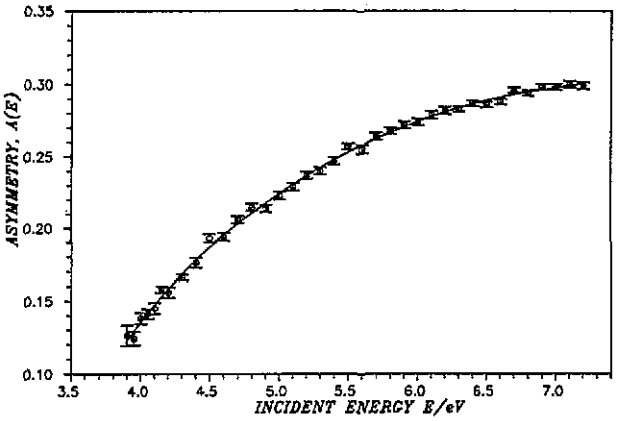

Figure 4. Measurements of $A(E)$ near threshold with improved energy resolution. The full curve is the best fit described in the text.

We searched for the presence of non-statistical structures in the data by first fitting the asymmetry measurements with a six-parameter polynomial in powers of the incident energy. The resulting reduced chi-square, 1.17 for 31 degrees of freedom (confidence level 23% compared to a norm of 50%), while slightly short of the ideal, is nonetheless sufficient for our purposes. We then calculated the parameter d of the Durbin–Watson statistics (Durbin and Watson 1950, 1951), according to the prescription $d = \Sigma_{i=1}^{N} (e_i - e_{i-1})^2 / \Sigma_{i=1}^{N} e_i^2$, where e_i is the normalized residual, i is the order parameter and $N = 37$ is the number of data points. The resulting value of $d = 2.48$ is so much larger than the upper limit of 1.53 for 5% significance, that we can safely rule out any non-random ordering of the residuals and hence any presence of structure at the statistical level of sensitivity of the experiment.

From the data of figure 4 we determined the slope of $A(E)$ at threshold as

$$\left(\frac{dA}{dE}\right)_{E=E_i} = (0.136 \pm 0.005)\ \text{eV}^{-1}.$$

This might be of interest for the theory of threshold behaviour which is not yet available for Cs.

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References

Bartschat K 1990 *J. Phys. B: At. Mol. Opt. Phys.* **23** 981
—— 1992 Private communication
Baum G, Fink M, Raith W, Steidl H and Taborski J 1989 *Phys. Rev.* A **40** 6734
Baum G, Granitza B, Hesse S, Leuer B, Raith W, Rott K, Tondera M and Witthuhn B 1991 *Z. Phys.* D **22** 431
Baum G, Moede M, Raith W and Schröder W 1985 *J. Phys. B: At. Mol. Phys.* **18** 531
Durbin J and Watson G S 1950 *Biometrika* 37 409
—— 1951 *Biometrika* **38** 159
Fletcher G D, Alguard M J, Gay T J, Hughes V W, Wainwright P F, Lubell M S and Raith W 1985 *Phys. Rev.* A **31** 2854
Gellrich A and Kessler J 1991 *Phys. Rev.* A **43** 204
Guo X Q, Crowe D M, Lubell M S, Tang F C, Vasilakis K, Slevin J and Eminyan M 1990 *Phys. Rev. Lett.* **65** 1857
Johnson J 1972 *Econometric Methods* 2nd edn (New York: McGraw-Hill)
Kelley M H, Rogers W T, Celotta R I and Mielczarek S R 1983 *Phys. Rev. Lett.* **51** 2191
Rott K 1991 *Diplomarbeit* Universität Bielefeld
Temkin A 1966 *Phys. Rev. Lett.* **16** 835
—— 1982 *Phys. Rev. Lett.* **49** 365
Zapesochnyi I P and Alekasakhin I S 1969 *Sov. Phys.-JETP* **28** 41-5