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Polarized electron-impact ionization of metastable helium

G. Baum, M. Fink,* W. Raith, H. Steidl, and J. Taborski†

Fakultät für Physik, Universität Bielefeld, Postfach 8640, Universitätsstrasse 25,
D-4800 Bielefeld, Federal Republic of Germany

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The singlet (σ_s) and triplet (σ_t) parts of the total ionization cross section were determined in the energy range from threshold to five times the threshold value with a crossed-beam arrangement of polarized electrons and spin-polarized He(2^3S) atoms. The measured spin asymmetry, $A_I=(\sigma_s-\sigma_t)/(\sigma_s+3\sigma_t)$, is compared with results for the lithium atom. Both asymmetries are quite similar. Comparison with a distorted-wave Born approximation shows strong disagreement in the vicinity of the threshold.

The spin dependence of integrated electron-impact ionization cross sections has been studied experimentally in the energy range from threshold (E_I) to about ten times the threshold value. Up to now different groups investigated the following atoms: H,[1-3] Li,[4,5] Na,[5-7] and K.[5,8] The results show that spin effects are sizable and that the triplet contribution is suppressed but is by no means negligible. The value of the asymmetry at threshold, especially that obtained from an experiment with high-energy resolution, has provided clear evidence that at threshold and close to its higher partial waves, in addition to the ^1S_e wave, determine the cross section.[4] This new insight gave rise to several theoretical treatments of the spin and orbital angular momentum behavior near threshold.[9-11] Predicted asymmetry oscillations near threshold[12] have not been found experimentally.[7] Unpolarized triple differential measurements on He ground-state atoms near threshold[13] were analyzed for their singlet and triplet partial wave content up to waves with $L=2$.[13,14] The analysis is based on models of threshold behavior and yields information on triplet contributions for the special geometric configuration of oppositely escaping electrons. No triplet contribution is expected for events where the two electrons move out symmetrically.

An *ab initio* theoretical treatment of the ionization process at low energies is a formidable problem. Progress in this field can only be made by extensive interaction between theory and experiment. In order to investigate the two-electron atom He, we looked at spin effects in ionization of the metastable triplet state (2^3S) for which the atomic electrons, the valence electron as well as the core electron, can be polarized to a high degree. The electron-impact ionization of atoms is a process whose energy dependence near threshold is dominated by the three-particle Coulomb interaction in the outgoing channel, the energy variation of the electron-atom interaction in the incoming channel being less important. The threshold ionization of metastable helium is related to that of ground-state helium for incident electrons of correspondingly larger energy which lead to the same excess energy in the two-electron escape. Our polarization experiment with He(2^3S) can be viewed as a way to study the ionization process for outgoing triplet two-electron wave functions which in the case of electron impact on ground-state helium atoms cannot be prepared.

He$^+$ ions were observed as a measure of the ionization rates $N\uparrow\downarrow$ and $N\uparrow\uparrow$ for antiparallel and parallel orientation of the two-beam polarizations, respectively, in a crossed-beam arrangement. The polarizations of the electron beam P_e and of the atomic beam P_a were measured and used to determine the spin asymmetry A_I from

$$A_I=\frac{1}{P_eP_a}\frac{N\uparrow\downarrow-N\uparrow\uparrow}{N\uparrow\downarrow+N\uparrow\uparrow}.$$

This asymmetry relates to the singlet and triplet total ionization cross sections with $A_I=(\sigma_s-\sigma_t)/(\sigma_s+3\sigma_t)$. Using the known cross section for unpolarized particles, $\sigma=\frac{1}{4}\sigma_s+\frac{3}{4}\sigma_t$, both σ_s and σ_t can be determined as the following:

$$\sigma_s=\sigma(1+3A_I),$$

$$\sigma_t=\sigma(1-A_I).$$

Pure singlet ionization corresponds to $A_I=+1$, pure triplet to $A_I=-\frac{1}{3}$.

The apparatus used to produce the polarized metastable He(2^3S) beam has recently been described in detail.[15] In short, a dc discharge produces the metastable atoms, which are collimated by a skimmer and then pass through a permanent magnetic sextupole field of 10-cm length on their way to the interaction region at a distance of 103 cm from the source. The pole-tip radius of 0.25 cm and the pole-tip field of 0.8 T were chosen to give a focal point at infinity for those $m_s=+1$ state atoms which have a velocity of 2×10^5 cm/s. All atoms with $m_s=-1$ are deflected away from the axis and do not pass through the collision region. Atoms with $m_s=0$ are not focused by the magnet and contribute with only a small solid angle to the intensity. In addition, they can be preferentially blocked by the insertion of a central stop with a 0.15-cm diameter at the magnet exit. The beam polarization P_a was measured with an analyzing Stern-Gerlach magnet located beyond the interaction region and was found to be 0.90 ± 0.02. Any possible contamination of the beam by metastable singlet atoms is included in this value. With the central stop in place a flux of about 5×10^{13} ground-state atoms/s existed in the polarized beam, about 100 times more than the flux of metastables. Fortunately, these ground-state

He atoms could be ignored as they did not interfere in the present experiment. However, we had to limit our investigation to incident electron energies below the ground-state ionization energy of 24.6 eV. The measured value of the atomic beam polarization includes the slight polarization reduction due to effects of He-He* collisions.[15]

The source was very stable in its operation with regard to the above-stated intensity and polarization values. Over months of operation the intensity dropped by about a factor of 5 due to degradation of parts in the discharge region. In conjunction with this, the polarization also dropped gradually to 0.84. During data acquisitions the polarization of the beam was frequently reversed with a spin flipper.[15] This method guarantees that systematic errors in the asymmetry measurement will be small.

The polarized electron beam is produced by photoemission from a (100) surface of a GaAsP crystal using circularly polarized light of a 30-mW He-Ne laser. The setup for the electron beam and the polarimeter is very similar to one described previously.[16] The beam polarization is reversed occasionally during data taking. The polarization is measured behind the interaction region by 100-keV Mott scattering. The value of $P_e = 0.38$ was stable within ± 0.02 for the crystal used during measurements. The electron beam intensity was in the range of 0.4 to 1 μA.

To guide the atomic spins, a magnetic field of 10^{-5} T, collinear with the atomic beam, was present in the interaction region. The He ions produced were extracted with a small electric field of about 2 V/cm, oriented perpendicular to the plane containing the two beams. The ions traversed an ion-optical region and were directed towards the entrance collimator of a quadrupole mass analyzer, set to transmit the He^+ ions which were then detected by a channel electron multiplier. This mass analyzer was essential in order to reduce the high background of ions originating from Penning ionization of residual gas atoms at a pressure of 5×10^{-9} Torr. Furthermore, Rydberg atoms in the metastable beam had to be eliminated to reduce the background and to obtain a clean signature for the ionization process to be studied. For this a strong electric field of 9 kV/cm was installed on the atomic beam line, ≈ 20 cm in front of the interaction region. The remaining background at a rate of about 1 s^{-1} is being attributed to He*-He* collisions within the atomic beam.[15] At the chosen energy and polarization direction of the incident electrons, data were accumulated in sequential runs, each consisting of ten miniruns in the following order: $B\uparrow$, $C\uparrow$, $C\downarrow$, $C\downarrow$, $C\uparrow$, $B\downarrow$, $C\downarrow$, $C\uparrow$, $C\uparrow$, and $C\downarrow$, where B symbolizes a background measurement, C symbolizes the counts from signal plus background, and the arrows indicate the atomic beam polarization direction with regard to the guiding magnetic field in the collision region. Background measurements were made by dumping the electron beam in an upstream section of the beam pipe connecting the electron source and collision chambers. Count rates of type C were 50 s^{-1} or less. The energy scale was calibrated by observing the onset of ionization of He($2\,^3S$) atoms at $E_I = 4.8$ eV.

The measured asymmetry for He($2\,^3S$) as a function of the incident electron energy is shown in Fig. 1. The error bars indicate the statistical error; the energy width is ΔE (full width at half maximum) $= 0.3$ eV. The asymmetry is positive throughout the energy range investigated, indicating dominance of singlet over triplet processes. The maximum of 0.4, occurring at 7 eV, corresponds to a ratio of triplet to singlet cross section of $r = 0.27$. The clear decrease of the asymmetry and therefore increase of triplet processes in going towards threshold is interesting as it implies an increasing contribution from partial waves with $L > 0$. According to the analyses[9-11] of the structure of two-electron wave functions at threshold, the following waves should be present strongly: $^1S_e, {}^3P_0, {}^1D_e, {}^3F_0$, etc. These states are all expected to obey the same threshold law. Other states are suppressed in the threshold region. Therefore the growing importance of triplet states cannot be seen as a feature of the two-electron escape process. As all contributing states follow the same threshold law the asymmetry should be energy independent. In order to explain the observed decrease of $A_I(E)$ one has to assume an energy dependence of the initial conditions prepared in the inner collision zone. This provides dynamical information on the ionization process.

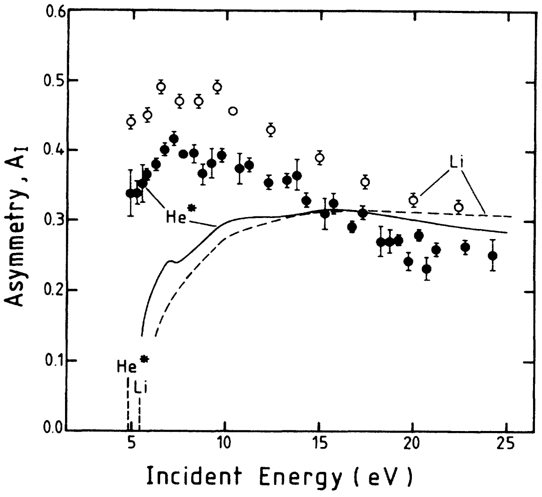

FIG. 1. The energy dependence of the ionization asymmetry A_I. The filled data points are the results of this experiment, and the open circles are measurements for the Li atom (Ref. 5). Both are shown with one-standard-deviation error bars. The full curve is the theoretical result for metastable He in the $2\,^3S$ state (He*), and the dashed curve is for Li. Both results are from the DWBA treatment of Bartschat (Ref. 17). The respective thresholds are indicated.

The analysis of electron-electron angular correlations in the near-threshold region by Selles, Huetz, and Mazeau[13] gives a very small triplet contribution for events where the two electrons move out in opposite directions. This small value is not in contradiction to our results because we study total ionization which includes all scattering angles and energy partitions.

There is only one calculation for comparison with our data (Fig. 1). Bartschat[17] used a distorted-wave Born-approximation (DWBA) assuming maximum interference (parameter $\alpha = 1$). The severe discrepancy in the threshold region clearly indicates that interaction effects, for instance electron correlations in the exit channels, have to be treated more thoroughly. The discrepancies cannot be explained by the inadequacy of the approximation for the α parameter since the maximum of the asymmetry within the framework of the theoretical method lies already considerably below the data points and would become even smaller for $\alpha < 1$. At higher energies the agreement between data and calculation is more satisfactory. Qualitatively, the slope of $A_I(E)$ near threshold is also exhibited by the theory.

In Fig. 1 a comparison with the experimental values for the lithium atom[5] is also shown. Lithium is, in some of its properties, very similar to He(2^3S). Throughout the measured energy range, the Li asymmetry values are higher by 0.05 to 0.07. Besides the statistical errors, there are normalization uncertainties in the electron and atomic beam polarizations. As the same electron polarimeter was used for the Li as well as the He(2^3S) measurements, only the uncertainties for the atomic beam polarizations enter in the comparison. By assuming uncorrelated errors the uncertainty is ± 0.05. Thus the two curves could be considered to be equal, but just barely within the margins of their error bars. For Li there is also an indication of a decrease of $A_I(E)$ towards threshold. The result of the DWBA calculation for Li is very much like the one for He(2^3S). The calculations reproduce the measured total ionization cross sections for the two atoms quite well.[18]

By using the measured asymmetry and the unpolarized cross section measured by Dixon, Harrison, and Smith,[19] we can extract the singlet and triplet cross sections, $\sigma_s = \sigma(1+3A_I)$ and $\sigma_t = \sigma(1-A_I)$. These cross sections are shown in Fig. 2. Whereas σ_s drops noticeably at higher energies, σ_t stays nearly constant in this range. As discussed above the two partial cross sections cannot have the same energy dependence near threshold.

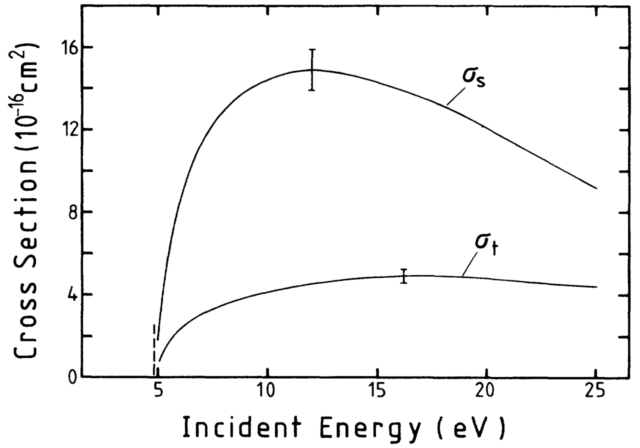

FIG. 2. The singlet (σ_s) and triplet (σ_t) part of the total cross section (σ) for electron impact ionization of He(2^3S). Typical sizes of statistical errors arising from the combination of the A_I (this experiment) and the σ measurements (Ref. 19) are indicated.

In conclusion one can say that the asymmetry of He(2^3S) is similar to those of the light alkali metals and hydrogen. The unpaired and also spin-polarized $1s$ electron of the metastable atom does not seem to have much influence on the spin behavior of the ionization process. There is, however, a marked decrease of A_I over a 2.5 eV region in going towards threshold. This can be interpreted as an increased contribution of triplet ionization which involves total orbital angular momenta of $L > 0$. Comparison of our data with a DWBA calculation points to the inadequacy of this method in the region from threshold to about three times the threshold energy. DWBA treatments, assuming maximum interference, have often been used to calculate unpolarized total ionization cross sections of atoms.

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[*] Permanent address: Department of Physics, University of Texas, Austin, TX 78712.

[†] Present address: Physikalisches Institut, Universität Stuttgart, D-7000 Stuttgart 80, Germany.

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