Experimental confirmation of left-right asymmetry in photoionization

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\textbf{Abstract.} Single-photon single ionization of noble gas atoms by linearly polarized synchrotron radiation has been studied by employing angle- and energy-resolved photoelectron spectroscopy. Left-right asymmetry parameters were measured for photoelectrons ejected from the outer s-shells of noble gas atoms He, Ne, Ar and Xe using a linearly polarized photon beam. A non-zero left-right asymmetry was observed relative to the photon propagation direction.

1. Introduction
Symmetries play a crucial role in physics. In quantum mechanics atomic transitions have space inversion symmetry. The electromagnetic interactions among the atomic electrons and the nucleus as well as the electromagnetic interactions between the ionizing and exciting particles or quanta and the constituents of the atom are assumed to conserve parity. Consequently, the angular distribution of the emitted particles or quanta should display left-right symmetry.

For a linearly polarized photon beam a right-handed XYZ coordinate system (Fig. 1) can be defined in the standard way \cite{1, 2, 3}: The photon momentum vector $\vec{k}$ points to the direction of the X-axis and the photon polarization vector $\vec{P}$ is aligned along the Z-axis. The Y-axis is perpendicular to the XZ-plane. The electric vector $\vec{E}(t)$ of the photon oscillates in the XZ-plane. The polar angle $\theta$ is the polar angle between the photoelectron momentum vector $\vec{p}_{phe}$ and the photon polarization vector $\vec{P}$, while $\phi$ is the azimuthal angle between $\vec{k}$ and the projection of the photoelectron momentum vector onto the XY-plane. The polar angle $\theta$ is measured from the positive Z-axis in the counterclockwise direction as usual. We arbitrarily label the $\theta = 0^\circ - 90^\circ$ and $\theta = 270^\circ - 360^\circ$ angular range as right hand side (R) and the $\theta = 90^\circ - 270^\circ$ angular range as left hand side (L). Using the above coordinate system for photoelectron emission the left-right asymmetry parameter $A_{LR}$ may be defined as \cite{1}:

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R},$$

where $\sigma_L$ and $\sigma_R$ are the cross sections for photoelectron emission to the left (L) and to the right (R) sides, respectively.
Recently, a left-right asymmetry (LRA) was observed in the double differential cross sections of the outer s-shell photoelectrons ionized by linearly polarized synchrotron radiation [1]. The investigated angular ranges for photoelectron emission were $\phi = 0 \pm 1.7^\circ$, $\theta = 0^\circ - 360^\circ$. For the interpretation of the experimental data two possible explanations were suggested in Ref. [1]: (a) the left-right asymmetry is the result of the electroweak interaction among the nucleons and the atomic electrons mediated by the exchange of $Z_0$ bosons; (b) left-right asymmetry is introduced by photon wave packets of only a few half cycles duration with an inherent left-right asymmetry in the number of oscillations of the electric-field vector $\vec{E}(t)$.

Explanation (a) addresses an interaction that is known to violate parity conservation and that can also produce a left-right asymmetry in photoexcitation/ionization [4]. In Ref. [1] parity violating transition amplitudes were calculated for the electron-nucleon weak interaction within the framework of the Standard Model (SM) and the derived asymmetry parameters were compared with the experimental data. The atomic mass dependence and the order of magnitude of the experimental non-zero left-right asymmetry parameters do not agree at all with the theoretical predictions. This indicates that the observed left-right asymmetry cannot be interpreted as resulting from the electroweak interaction.

Explanation (b) is based on observations of left-right asymmetry associated with the interactions of ultra short laser pulses [5]. Ultimately, half cycle light pulses with an unidirectional electric field can be expected to produce maximum asymmetry of the angular distribution of photoelectrons released. If the photon wave packet is extremely short also in the case of synchrotron radiation and the phase difference between the carrier-envelope and the VUV photons is constant, left-right asymmetry (or virtual parity violation) may exist similar to the phenomenon observed by Paulus et al [5]. However, such time structure of photon wave packets emitted by a synchrotron light source has not been observed so far.

The aim of the present work was to check the observation reported in Ref. [1] under different experimental conditions. In order to study the possible effect of the photon wave packets in different synchrotrons on the observed left-right asymmetry parameters, the present measurements were carried out at the DORIS III synchrotron light source (HASYLAB, Hamburg, Germany), while the previous experiments [1] were done at the third generation MAX-II synchrotron (MAX-lab, Lund, Sweden). In the recent work the He 1s, Ne 2s, Ar 3s and Xe 5s outer shells were ionized using linearly polarized synchrotron radiation.
2. Experiment

The present experiment was carried out using the beam line BW3 of the third generation DORIS III storage ring at HASYLAB, Hamburg, Germany [6]. The operating energy of this synchrotron is 4.45 GeV, almost three times higher than that of MAX-II (1.5 GeV) [7]. In DORIS III both electrons and positrons can be used for creating synchrotron radiation while MAX-II can use only electrons. During the present experiment positrons were used in DORIS III. The photon source of the beam line BW3 is a combination of 2 undulators. At the beam line I411 of the MAX-II synchrotron, where the previous measurements [1] were conducted, an undulator is used as well.

The photoelectrons released from outer s-shells of rare gas atoms were analyzed with the ESA-22G electrostatic electron spectrometer. This analyzer is a newly built ESA-22 type electron spectrometer [8] (Fig. 2) of the Institute for Atomic and Molecular Physics of the Justus-Liebig University Giessen (Giessen, Germany). It consists of a spherical and a cylindrical mirror. The spherical part focuses the electrons from the scattering plane to the entrance slit of the cylindrical mirror which then performs the energy analysis of the electrons. A spherical deceleration lens is placed around the source volume to improve the energy resolution of the system. The emission angles of the electrons are conserved from the target to the detectors due to the applied radial electrostatic field. The analyzer and the interaction region are shielded from the Earth’s magnetic field by three layers of µ-metal sheets. The residual magnetic field in the scattering plane and in the analyzer is less than 500 nT. A detailed description of the ESA-22 type analyzer is presented in Ref. [8].

![Figure 2. Schematic cross section of an ESA-22 type electron spectrometer.](image)

The photoelectrons were detected with 22 channeltrons at \( \phi = 0^\circ \) azimuthal angle and at 22 polar angles in 15° steps between 0° and 360° (except 90° and 270°) relative to the photon polarization vector (in the XZ plane in Fig. 1). The acceptance angles of each channeltron were \( \Delta \theta = \pm 5^\circ \) and \( \Delta \phi = \pm 1.7^\circ \). An important difference comparing to the previous experiments [1] is that here two additional observation angles were used, i.e., 0° and 180° with respect to the polarization vector. Another difference is a different geometry of the gas target. In the ESA-22G electron spectrometer a simple tube was used as a gas nozzle and the gas was flowing upwards while in the ESA-22L analyzer [8] employed in the earlier experiment a channelplate was used as a gas nozzle and the gas was directed downwards. In the latter case a much more directed gas flow is to be expected. In addition, in the present experiment a new analyzer control and a faster signal processing system as well as a new software were used to control the spectrometer and to collect the data. The main working principles and dimensions are the same for both spectrometers.
Every ESA-22 type electron spectrometer is capable of measuring the entire angular range of emitted electrons simultaneously. Any instabilities in the density of the target atoms, in the photon flux, in the high voltage power supplies of the spectrometer and detectors and in the current of the photodiode produce the same effect at all angles. Changes in the experimental conditions can modify the intensities or the line shapes in the different angular channels simultaneously however the relative values remain unaffected.

The left-right-asymmetry parameters were determined experimentally for the photoionization of the He 1s, Ne 2s, Ar 3s and Xe 5s shells using linearly polarized synchrotron radiation at 203.3 eV photoelectron energy in the XZ-plane (see Fig. 1) perpendicular to the spectrometer axis (the source size is $\pm 0.85$ mm perpendicular to the XZ-plane). The corresponding photon energy range was 226.7-256.3 eV. The photon energies were chosen such that photoelectrons ejected from the outer s-shells were collected at the same kinetic energy where also the Auger electrons appear. Thereby, identical conditions for the measurements of Auger electrons and photoelectrons could be ensured. The energy and angular distributions of the Auger- and photoelectrons were measured at 80 eV pass energy and the energy resolution of the analyzer was about 160 meV full width at half maximum (FWHM). For He 1s and Ne 2s shells a 500 $\mu$m monochromator slit size (corresponding to a bandwidth of $\approx 400$ meV) and for Ar 3s and Xe 5s shells a slit size of 180 $\mu$m (corresponding to a bandwidth of $\approx 130$ meV) were used. This allowed us (together with the high-resolution of the spectrometer) to separate the satellite lines from the photolines.

![Figure 3](image_url)

**Figure 3.** The Ar $L_{2,3} - M_{2,3}M_{2,3}$ Auger group measured at 461.2 eV photon energy with a 500 $\mu$m monochromator slit size. The shaded Auger peaks were used to normalize the photoelectron spectra. In the present experiment the dark (red) shaded line was employed, while in the previous measurement [1] the light (yellow) shaded peak was used.

The relative efficiencies of the detectors were determined by measuring the angular distribution of the almost isotropic Ar $L_{3} - M_{2,3}M_{2,3} {^1D_2}$ diagram Auger line at 203.3 eV kinetic energy obtained with 461.2 eV incident photons using a 500 $\mu$m monochromator slit size. All
photoelectron spectra in the various angular channels were normalized to this Auger electron line. The angular distribution of the \( ^1D_2 \) Auger electrons is slightly anisotropic with deviations from the isotropic case of the order of \( \approx 2.3 \% \). Since the Auger distribution is symmetric with respect to the photon beam axis, the normalization of the photoelectron angular distribution to the anisotropic angular distribution of Auger electrons cannot introduce any LRA. In the previous experiments [1] the weaker isotropic Ar \( L_2 - M_{2,3} M_{2,3,3}^3 P_{0,1,2} \) diagram Auger transitions were used to normalize the photoelectron spectra. The Auger lines of interest for the present and previous studies are highlighted in Fig. 3 (shaded peaks).

The linear polarization of the photon beam was monitored by recording the angular distribution of the Ne 2s photoelectrons at 250 eV photon energy where the non-dipole contribution is negligible [9]. The radiation was found to be essentially completely linearly polarized: 100 \% within 2 \% uncertainty. To the best of our knowledge if there is any contribution of an elliptically polarized light to a linearly polarized photon beam, the angular distribution of the photoelectrons remains symmetric (see e.g. [2, 10]) relative to the photon propagation direction as in the case of a completely linearly polarized light.

The following instrumental sources can, in principle, produce an experimental left-right asymmetry: (1) the finite mechanical precision of the electrodes; (2) the alignment of the system to the photon beam: (a) an angular difference between the photon beam propagation direction and the one defined by the spectrometer and its slit system, (b) the axis of the spectrometer does not cross the axis of the photon beam; (3) the effect of the residual magnetic field; (4) the effect of the monochromator exit slit; (5) the time dependence of the detector efficiency and (6) the effect of the deceleration. These possible sources were checked carefully and (2.b) was found as the main component of the instrumental LRA. When the axis of the spectrometer does not cross the axis of the photon beam, an acceptance angle difference between the two spectrometer halves can result. The estimated value of the left-right asymmetry parameter generated by these acceptance angle differences would be maximum 0.022 if no normalization of the photoelectron spectra to an Auger line was carried out. However, this normalization removes the effect of the off-axis alignment because the solid angle is the same for both the Auger electron and the photoelectron lines. Furthermore, this misalignment gives a constant asymmetry independent of the atomic mass. Thus the mass dependence of the present and the previous [1] experimental data cannot be explained with this misalignment (see Fig. 4 in Section 3). Additionally, it seems very improbable that the misalignment should have been identical in all experiments. The other instrumental effects altogether can produce a maximum left-right asymmetry of \( 2 \times 10^{-3} \) but the normalization of the photoelectron lines to the Auger peak intensities eliminates most of the above instrumental sources.

The measurement and the evaluation of the experimental data were performed similar to the procedures described in Ref. [1]. The photon flux was measured by a photodiode. The collection times of the photoelectrons were several tens of seconds and the energy sweeps were repeated 10 to 90 times depending on the magnitude of the photoionization cross sections. Before and after the collection of photoelectron spectra an Ar LMM Auger spectrum was recorded. After linear-background subtraction the angular distribution of the photoelectrons was determined by normalizing the intensity of the photoelectron line to the area of a selected Auger peak in every single angular channel. The relative double differential cross sections obtained at 22 different emission angles were then summed over the left and right half-spectrometers separately for determination of the left (\( \sigma_L \)) and right (\( \sigma_R \)) experimental cross sections. Finally, the asymmetry parameter was calculated by using Eq. 1 and its error was derived from statistical uncertainty, background substraction, normalization and reproducibility.
Figure 4. Comparison of the present experimental left-right asymmetry parameters with the earlier experimental results [1] and the theoretical values [1] as a function of the atomic mass for the H$_2$ molecule and for the noble gas atoms from He to Xe. The solid circles show the previous measurements [1] and the solid triangles are the present data. The dashed line and the right hand scale represent the theoretical estimation of the left-right asymmetry parameters [1].

3. Results and discussion

Fig. 4 compares the present (solid triangles) and the previous [1] (solid circles) experimental left-right asymmetry parameters as well as the calculated data [1] (dashed line and right hand scale) as a function of the atomic mass. In Fig. 4 the average of the three experimental data sets reported in Ref. [1] is plotted as the result of the earlier measurement. The figure shows agreement between the two experiments. Both the present and the previous [1] experimental asymmetry parameters differ significantly from zero. Differences can be seen between the results of the MAX-II and DORIS III measurements. These may originate from the slightly different photoelectron energies (i.e., also different photon energies) in the two sets of experiments. The difference in energies was 3.7 eV. Furthermore, two different Auger lines were used to normalize the photoelectron spectra in the previous (Ar $L_2-M_{2.3}M_{2.3}^3P_{0,1,2}$) [1] and the present (Ar $L_3-M_{2.3}M_{2.3}$ $^1D_2$) measurements. Thus, the agreement between the two experimental asymmetry parameter sets indicates that the observed left-right asymmetry appears in the photoionization process, not in the Auger transition. If the asymmetry were in the Auger process, the curve of the asymmetry parameters as a function of the target atomic mass would be constant. Obviously, the experimental asymmetry parameters decrease with increasing mass. It should be noted that the normalization of the photoelectron spectra to an asymmetric Auger line can shift the magnitude of the asymmetry parameters measured in photoionization but it cannot change their dependence on the atomic mass.

As mentioned above in the ESA-22G electron spectrometer used in the present experiment the gas nozzle was a simple tube and the gas was going upwards, and in the ESA-22L analyzer [8] applied in the previous measurement [1] a channelplate was used as a gas nozzle and the gas was flowing downwards. The differences between the two gas nozzles employed in the two sets of experiments are in the shapes of the gas beams and the directions of the target atoms.
The agreement of the two experimental data sets shows that the observed LRA effect cannot be strongly influenced by the geometry of the gas target.

The theoretical estimation in Fig. 4 is based on parity violation by the electroweak interaction through the exchange of a \( Z_0 \) boson among the nucleons and atomic electrons. The theoretical asymmetry parameters are calculated within the framework of the Standard Model (for details see [1]). The atomic mass dependence of the calculated data [1] is totally different from the results of the measurements. Moreover, the experimental asymmetry parameters are orders of magnitude larger (a factor of \( 10^{10} - 10^{11} \)) than the calculated values. Thus, the present measurement confirms the statement in Ref. [1] that the observed left-right asymmetry cannot originate from the electroweak interaction among the nucleons and the atomic electrons.

Another possible interpretation of the LRA phenomena reported in Ref. [1] is that the photon wave packet may be extremely short. A left-right asymmetry (or virtual parity violation) was observed in ultra short laser light-atom interactions by Paulus et al [5] and was explained as a phase effect between the carrier-envelope and the few-cycle laser light (for details see Milosević et al [11]). The order of magnitude of the asymmetry parameters in the present measurement (as well as in the earlier one [1]) is approximately the same as that observed in the Paulus et al experiment [5]. Thus, the time structure of the synchrotron radiation can be extrapolated from their laser pulse length. For the photon energies applied in the present and the previous [1] measurements the duration time of the photon wave packet should then be of the order of the cycle time of an individual photon (i.e., ca. 42 attoseconds at 230 eV photon energy [1] regarding 2 cycles photon pulse). This is much shorter (a factor of \( 10^{-6} \) to \( 10^{-7} \)) than expected for synchrotron radiation. The agreement between the two experimental data sets could indicate that the time structure and phase differences between the carrier-envelope and the photons are the same for both synchrotrons (MAX-II in Lund, Sweden [7] and DORIS III in Hamburg, Germany [6]) which is inconceivable. All these arguments work against an explanation of the present (and also the earlier [1]) experimental asymmetry parameters with the model of a few-cycles photon beam and the time structure of the photon wave packets.

4. Conclusion

In conclusion, left-right asymmetry parameters were measured for photoionization of the outer \( s \)-shells of the noble gases He, Ne, Ar and Xe using linearly polarized synchrotron radiation. Previous measurements [1] had resulted in the observation of an unexpectedly large left-right asymmetry. For a crucial test of the observations made, similar and partially improved measurements were carried out in a totally different experimental environment with another synchrotron light source and a different electron spectrometer. As before, a non-zero left-right asymmetry was also observed in the present work. The asymmetry parameters \( A_{LR} \) resulting from the two different studies are in fair agreement with one another and significantly differ from zero. Both sets of data show a decrease of \( A_{LR} \) with increasing atomic mass. This behavior and the order of magnitude of the measured values are totally different from theoretical predictions for parity violation by the electroweak interaction between the nucleons and the electrons in an atom.

In both experiments great care has been taken to exclude or quantify all possible sources of systematic errors that could introduce an experimental asymmetry. We are not aware of any additional experimental effects that could produce a left-right asymmetry in the measurements. We have to conclude that the observed left-right asymmetry is the result of a real physical process. Currently, there is no explanation for the non-zero asymmetry parameter. If the non-zero asymmetry is a real physical effect, it means the breakdown of space inversion symmetry in the photon-atom interaction. Theoretical models and further experiments are required to understand the origin of the observed left-right asymmetry.
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