The main goal of our research activity in this project was to open a new scientific direction to investigate the photon - atom interaction in a wide photon energy range: from ultra-short pulse duration high intensity laser light to XUV by using high energy and angle resolved photoelectron spectroscopy (HAPES). We planned to study the angular distribution of photoelectrons from multi-photon single ionization of valence and inner shells of free atoms and molecules with high energy- and angular resolution at the Attosecond Beamline, Szeged University (and later at ELI-ALPS) in order to investigate the channel interaction between the direct and indirect multi-photon ionization processes to resolve the disagreement between the theoretical end experimental data. Unfortunately the ELI-ALPS project at Szeged was delayed several years therefore we carried out measurements at the femtosecond laser beamline of the Wigner Research Institute, Budapest.

We also planned to carry out measurements at the beamlines of DORIS III and PETRA III synchrotrons at HASYLAB, Hamburg, to investigate the second order non-dipole contribution to the angular distribution of photoelectrons in a photon energy range where the dipole and first order non-dipole matrix elements have minimum. Furthermore we wanted to study the ionization process at photon – ion collisions with PIPE (Photon Ion Spectra for Petra III) in cooperation with the Institut für Atom- und Molekülphysik, Justus-Liebig-Universität Giessen.

In order to carry out the above mentioned measurements we had to reconstruct our unique electron spectrometer (ESA-22), which was built more than 15 years ago.

In addition we also investigated the ionization process with antiparticles at the Department of Physics and Astronomy, University College London.

The results:

I. The reconstruction of ESA-22 electron spectrometer and the efficiency calibration.

The ESA-22 electrostatic electron analyzer (Fig. 1), built more than 15 years ago, consists of a spherical and a cylindrical mirror analyzer. The spherical mirror focuses the electrons from the scattering plane to the entrance slit of the cylindrical analyzer performing the energy analysis of the electrons. The spectrometer has second order focusing property. 24 channel electron multipliers (CEM) were installed at the exit of the cylindrical mirror at 90 mm focal diameter to detect the energy analyzed electrons. A spherical deceleration lens was placed around the source region to improve the energy resolution of the system. The relative energy resolution is better than 2.8×10^{-3} without deceleration.

The main advantages of the analyzer beside the high energy resolution are the simultaneous detection of the angular distribution of energy analyzed electrons at 22 angles from 0^{o} to 360^{o} at every 15^{o} (except $\pm 90^{o}$). In this way we reduced the measuring time and increased the accuracy of the measured data.

During the reconstruction we designed and built a new UHV vacuum chamber equipped with three turbo pumps and a dry forevacuum pump ensuring the oil free vacuum in the chamber. During the test the best vacuum was 1×10^{-8} mbar without baking. On this basis we are sure to reach the 5×10^{-10} mbar or better vacuum in the near future when we use solid targets. We also renewed the 43 high voltage feedthroughs welded onto three flanges. They ensure the electric connection between the spectrometer inside the chamber and the outside control electronics. 12 vacuum ports are located in the collision plane for installing different devices which will be used during the measurements. New mu-metal magnetic shielding was manufactured to reduce the Earth magnetic field to less than 5 mG (5×10^{-7} T).

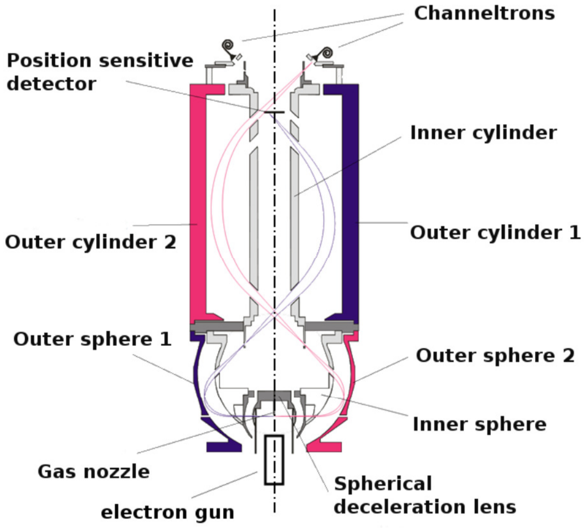

Fig. 1. The ESA-22 electron spectrometer

A special system was built to rotate the vacuum chamber under UHV condition around the projectile beam in order to detect the ejected photoelectrons not only in the collision plane determined by the momentum (**k**) and polarization (**P**) vectors of the photons but other planes from 0^{o} to 90^{o} relative to the (**P**,**k**) plane, too. It means that we can record real 3D angular distribution. Fig.2. shows the analyzer at different angle positions.

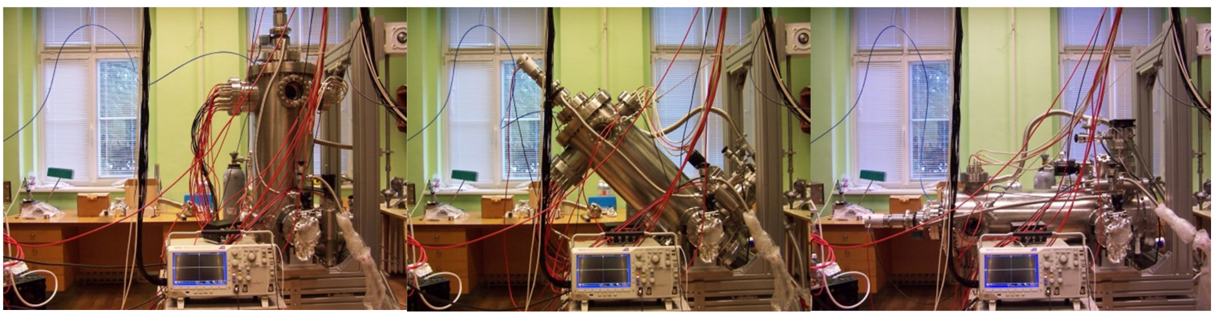

Fig. 2. The ESA-22 analyzer where the scattering plane is at different angular positions (0^{o}, 45^{o}, 90^{o}) relative to the horizontal plane.

24 new Channel Electron Multipliers (CEM) (Magnum 5901 manufactured by Photonics) were mounted at the exit of the spectrometer to detect the energy analyzed photoelectrons at every 15^o (except ±90^o). The holder of the detectors can also be rotated from outside with a precision step motor around the spectrometer axis from 0^o to 360^o (Fig.3.).

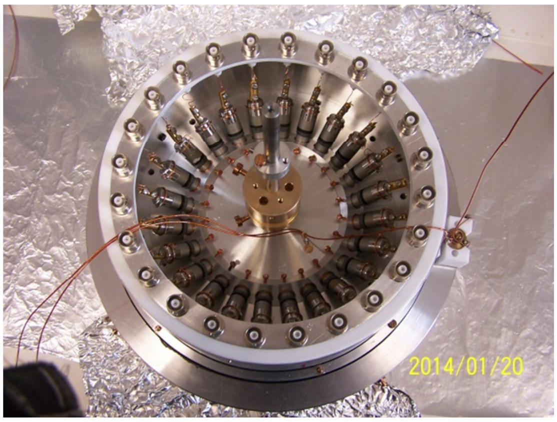

Fig. 3. The channel electron multipliers and the detector holder

The analyzer control and data acquisition system consists of a main control unit based on microprocessors, high voltage precision power supplies and a laptop. LabView program was used as the new control software, developed to control the analyzer and the new high precision high voltage power supplies (manufactured by FUG). Recently a new control unit, based on FPGA with ethernet connection, was built. This new unit and the control software will enable us to record the pulses originating from the detectors in list mode with timestamps. It will be used to measure coincidences between the different detectors.

We also worked out a new method to determine the efficiencies of the detectors and the angle dependent transmission of the system and in this way the absolute double differential cross sections could be determined. In the previous measurements the intensities of all photoelectron spectra measured at different angular channels were normalized to the intensity of the isotropic Ar LMM Auger peaks (around 205 eV). This normalization was necessary since the individual detection efficiencies of the channeltrons were not known. This normalization procedure, however, limited the energy range where the photoelectrons could be detected, because the energy of the photoelectrons should be close to the Auger lines in order to avoid the changes of the detector efficiencies which depend on the electron energy. Recently we worked out a method to avoid this limitation [Abr16a]:

1. An electron gun was installed in the axis of the ESA-22 electron spectrometer. In this case the scattering plane is perpendicular to the projectile beam, therefore the angular distributions of the elastically scattered or the ejected Auger electrons are isotropic due to the cylindrical symmetry of the collision system. Using the elastically scattered electrons the efficiency and transmission calibration for the ESA-22 system can be determined for arbitrary electron energies.
2. Rotation of the detector holder: Every CEM measures the number of electrons at every ejected electron angles. These angle dependent intensities reflect the transmission of the analyzer at every angle. At a given angle the detector dependent intensity shows

the efficiency difference between the different detectors. It means that the relative transmissions and efficiencies can be determined at arbitrary electron energies.

3. The experimental transmissions and efficiencies can be absolutized by using previously measured absolute data e.g. absolute double differential cross sections of elastically scattered electrons using the NIST database [Jab10].

We compared the measured efficiencies and transmissions for Ne, Ar, Kr targets using the elastically scattered and Auger electrons at the same electron energies. The intensity ratio of the elastic and Auger electrons are constant, ensuring the calibration of the analyzer at every electron energy. This method is unique; nobody published such calibration method in the literature. The paper which described this new calibration method was published in [Abr15, Abr16a].

II. Investigation of the photoionization process induced by synchrotron radiation.

a) Determination of anisotropy parameters of photoelectron angular distributions.

The angular distribution of electrons ejected in photoionization provides detailed information on the dynamics of multielectron correlation effects. A good example is the interference between the indirect and direct photoionization channels [Ric05] which strongly modifies the angular distribution. The multipole expansion of the double differential cross section of photoelectrons for linearly polarized photons can be written as [Dev99] (applying the first- and second-order non-dipole corrections):

$$\frac{d\sigma_{nl}}{d\Omega}(\vartheta,\phi) = \frac{\sigma_{nl}}{4\pi}\{1 + (\beta + \Delta\beta)P_2(\cos\vartheta) + (\delta + \gamma\cos^2\vartheta)\sin\vartheta\cos\phi + \lambda P_2(\cos\vartheta)\cos 2\phi + \mu\cos 2\phi + \upsilon(1+\cos 2\phi)P_4(\cos\vartheta)\}, \quad (1)$$

where σ_{nl} is the ionization cross section of the *nl*th shell, ϑ and ϕ are the polar and azimuth angles of the emitted photoelectrons relative to the polarization vector of the photon, β is the dipole anisotropy parameter (electric dipole E1), δ and γ are the first-order non-dipole parameter (electric quadrupole E2, magnetic dipole M1), $\Delta\beta$, λ, μ and υ are the second-order non-dipole anisotropy parameters (electric octupole E3, magnetic quadrupole M2), and P_j $(\cos\vartheta)$ denotes the *j*th order Legendre-polynomial.

In 2013 we were granted one week beamtime at the Doris III synchrotron, Hamburg. (Later the DORIS III was closed down and the Petra III was also closed for reconstruction.) As it was planned we investigated the angular distribution of Kr 4*p* photoelectrons with linearly polarized photon beam at energies from 63 eV to 113 eV. The measurements were carried out with our ESA-22 analyzer. The experimental anisotropy parameters were determined for the Kr 4*p* shell and its fine structure components. The experimental data were fitted with two model functions. In the first approximation electric dipole, electric quadrupole and magnetic dipole interactions were assumed. In the second step the model function was extended with the electric octupole and magnetic quadrupole interactions and the fit procedure was repeated. The comparison between the measured and two fitted data shows a significant contribution of the electric octupole and magnetic quadrupole interactions to the angular distribution of the Kr 4*p* photoelectrons [Fig. 4.]. The results were presented at the XXVIII ICPEAC [Hol14]. Unfortunately theoretical calculations have not been found for this angular distribution. Recently we are working on to find the theoretical interpretation for the measured data. The final results will be published soon.

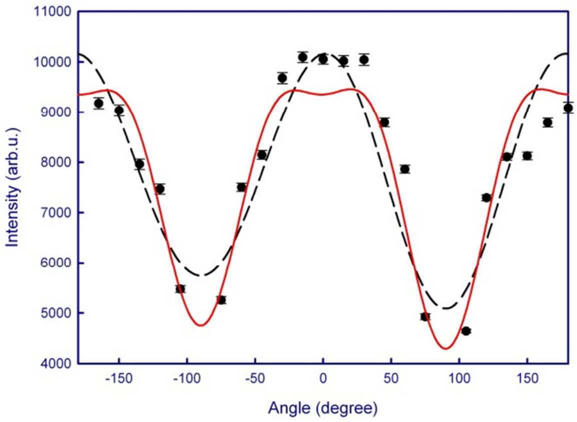

Fig. 4. Angular distribution of Kr 4*p* photoelectrons relative to the polarization vector at 93.1 eV photon energy (solid circles with error bars). The dashed and solid line are the result of two fitting procedures

In April 2016 we were invited to carry out double differential ionization cross section measurements at the beamline of Bessy II synchrotron in Berlin by the PTB (Physikalisch-Technische Bundesanstalt (PTB), Berlin, Germany). During the measurements 100 eV and 200 eV photon energies were applied. He and Ne were used as target (Fig 5.) [Abr16]. This

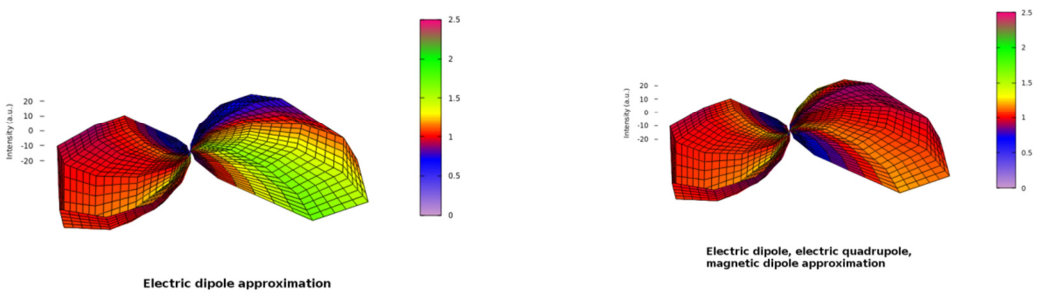

Fig.5. Photoionization of Neon 2s at 100 eV energy. Colors represent the ratio of the experimental data and the theoretically fitted values.

was the first time when we rotated the analyzer around the photon beam so the collision plane of the analyzer was at an angle relative to the plane determined by the photon momentum and the polarization vectors. The angle was changed from 0^{o} to 90^{o}. It was the first real 3D measurement in the field of photon - atom collisions. Fig 5. shows the ratio of the experimental and theoretically fitted data for Ne target. It is clearly seen (the ratios differ from one) that the simple dipole approximation could not describe well the experimental data. Higher order approximations are needed as it is seen on the right in Fig. 5.

The preliminary experimental data were presented at the Magyar Fizikus Vándorgyűlés (Conference for Hungarian Physicists). The detailed evaluation of our measurements will be published soon.

b) Determination of the asymmetry parameter of photoelectron angular distributions.

According to quantum mechanics electromagnetic atomic transitions have space inversion symmetry. The electromagnetic interactions between the atomic electrons and nucleus as well as between the ionized and excited particles are assumed to conserve parity. Consequently for photoionization with linearly polarized light the angular distributions of the emitted particles or quanta should show left - right symmetry relative to the photon propagation direction. In other words, the right side intensity of the ejected particles with respect to the beam direction should be equal to the left side intensity. The asymmetry parameter can be determined as:

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \tag{2}$$

where σ_L and σ_R are the intensity of the left and right side, respectively. For explanation see Fig. 6.

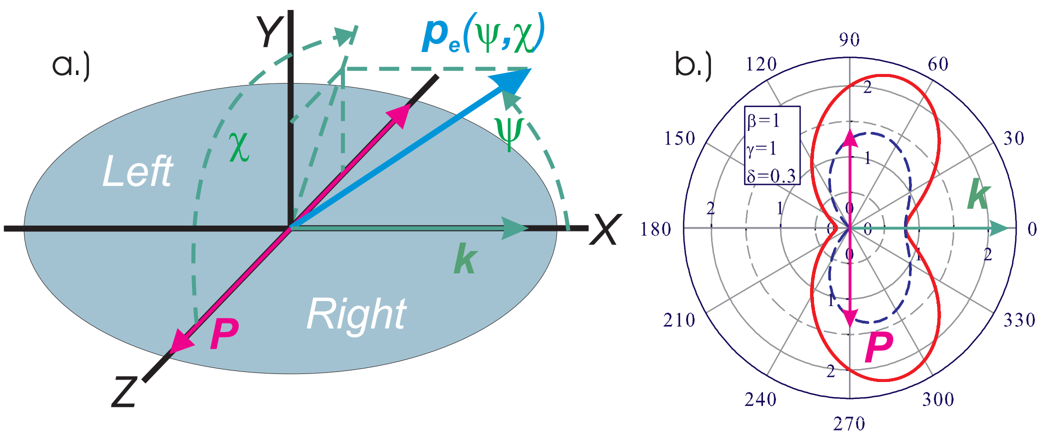

Fig. 6. (a) Definition of the coordinate system. (b) An example for the double differential cross section of photoelectrons in the scattering (P,k) plane. The solid and the dashed lines represent the angular distribution of the emitted photoelectrons for linearly polarized and unpolarized light calculated from Eq. 1 for the given parameter values.}

Our unique electron spectrometer which measures the ejected photoelectrons at 22 angles enables us to determine the fine angular distribution. We experimentally discovered the asymmetric photoelectron emission for H_2 molecule and outer *s*-shells of noble gases [Ric07] for a given photon energy ($h\nu = 203$ and 207 eV). Non-zero asymmetry parameters were observed.

In this project our earlier measured and published data of photoelectron angular distributions were reevaluated to determine the left - right asymmetry (LRA) parameters for the photoionization of the outer s- and p-shells of noble gas atoms and H_2 molecule. The aim of this data evaluation was to verify the existence of the large left - right asymmetry of the photoelectron angular distributions published earlier. The determined LRA parameters significantly differ from zero. The data sets show a decrease of the LRA parameter with increasing atomic mass for s-shells. The sign and the shape of the experimental values for p-shells differ from the data determined for s-shells indicating the existence of an unknown effect which is sensitive to the angular momentum of atomic shells. We found that the observed left - right asymmetry is a result of a real physical process. Fig. 7. shows the asymmetry parameter as a function of the photoelectron energy for different atomic shells. Currently, there is no explanation for the reason of the non-zero asymmetry parameter which breaks down the 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. The non-zero asymmetry parameters are in contradiction with the quantum mechanical description of photoionization due to the conservation of space inversion symmetry in electromagnetic interactions. However, virtual breakdown of parity conservation was observed and predicted for photoionization by few cycle laser pulses. The results were published in [Ric14].

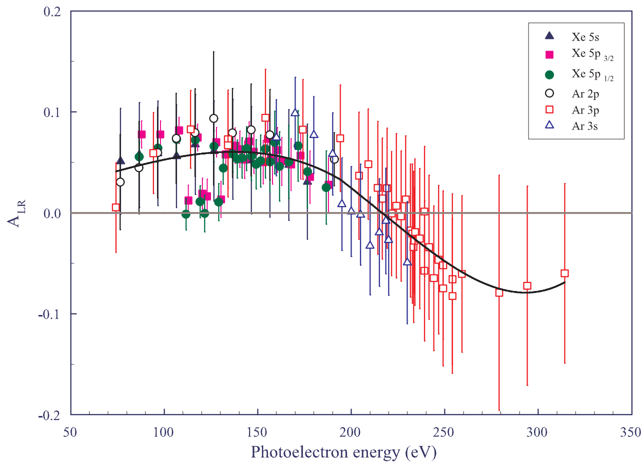

Fig. 7. The photoelectron energy dependence of the experimental LRA parameter. The solid line has been obtained by smoothing the data

c) Investigation of photoionization with PIPE (photon - ion spectrometer)

In cooperation with the Institut für Atom- und Molekülphysik, Justus-Liebig-Universität Giessen we took part in several measurements at PETRA III synchrotron in Hamburg. The experiments were carried out at the newly developed photon - ion merged - beam setup PIPE (developed with the participation of Atomki researchers) using monochromatized undulator radiation from PETRA III. Single, double, and triple ionization of C^{1+} ions by single photons were investigated in the energy range of 286 – 326 eV, i.e., in the range from the lowest-energy K-vacancy resonances to well beyond the K-shell ionization threshold. Clear signatures of C^{1+} (1s2s2 2p2 2D; 2P) resonances were found in the triple-ionization channel. The only possible mechanism producing C^{4+} (1s2) via these resonances is direct triple-Auger decay, i.e., a four-electron process with simultaneous emission of three electrons. This work was published in [Mul15]

We also investigated the photoionization and photo-fragmentation of multiply charged Lu3N@C80 ions at Petra III using the PIPE system. The relative cross sections for photoionization of endohedral fullerene ions Lu3N@C80^{q+} (q = 1,2,3) have been measured employing the photon-ion merged-beam technique. The investigations included various ionization channels Lu3N@C80 $+q\rightarrow+p$ (q = 1,2,3 and p = 2,3,4,5,6), in some cases accompanied by fragmentation of the carbon cage. Prominent structures related to the carbon *K*-shell ionization threshold were observed in the energy range of 280 – 330 eV. These resonance structures have been analyzed in seven product channels and were compared with previously known absorption spectra of several fullerene species. By comparing the energies for double ionization of Lu3N@C80^{+} and Lu3N@C80^{2+}at the carbon 1*s* *K*-shell threshold, we derived a value of 5.0 ± 0.4°A for the radius of the carbon cage. The paper was published in [Hel15].

Another measurement with the PIPE system was the stepwise contraction of the nf Rydberg shells in the 3d photoionization of multiply charged xenon ions. Triple photoionization of Xe^{3+}, Xe^{4+} and Xe^{5+} ions have been studied in the energy range of 670 – 750 eV, including the 3d ionization threshold. These absolute cross sections exhibit a progressively larger number of sharp resonances as the ion charge state is increased. This clearly visualizes the re-ordering of the ϵf continuum into a regular series of Rydberg orbitals as the ionic core becomes more attractive. The paper was published in [Sch15].

Unfortunately the German cooperation partner, who managed the publications, forgot to indicate the OTKA number in the *Acknowledgement* of the papers.

Investigation of the ionization process by laser light.

At the time of the application for this OTKA project it was not known that the ELI-ALPS project at Szeged would be delayed several years. Therefore we could not carry out the planned measurements at ELI-ALPS with our ESA-22 analyzer.

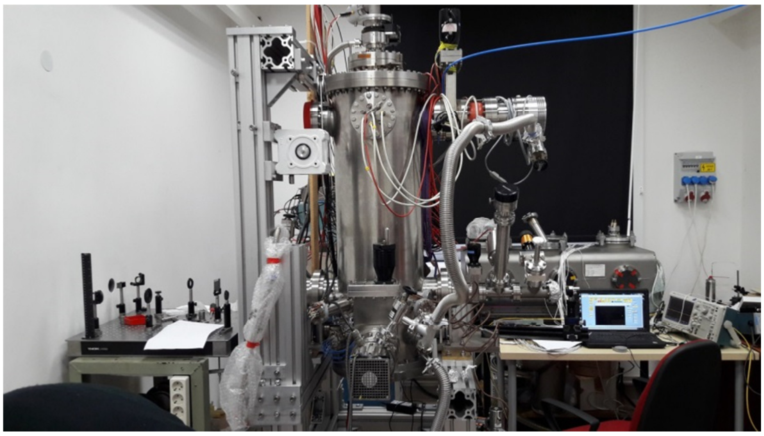

Fig. 8. The ESA-22 electronspectrometer at the femtosecond laser facility.

However, in October 2016 we carried out experiments in cooperation with the "Ultrafast Nanooptics Lendület" group at the Wigner Research Center for Physics, Budapest. The high energy resolution ESA-22 analyzer was installed to the femtosecond laser beamline. (Fig. 8.) The energy spectra and the angular distribution of photo-electrons originating from multiphoton ionization were measured (Fig.9.). The measured data gave valuable information on the ionization process itself and its dynamics. Currently we are evaluating the data and we collected useful experience for future investigations at ELI-ALPS. The results will be published soon.

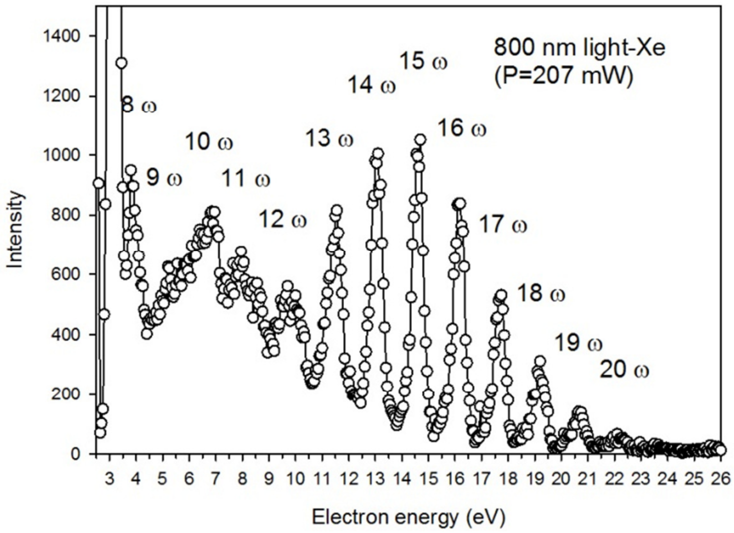

Fig. 9. The measured electron spectrum for Xe target. The numbers above the peaks indicate the number of photons absorbed during ionization.

The MTA News presented this pioneering experiment [MTA16]:

III. Investigation of the ionization process by charged particles.

Due to the shortage of synchrotron and laser beamtimes we accepted the invitation of the PTB (Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany) to carry out double differential ionization cross section measurements on tetrahydrofuran by proton impact using the upgraded ESA-22 analyzer. The experiments were carried out at the 150 kV electrostatic and the 3.75 MV Van de Graaff accelerators at PTB. The emitted electrons were detected simultaneously at different polar angles between ±15° and ±165° (except ±90°) in 15° steps relative to the beam direction.

The absolute normalization was performed by collecting electron spectra from collisions of 100 keV, 300 keV and 2 MeV protons with argon. Because of the cylindrical symmetry of the collision system (the tetrahydrofuran molecules were randomly oriented), the experimental double differential cross sections were averaged for the symmetric emission angles relative to the projectile momentum vector. Fig. 10. shows the experimental double differential ionization cross sections for 100 keV proton-tetrahydrofuran collisions. We should note that the intensity of the measured data covers five orders of magnitude showing the power of our analyzer. The absolute values were derived by comparing our measurements and the experimental data from Rudd *et al* [Rud79] for the collision of 100 keV protons with Ar.

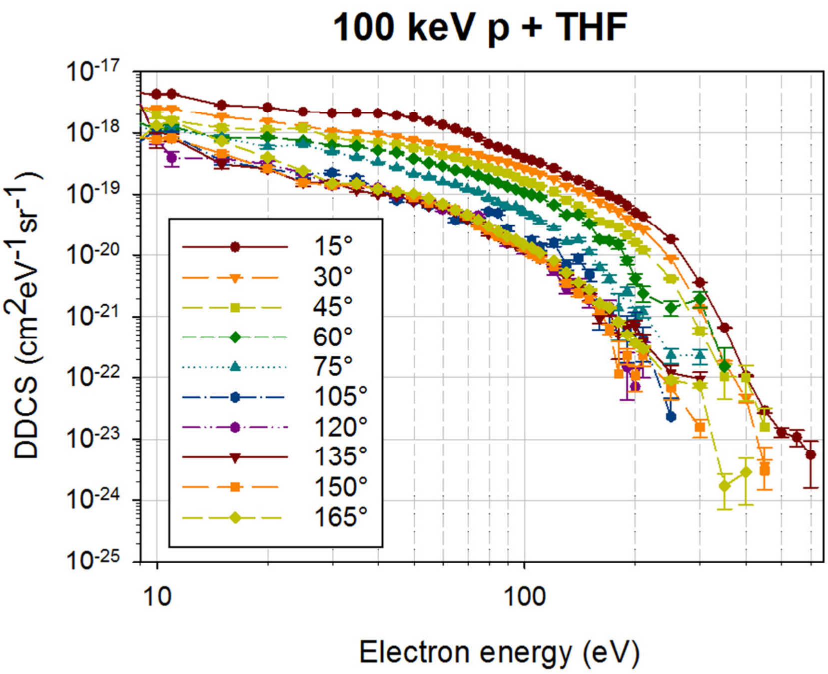

Fig. 10. The absolute double differential ionization cross section (DDCS) for the ejection of secondary electrons by collision of 100 keV protons with tetrahydrofuran (THF) at different emission angles relative to the proton beam direction as a function of the electron energy.

The preliminary results were presented at the XXIX. ICPEAC conference [Buh15]. Unfortunately the PTB did not give the approval to publish the detailed results.

IV. Investigation of the ionization process by positrons.

The ionization by positrons is a special part of the investigation of the atomic collision process. The positron has identical mass and absolute value of charge but with opposite sign compared to the electron. In comparison with protons the positron has the same charge but the mass of the proton is about 1800 times larger. The comparison of the experimental ionization data by positron impact with the data measured at electron and proton impact gives valuable information on the dynamics of the ionization process. In cooperation with the positron group at the Department of Physics and Astronomy, University College London (UCL) we took part in designing and building an electrostatic brightness-enhanced timed positron beam for atomic collision experiments in UCL. Very few electrostatic systems are used in positron collision physics, mainly magnetically guided beam is applied due to their simplicity and higher intensity. However, the advantage of an electrostatically guided positron beam is the lack of magnetic field around the target, so the angular distribution of the ejected particles can be measured very accurately. Such systems are very well applicable for measuring double or triple differential cross sections.

This unique system (Fig.11.) consists of a primary lens including the radioactive source and the W moderator, which accelerates (to about 2 keV) and focuses the moderated positrons to the remoderator creating a small (dia. 1-2mm) spot. The advantage of the remoderation is that the energy of the remoderated positrons are close to zero and they originate from a small volume. In this way we can produce better beam quality in the secondary lens. Further advantage is that when a positron hits the remoderator a secondary electron is ejected. This electron can also be detected and used for a start signal in a time-of-flight measurement. The secondary lens accelerates the remoderated positrons to the impact energy used in the collision. A cylindrical mirror analyzer is used to bend the beam by 90^o in order to separate the high energy positrons and γ photons from the low energy positron beam. The last lens is used to focus the positron beam to the target. The system works well, several measurements were carried out with it. The system was published in [Kov14]. A separate paper was also published on the moderation and diffusion of positrons in tungsten meshes and foils [Wil15].

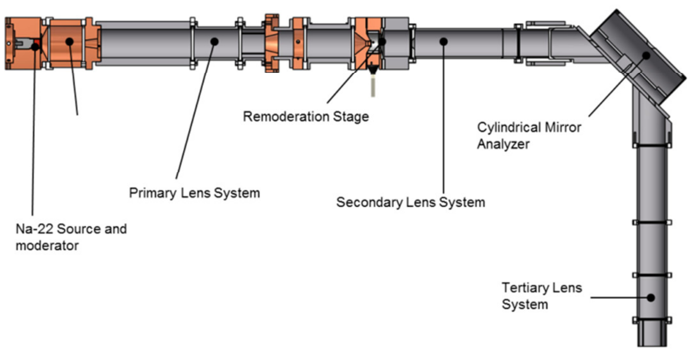

Fig. 11. The electrostatic lens system for the timed monoenergetic positron beamline.

The investigation of total cross sections for positron scattering is important to understand the interaction of antimatter with matter. In comparison with electrons the opposite signs of the static and polarization interaction for positrons tend to reduce their scattering probability at low energies (despite the presence of extra channels: annihilation and Ps formation). The previously measured data show significant discrepancies between the different experiments and theories in the energy range of 2-20 eV. The main reason of the deviations originate from ascribing particles elastically scattered to small forward angles to the unscattered beam. The good angular resolution associated with our electrostatic system should help to minimize this effect. The angular discrimination of the above mentioned system is $<2^{o}$ therefore well applicable to perform scattering measurements. The total cross sections of positrons scattered from helium and krypton have been determined in the energy range of 10–300 eV. Our results show good agreement with theories and several other measurements, even with those characterized by a much poorer angular discrimination, implying a small contribution from particles elastically scattered at forward angles, as theoretically predicted for He but not for Kr. More details can be found in [Fay16].

The total cross section of positrons scattered from H_2O has been measured for the first time with a high angular discrimination ($\simeq 1°$) against forward scattered projectiles in the energy range of 10–300 eV. The high angular discrimination of the current experiment ($\simeq 1°$) greatly reduces the systematic errors arising from forward scattered projectiles enabling, for the first time, a direct comparison with theories. Significant deviations from previous measurements were found which are, if ascribed entirely to the angular acceptances of various experimental systems, in quantitative accord with ab initio theoretical predictions of the differential elastic scattering cross section. More details can be found in [Lor16].

In cooperation with scientists at Bariloche, Argentina a new theoretical approximation of quantum vortices was worked out and used for the case of electron capture to continuum process (ECC cusp). The quantum vortices in atomic and molecular processes were found only a few years ago. Previously they were experimentally observed in the ionization of atoms by the impact of electrons and ions, and theoretically analyzed for positrons and electric pulses. Vortices and cusps are different in their origin and structure. Vortices formed in the wave function during the early stages of the collision might collapse at later times, but some can eventually survive up to the asymptotic regime and manifest themselves as zeros of the ionization matrix element $\boldsymbol{T}$. More details can be found in [Nav15].

We were invited to write a summary of the recent results into the book series of *Topics in atomic and molecular physics* [Lar14]. The overall title was *"*Fragmentation processes: Experimental aspects of ionization studies by positron and positronium impact*"*. The aspects of experimental methods and results for positron- and positronium induced ionization and fragmentation in collision with atoms and molecules were considered. In the case of positrons, these include recent photon–ion coincident measurements and differential cross-sections; for positronium, although scarce, data comprise of integral and differential cross-sections for positronium break-up. Our contribution to the summary was mainly the chapter: *1.3 Differential cross-sections for positron impact ionization.* The acknowledgment thanks the Hungarian Research Fund but unfortunately the OTKA number was missing.

References:

[Abr15] Ábrók L._Balog R., Herczku P., Kovács S. T. S., Hatvani D., Ricz S., Kövér Á.: *Upgrade of ESA-22D photoelectron spectrometer.* Journal of Physics: Conference Series **635** (2015)9:2092.

[Abr16a] Ábrók L., Buhr T., Kövér Á., Balog R., Hatvani D., Herczku P., Kovács S. T. S., Ricz S.: *A method for intensity calibration of an electron spectrometer with multi-angle detection* Nucl. Instrum. and Meth. in Phys. Res. Section B: Beam Interactions with Materials and Atoms **369** (2016) 24-28.

[Abr16b] Ábrók Levente, Buhr Ticia, Kövér Ákos, Ricz Sándor, Varga Dezső,: *Hélium 1s, neon 2s fotoelektronok 3-dimenziós szögeloszlása.* Magyar Fizikus vándorgyülés, Szeged, 2016 augusztus 24-27.

[Buh15] Buhr T., Ricz S., Ábrók L., Kövér Á., Mingjie Wang., Hilgers G., Rabus H.: *Double differential ionization cross section of tetrahydrofuran for proton impact.* Journal of Physics: Conference Series **635** (2015) 032047.

[Dev99] Derevianko A., Johnson W. R. and Cheng K. T., At. Data and Nucl. Data Tab. **73** (1999) 153.

[Fay16] Fayer S. E., Loreti A., Andersen S. L., Kövér Á., Laricchia G.: *Magnetic field-free measurements of the total cross section for positrons scattering from helium and krypton* J. Phys. B: At. Mol. Opt. Phys. **49** (2016)075202.

[Hel15] Hellhund J., Borovik A., Jr., Holste K., Klumpp S., Martins M., Ricz S., Schippers S., and Müller A.: *Photoionization and photofragmentation of multiply charged Lu3N@C80 ions.* Phys. Rev. **A** 92 (2015) 013413.

[Hol14] Holste K., Borovik A. Jr., Buhr T., Ricz S.,Kövér Á., Bernhardt D., Schippers S., Varga D., Müller A.: *Electric octupole contribution to the angular distribution of the krypton 4p photoelectrons.* Journal of Physics: Conference Series **488** (2014) 022041.

[Jab10] Jablonski A., Salvat F., Powell C.J., NIST *Electron Elastic-Scattering Cross-Section Database* – Version 3.2 (2010).

[Kov14] Kövér Á, Williams A. I, Murtagh D J, Fayer S E and Laricchia G: *An electrostatic brightness-enhanced timed positron beam for atomic collision experiments,* Meas. Sci. Technol. **25** (2014) 075013.

[Lar14] Laricchia G., Cooke D. A., Kövér Á., Brawley S. J.: *Experimental aspects of ionization studies by positron and positronium impact,* Fragmentation processes. Topics in atomic and molecular physics. Ed.: Whelan, C.T. Cambridge, University Press **0** (2013)116-136.

[Lor16] Loreti A., Kadokura R., Fayer S. E., Kövér Á., Laricchia G.: *High-resolution measurements of* $e^+ + H_2O$ *total cross section,* Phys. Rev.Lett. **117** (2016)253401.

[MTA16] http://mta.hu/tudomany_hirei/magyar-kutatok-egyuttmukodese-a-lezergerjeszteses-fotoelektron-spektroszkopia-hazai-megvalositasara-107213

[Mul15] Müller A., Borovik A. Jr., Buhr T., Hellhund J., Holse K., Kilcoyne A.L.D., Klumpp S., Martins S., Ricz S., Viefhaus J., and Schippers S., Observation of a four-electron Auger process in nea-K-edge photoionization of singly charged carbon ions. Phys. Rev. Lett. **114** (2015) 013002.

[Nav15] Navarrete F., Feole M., Barrachina R. O., Kövér Á.: *When vortices and cusps meet.* Journal of Physics: Conference Series **583** (2015) 012026.

[Ric05] Ricz S., Nikkinen J., Sankari R., Ricsóka T., Kövér Á., Varga D. , S. Fritzsche, Aksela H., Aksela S.: *Interference effects in the angular distribution of Ar 3p photoelectrons across the 2p\ns/md resonances* Phys. Rev. **A72** (2005) 014701

[Ric07] Ricz S., Ricsóka T., Kövér Á., Varga D., Huttula M., Urpelainen S., Aksela H. and Aksela S.: *Experimental observation of left–right asymmetry in outer s-shell photoionization* New Journal of Phys. **9** (2007) 274.

[Ric14] Ricz S., Buhr T., Kövér Á., Holste K., Borovik A., Jr., Schippers S., Varga D., and Müller A. *Experimental investigation of left-right asymmetry in photon-atom interaction* Phys. Rev. **A90** (2014) 013410**.**

[Rud79] Rudd M.E., Toburen L.H., Stolterfoht N.: *Differential cross sections for ejection of electrons from argon by protons* (*At. Data Nucl. Data Tables* **23** (1979) 405.

[Sch15] Schippers S., Borovik A. Jr., Buhr T., Hellhund J, Holste K., Kilcoyne A.L.D., Klumpp S., Martins M., Müller A., Ricz S. and Fritzsche S., *Stepwise contraction of the nf Rydberg shells in the 3d photoionization of multiply charged xenon ions* J. Phys. B: At. Mol. Opt. Phys. 48 (2015) 144003.

[Wil15] Williams A. I., Murtagh D. J., Fayer S. E., Andersen S. L., Chevallier J., Kövér Á., Van Reeth P., Humberston J. W., and Laricchia G.: *Moderation and diffusion of positrons in tungsten meshes and foils.* J. of Applied Physics **118** (2015) 105302.

Debrecen, 27 January, 2017.

Ákos Kövér

Dr. Ákos Kövér

principal investigator