Annex D

TMR RESEARCH NETWORKS

DATABASE REPORT

Network Acronym: **EUROTRAPS**

Title: **EUROTRAPS - A NETWORK FOR ULTRA-HIGH PRECISION SPECTROSCOPY OF HIGHLY CHARGED, STORED AND COOLED IONS**

Contract Number: **ERBFMRX-CT97-0144**

Contractual Period: **1998-01-01 to 2001-12-31, duration 48 months**

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Objectives of the Network: **The EUROTRAPS network aims at a co-ordinated European effort to enable high-accuracy tests of the theory of Quantum Electrodynamics (QED) in extremely strong electromagnetic fields by measuring masses of bare and few-electron highly charged heavy ions up to U^{92+}, U^{91+}, U^{90+} etc. and the g-factors in the ground state of hydrogen-like ions up to U^{91+}. This goal will be achieved by performing accurate calculations of binding energies, g-factors and lifetimes in few-electron ions, improving the accuracy of mass determinations to better than 10^{-10}, setting up a facility at GSI/Darmstadt for high-accuracy experiments on heavy highly charged ions, implementing cooling of highly charged ions by electrons or positrons and resistive cooling, and putting expertise in Penning trap techniques at the disposal of European groups inexperienced in trap technology and also that of industry.**

Roles of the Participating Teams:

GSI team: The role of the team in the network is the construction, test and application of HITRAP for g-factor measurements in hydrogen-like ions and for mass measurements of bare and few-electron HCI up to U^{92+}. The HITRAP facility is being built up in close collaboration with the Mainz team. It will be operated at the temperature of liquid helium, which is necessary to achieve extremely good vacuum, and by using image-current detection. A decelerator for HCI is being designed.

Stockholm team: The group is driving the accuracy of precision mass measurements for stable heavy atoms to the ultimate limit. The method exploits highly charged ions and the increase of the cyclotron frequency with charge state. In the first phase the group reached an accuracy of 1ppb without cooling, using a "warm" trap and the time-of-flight detection method. After improving the vacuum, stabilizing the trap temperature to 0.01°C, and coupling a synthesizer frequency via GPS to atomic clocks, the group reached accuracies on the 10^{-10} level. Mass measurements relevant for a new determination of the fine-structure constant α, the heavy atom mass-table, and the Q-values of the neutrino-less double-β decay as well as the tritium β-decay were done. The role of the Stockholm theory team in the network is to calculate the atomic binding energies of highly charged heavy ions. Together with the Paris group a development was carried through to reach a sub-10eV accuracy of total atomic binding energies.

Mainz team: The role of the team in the network is the construction, test and application of HITRAP for g-factor measurements in hydrogen-like ions and for mass measurements of bare and few-electron HCI. The HITRAP facility is being built up in close collaboration with the GSI team. It differs from all other traps used in the network by operating at the temperature of liquid helium, which is necessary to achieve extremely good vacuum, and by using image-currents for single ion detection. The trap also allows for ion confinement at different spatially separated positions. Furthermore, the team collaborates with the Aarhus and London teams in order to accumulate and cool positrons in Penning traps. The positrons are produced by a radioactive source and by bremsstrahlung from a microtron. The Aarhus positron accumulator trap was constructed at Mainz.

Aarhus team: The role of the team in network is the development of a microtron-based intense pulsed positron source. Furthermore, techniques for bunching of positrons were developed. In collaboration with other EUROTRAPS teams a large number of positrons is injected into a cryogenic Penning trap, cooled, and accumulated. High-intensity cooled positrons can be transferred into a second trap for experimentation.

Swansea team (before London team): The role of the team in the network is the development of a slow-positron source, its use to form a cold positron plasma for the cooling of highly charged and exotic ions and the implementation of cooling in a Penning trap. The London team built up a dc positron source using a radioactive source.

CERN team: The role of the team in the network is the development of efficient deceleration and capture schemes for

high-energy HCI and positrons into traps and further improvement of the data acquisition and control system. The accuracy limits of on-line mass measurements in a Penning trap are being explored. In addition, members of the team take part in experiments with SMILETRAP.

Leuven team: The role of the team in the network is to investigate the use of Penning traps for high-precision tests of the predictions of the standard electroweak model. A set-up including a Penning trap for storing large quantities (i.e. $>10^6$) of cooled radioactive ions, and a retardation spectrometer for recoil ions resulting from beta decays in the trap, was designed and is being constructed now at ISOLDE/CERN. With this set-up, the possible presence of scalar type gauge bosons, not included in the Standard Model, will be investigated.

The industry partner Bruker-Franzen Analytik GmbH (BFA) actively participates as an experimental team in the network. BFA performs high-resolution mass measurements of singly, multiply and highly charged biomolecules and clusters using the Fourier transform ion cyclotron resonance (FT-ICR) detection technique. The aim is to investigate the enhancement of sensitivity and accuracy in mass determination using the FT-ICR detection technique. It brings into the network its know-how in FT-ICR for broad-band analysis of charge state distributions of trapped ion species. Cyclotron frequency measurement with ultra-high resolving power leads to better insight to the cause of magnetic-field instabilities of superconducting magnets.

Paris team: The role of the team in the network is to develop methods to calculate accurately atomic binding energies. The group is working on ab-initio calculations of relativistic correlation and of the self-energy screening correction to the binding energy. It also works on the calculation of the lifetimes of metastable states (including hyperfine quenching) of interest in studying atomic and nuclear properties inside the traps.

The Göteborg team calculates correlation contributions to atomic binding energies of heavy ions. Further, the team calculates QED corrections to atomic binding energies and g-factors of highly charged ions with the aim of testing fundamental QED theory in strong fields.

The Lisbon team uses the MCDF (Multi-Configuration Dirac-Fock) method to compute term energies, transition probabilities and lifetimes of atomic systems and other quantities of interest, namely Auger transition probabilities, to interpret data from trap measurements. In the calculations residual terms are included, incorporating Breit interaction, self-energy and vacuum polarisation, and two-electron radiative corrections.

Training:

The EUROTRAPS network trains young researchers in front-line technology and physics like: production of highly charged ions, production, storage and cooling of positrons from radioactive sources and a microtron electron accelerator, ion trap technology including manipulation and cooling of stored ions, extreme ultra-high vacuum technology, technology of superconducting magnets, advanced electronics for ultra-sensitive detection of single ions, Fast-Fourier-Transform

(FFT) hardware and software, and highly advanced calculations of few-electron systems and QED effects.

Industry Involvement:

Penning traps or ion traps in general are becoming increasingly important for a variety of industrial and technological applications. Examples are: the commercial Fourier Transform Mass Spectrometer (FTMS) for chemical or biological studies, environmental applications, the investigation of highly charged ions and the most accurate mass determinations of stable and radioactive isotopes. Because of the growing importance of traps in industry, the physics and technology of ion traps is becoming part of the basic education of physicists and engineers.

Joint Publications of the EUROTRAPS Network 1998 – 2001 with EU acknowledgement which appeared in refereed journals:

1. **J.P. Merrison, N. Hertel, H. Knudsen, S. Stahl and E. Uggerhoej, A new electro-produced slow positron facility, Applied Surface Science 149, 11 (1999).**
2. **J.P. Santos, J.P. Marques, F. Parente, E. Lindroth, P. Indelicato and J.P. Desclaux, Relativistic $2s_{1/2}$ (L1) atomic subshell decay rates and fluorescence yields for Yb and Hg, J. Phys. B: At. Mol. Phys. 32, 2089-2097 (1999).**
3. **H. Weidele, M. Vogel, A. Herlert, S. Krückeberg, P. Lievens, R.E. Silverans, C. Walther, L. Schweikhard, Decay Pathways of Stored Metal Cluster Anions after Collisional Activation, Eur. Phys. J. D 9, 173-177 (1999).**
4. **H. Häffner, N. Hermanspahn, P. Indelicato, H.-J. Kluge, E. Lindroth, V. Natarajan, W. Quint, S.Stahl, J.Verdu, and G. Werth, Testing atomic structure theories with high-accuracy mass measurements on highly charged ions, Hyp. Int. 127, 271-276 (2000).**
5. **N. Hermanspahn, H. Häffner, H.-J. Kluge, W. Quint, S. Stahl, J. Verdu, G. Werth, Observation of the Continuous Stern-Gerlach Effect on the Electron Bound in an Atomic Ion, Phys. Rev. Lett. 84, 427 (2000).**
6. **H. Häffner, T. Beier, N. Hermanspahn, H.-J. Kluge, W. Quint, S. Stahl, J. Verdu, G. Werth, High-Accuracy Measurement of the Magnetic Moment Anomaly of the Bound Electron in a Hydrogen-like Carbon, Phys. Rev. Lett. 85, 5308 (2000).**
7. **T. Beier, I. Lindgren, H. Persson, S. Salomonson, P. Sunnergren, H. Häffner, and N. Hermanspahn, g_j factor of an electron bound in a hydrogenlike ion, Phys. Rev. A 62, 032510 (2000).**
8. **G.C. Rodrigues, M.A. Ourdane, J. Bieron, P. Indelicato, and E. Lindroth, Relativistic and many-body effects on total binding energies of cesium ions, Phys. Rev. A 63, 012510-1 (2000).**
9. **S. Schwarz, F. Ames, G. Audi, D. Beck, G. Bollen, C. De Coster, J. Dilling, R. Fossion, J.-E. Garcia-Ramos, S. Henry, F. Herfurth, K. Heyde, A. Kellerbauer, H.-J. Kluge, A. Kohl, D. Lunney, R.B. Moore, H. Raimbault-Hartmann, C. Scheidenberger, G. Sikler, J. Szerypo, and the ISOLDE Collaboration, Accurate masses of neutron-decient nuclides close to Z =82 at ISOLTRAP, Nucl. Phys. A 693, 533 (2001).**
10. **F. Herfurth, J. Dilling, A. Kellerbauer, G. Audi, D. Beck, G. Bollen, S. Henry, H.-J. Kluge, D. Lunney, R.B. Moore, C. Scheidenberger, S. Schwarz, G. Sikler, J. Szerypo and the ISOLDE collaboration, Breakdown of the Isobaric Multiplet Mass Equation (IMME) at A=33, T=3/2, Phys. Rev. Lett. 87, 142501 (2001).**
11. **F. Herfurth, J. Dilling, A. Kellerbauer, G. Audi, D. Beck, G. Bollen, S. Henry, H.-J. Kluge, D. Lunney, R.B. Moore, C. Scheidenberger, S. Schwarz, G. Sikler, J. Szerypo and the ISOLDE Collaboration, Towards shorter-lived nuclides in ISOLTRAP mass measurements, Hyperfine Interactions 132, 309 (2001).**
12. **P. Indelicato, E. Lindroth, T. Beier, J. Bieron, A. M. Costa, I. Lindgren, J. P. Marques, A.-M. Mårtensson-Pendrill, M. C. Martins, M. A. Ourdane, F. Parente, P. Patté, G. C. Rodrigues, S. Salomonson, and J. P. Santos, Relativistic Calculations for Trapped Ions, Hyperfine Interactions 132, 349 (2001).**
13. **G. Werth, H. Häffner, H.-J. Kluge, W. Quint, T. Valenzuela, J. Verdu, A possible new value for the electron mass from g-factor, measurements on hydrogen-like ions, Hyp. Int. 132, 209 (2001).**
14. **W. Quint, J. Dilling, S. Djekic, H. Häffner, N. Hermanspahn, H.-J. Kluge, G. Marx, R. Moore, D. Rodriguez, J. Schönfelder, G. Sikler, T. Valenzuela, J. Verdu, C. Weber, G. Werth, HITRAP: A Facility for Experiments with Trapped Highly Charged Ions, Hyp. Int. 132, 457 (2001).**

Keywords: **Ion traps, Quantum Electrodynamics, highly charged ions, high-accuracy atomic spectroscopy, mass spectrometry.**

Network Home Page: http://www.gsi.de/eurotraps/

Results and Achievements:

The EUROTRAPS Network has to be regarded as very successful. The experimental and theory groups working in the field of ion traps and highly charged ions made substantial progress towards the goal of high-accuracy tests of Quantum Electrodynamics in strong fields. A breakthrough was achieved by the team in Mainz who was able to measure for the first time the electronic g-factor of a highly charged ion. The g-factor measurements reached an accuracy of better than 10^{-9}, a factor of 100 more accurate than planned. This measurement and the comparison with the theoretical result of the Göteborg team is a precision test of bound-state quantum electrodynamics. From the measured g-factor and the theoretical value for the g-factor it was possible to determine a new independent value for the electron's mass in atomic mass units u, $m_e = 0.000\,548\,579\,909\,2\,(4)\,u$. Our total precision is three times better than that of the internationally accepted value for the electron's mass. The Mainz and GSI teams continued their program of g-factor experiments on highly charged ions by measuring the g-factor of hydrogen-like oxygen ($^{16}O^{7+}$) on the 10^{-9} level of accuracy. The team in Stockholm performed mass spectrometry on highly charged ions in a Penning trap with an accuracy in the range $\delta m/m \approx 10^{-10}$ for the determination of atomic binding energies, and also e.g. on tritium (^{3}H) and helium (^{3}He) which is relevant for tests of fundamental theories. A technological breakthrough was achieved by the CERN team which demonstrated that high-accuracy mass spectrometry in Penning traps is applicable to unstable isotopes with lifetimes in the millisecond time range. This joint GSI-CERN effort to improve the ISOLTRAP mass spectrometer apparatus was extremely successful and allowed for a large number of precision mass measurements, for example of ^{34}Ar and ^{74}Rb, which have a half-life of about 100 ms. The Mainz team constructed a Penning trap which was shipped to Aarhus and installed at an accelerator based positron source for the accumulation and cooling of positron. A substantial step forward was also made by the Swansea team which succeeded in accumulating positrons in their Penning trap from a radioactive β-source by cooling in a buffer gas. This method is now routinely employed to capture over one million positrons and hold them for extended periods of time. In close collaboration all the theory teams supported the experimental teams in the interpretation of their experimental results.

The fruitful collaboration among the theory groups resulted in theoretical calculations of the g-factors of hydrogen-like highly charged ions and of the atomic binding energies of highly charged ions, i.e. the ionisation potentials of the elements of the periodic table in different charge states, with unprecedented accuracy. The systematic comparison of the results of different theoretical methods proved that the fractional accuracy of the calculations is about 10^{-10}. Large-scale coordinated efforts have been under way, which resulted in a table of binding energies for all charge states of all elements with nuclear between Z = 10 and 92. An application of the theoretical results was the interpretation of the successful high-accuracy mass measurements of the Stockholm team.

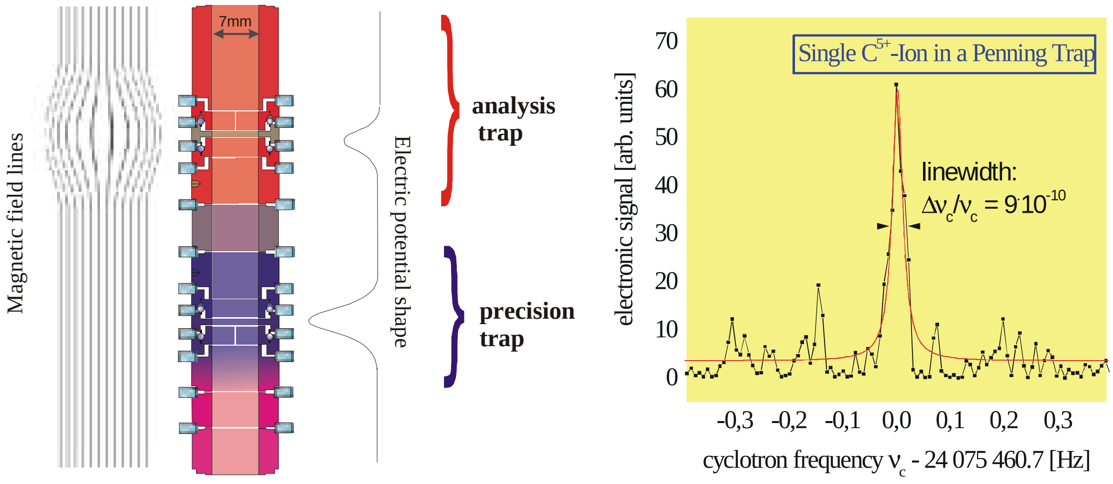

Fig.: Left side: sketch of the double Penning trap used by the Mainz team for g-factor measurements and the determination of the electron's mass. Right side: cyclotron frequency spectrum of a single trapped C^{5+} ion with a relative resolution of $9 \cdot 10^{-10}$ in the precision trap.

Some Scientific Highlights of the EUROTRAPS Network:

- **The determination of the ^{133}Cesium/proton mass ratio with a 4 ppb uncertainty (ppb = 10^{-9}). This is part of an effort to improve our knowledge of the fine-structure constant α. By utilizing the ^{133}Cesium/proton mass ratio, the well-known Rydberg constant, the defined velocity of light, the sufficiently well-known proton/electron mass ratio and a determination of the h/m(sCs) ratio (being pursued by S. Chu, Stanford) it is possible to get an alternative and hopefully improved determination of the fine-structure constant.**

- **The measurement of the g-factor of hydrogenlike carbon ($^{12}C^{5+}$) with an accuracy of 10^{-9} is a highlight. With the improvement of the measurement accuracy by a factor of 1000 it is now possible, for the first time, to test the bound-state QED contributions to the g-factor of the bound electron in highly charged ions with high sensitivity.**

- **First trapping of low-energy positrons in the positron accumulator by the Swansea team. This is the first time that this has been performed in Europe using a radioactive source-based beam. This achievement will pave the way for applications of low-energy positrons in particle cooling and in low-energy antihydrogen production.**

- **Joint efforts by the theory teams has resulted in a benchmark calculation on total binding energies of ions in all charge states. The Paris team has, together with the Lisbon team, provided the experimental teams with a complete database of ion binding energies, with an accuracy 40 times better than previously available. We did a detailed breakdown of the energy contributions due to different effects and a comparison of these individual parts when calculated with the very different computational schemes MCDF (Multi-Configuration Dirac-Fock) and RMBPT (Relativistic Many-Body Perturbation Theory). We have shown that the total binding energies can be predicted well within an accuracy of 10 eV. Such a systematic evaluation of the accuracy with which total binding energies can be calculated has never been made before.**

- **The theory teams have developed a new code for treating two-photon transitions in simple atomic systems. This method employs a new computer code for Multiconfiguration-Dirac-Fock wave functions. A large effort was made to calculate transition energies, ionisation and excitation cross-sections to describe electron-cyclotron ion sources plasma, which will be very useful for new heavy-ion source developments.**

- **The CERN team (ISOLTRAP) has impressively demonstrated the capability of storing and performing high-precision mass measurements on ions with a lifetime of less than 100 milliseconds. Scientific highlights are the measurements of the very short-lived nuclides ^{32}Ar ($T_{1/2}$=98 ms), ^{33}Ar ($T_{1/2}$=174 ms) and ^{74}Rb ($T_{1/2}$=65 ms). ^{74}Rb is the shortest-lived nuclide ever investigated in a Penning**

trap. The mass of ^{34}Ar ($T_{1/2}$=944 ms) was determined with a relative accuracy of about 10 ppb, a world record for direct mass measurements on short-lived nuclide.

- **In close collaboration with the Mainz team, during the four years duration of the EUROTRAPS Network the Aarhus team has built a trap facility which delivers an intense, bunched positron beam. This is the first time that positrons have been injected into such a trap from an electron accelerator.**

- **The intense collaboration of the experimental teams with the theory team in Göteborg made it possible to determine a new independent value for the electron's mass in atomic mass units *u*, m_e = 0.000 548 579 909 2 (4) *u*. The value is obtained from the measurement of the g-factor of the electron in $^{12}C^{5+}$ in combination with the most recent quantum electrodynamical (QED) predictions. Our total precision is three times better than that of the internationally accepted value for the electron's mass. This high-precision determination of a fundamental constant of physics by the EUROTRAPS Network is of great scientific importance (joint publication in Phys. Rev. Lett. 88, 011603, 2002).**