Final Report of the EUROTRAPS Network
FRMX CT97-0144
(1998 – 2001)

1. Results of the Network

1.1 Scientific Highlights

Mainz and GSI teams (1998):
A breakthrough was achieved by the Mainz/GSI teams who were able to measure for the first time the electronic g-factor of a highly charged ion. The measurement was performed on a hydrogenlike carbon ion ($^{12}C^{5+}$). A measurement accuracy of 10^{-6} was reached. This is an important step towards high-accuracy tests of Quantum Electrodynamics in strong fields.

SMILETRAP team (1998):
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(Cs) ratio (being pursued by S. Chu, Stanford) it is possible to get an alternative and hopefully improved determination of the fine-structure constant.

Stockholm and Paris theory groups (1998):
From the comparison of MCDF (Multi-Configuration Dirac-Fock) and RMBPT (Relativistic Many-Body Perturbation Theory) calculations we have shown that total atomic binding energies can be predicted within 20 eV for ions with closed-shell electron configurations. This uncertainty amounts to one part in 10^{10} of the Cs mass.

CERN and GSI teams (1998):
The motion of stored ions in Penning traps was investigated both experimentally and theoretically with respect to DC and AC perturbing electric fields. This way a deeper understanding of the dynamics of trapped ions was attained. Significant progress in the use of ion trap technology for the manipulation of ion beams and for precision experiments was achieved.

Leuven/Louvain-la-Neuve team (1998):
The design study for the trap to investigate weak interaction was finished. A Penning trap combined with a retardation spectrometer will be constructed to measure the energy spectrum of the recoil ions after beta decay.

Göteborg theory team (1998):
All QED contributions to the hyperfine-structure splitting were calculated for the first time. In connection with the g-factor calculations, this is an important step in understanding and describing QED under the influence of strong electromagnetic fields. Furthermore, for the first time strong-field QED corrections to a dynamical process (radiative electron capture) were compiled.

Mainz and GSI teams (1999):
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.

Mainz team (1999):
When electrons were applied to stored negatively charged clusters the first observation ever of doubly (and multiply) charged negative metal clusters was made. This discovery adds a whole new dimension (charge-state dependences in addition to size dependences) to metal cluster research.

Swansea team (1999):
First trapping of low-energy positrons in our accumulator. 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.

CERN team (1999):
A scientific highlight of the CERN team was the mass measurement of ^{33}Ar with ISOLTRAP. This isotope has a half-life of only 173 ms. It was the first time that such a very short-lived exotic atom was stored in a Penning trap and investigated with high accuracy.

Paris team (1999):
Very-large configuration space capabilities and new possibilities have been added to the MCDF code, which was already the world's most complete implementation of the MCDF method (energies, negative continuum treatment, one and two-photon transition probabilities, hyperfine interaction, parity violation, g-2 calculation, electron excitation, Auger transitions, muonic, antiprotonic, pionic and other exotic atoms).

Paris and Stockholm theory teams (1999):
Joint efforts by Stockholm and Paris has resulted in a benchmark calculation on total binding energies of Cs ions in all charge states corresponding to rare-gas electron configurations as well as a selection of open shell configurations. 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 (Paris expertise) and RMBPT (Stockholm expertise). 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.

Göteborg and Paris teams (1999 and 2001):
The challenge of applying QED to quasi-degenerate problems has been taken up. The procedure developed so far is now being tested by numerical one- and two-photon-exchange calculations on fine-structure levels in heliumlike ions.

Stockholm team (2000 and 2001): The measurement of the masses of tritium (^{3}H) and the helium isotopes ^{3}He and ^{4}He showed that previous measurements of other research groups were wrong by a relatively large amount. We reached an accuracy of the Q-value of the beta decay of tritium close to 1 eV. The Q-value of the double-beta decay of ^{76}Ge was measured with an uncertainty of only 50 eV, using ^{76}Ge ions in the charge states with $q = 22+$ and $23+$ and ^{76}Se ions with $q = 24+$

and 25+ corresponding to Ne-like and F-like ions. For two decades there has been a serious mass problem with the mercury isotopes (atomic mass tables by Audi and Wapstra published in several issues of Nuclear Physics A). It was shown at SMILETRAP that likely the masses used for the extrapolation are wrong.

Aarhus team (1998 - 2001):
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. New knowledge was obtained on how positrons situated in a Penning trap interact collisionally, with respect to transfer of energy between the longitudinal and transverse directions. The aim was further to investigate the technical possibility of this set-up for cooling of trapped ions.

Mainz team (2000): The decay channels of multiply charged negative metal clusters have been studied for the first time. A new method to determine dissociation energies of polyatomic systems was invented that is independent of any assumptions based on the modelling of the decays.

Swansea team (2000): The efficient transfer of cold positrons into a trap which is capable of holding antiprotons, located at the Antiproton Decelerator at CERN, has set the stage for the production of antihydrogen at very low energies.

Mainz and GSI teams (2000 + 2001):
The g-factor measurements were extended in 2000 to hydrogenlike oxygen ($^{16}O^{7+}$). A single oxygen ion $^{16}O^{7+}$ was prepared in the trap, and quantum jumps between the two electronic spin orientations were induced. An experimental value for the g-factor of $^{16}O^{7+}$ was obtained in 2001. This is the second test of bound-state QED contributions to the g-factor of the bound electron in highly charged ions.

CERN team (2000 + 2001):
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. The measured mass values provide important new input for tests of the standard model of weak interaction via precision beta-decay studies. In addition, mass measurements were carried out on short-lived mercury, tin, xenon, krypton and strontium isotopes. These data help to improve our understanding of the element synthesis in explosive astrophysical scenarios and to gain insight into the structure of nuclei far from stability.

Göteborg team (2001):
The Göteborg team has provided new calculations of the radiative corrections to the Landé g-factor that, combined with the experimental results of the Mainz team have provided a value for the mass of the electron, which is more accurate (about three times) than that obtained in the recent adjustment of the fundamental constants (CODATA 1998). The QED procedure, developed for quasi-degenerate problems, may represent a breakthrough in joining QED and Many-Body Perturbation Theory. The experimental determination of nuclear magnetic moments is analysed, prompted by new hyperfine-structure measurements for highly charged ions.

Paris and Stockholm theory teams (2001):
The Paris and Stockholm teams together have set a new standard for calculations on total binding energies. We have demonstrated the accuracy by doing calculations with very different methods and by comparison with experiments, also made within the present network program. The same holds for predictions of X-ray transitions.

Paris and Lisbon teams (2001):
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 have performed highly accurate calculations on Landé g-factors for 3-electron ions and for the Ca^+ ion to motivate, and compare with, experiments in Mainz.

Lisbon team (1998 - 2001):
The Lisbon team has developed, together with the Paris team, 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. We contributed to the calculation of binding energies and computed very accurate lifetimes. 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.

Mainz, GSI and Göteborg teams (2001):
Meanwhile, 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 PRL, Jan. 2002).

1.2 Comparison of Results with Objectives and Milestones

In the following, we discuss the cooperation and the achievements of the EUROTRAPS teams by comparing their results with the time schedule and milestones as given in *Tables 1a and 1b* of the EUROTRAPS Proposal (1997).

1.2.1 Comparison of Results: Theory Groups

General remarks: The Paris team has been in charge of the subcoordination of the four theory teams acting as a sub-network. The Paris team has organized the mid-term review meeting. All the milestones and objectives have been successfully met. Many new developments that were not foreseen at the beginning of the network have occurred. The participation of the teams in the EUROTRAPS Network has led to many new additions to their relativistic atomic structure calculations, like two-photon transition rates or Landé g-factors that were needed for the interpretation of the experiments performed in Mainz and Stockholm. We have developed a new basis set for the Dirac equation that will be most helpful in relativistic many-body calculations. The theory teams also have made important progress in two-electron atom QED.

A time schedule and milestones are given in Table 1a for the theory groups (EUROTRAPS Proposal, 1997).

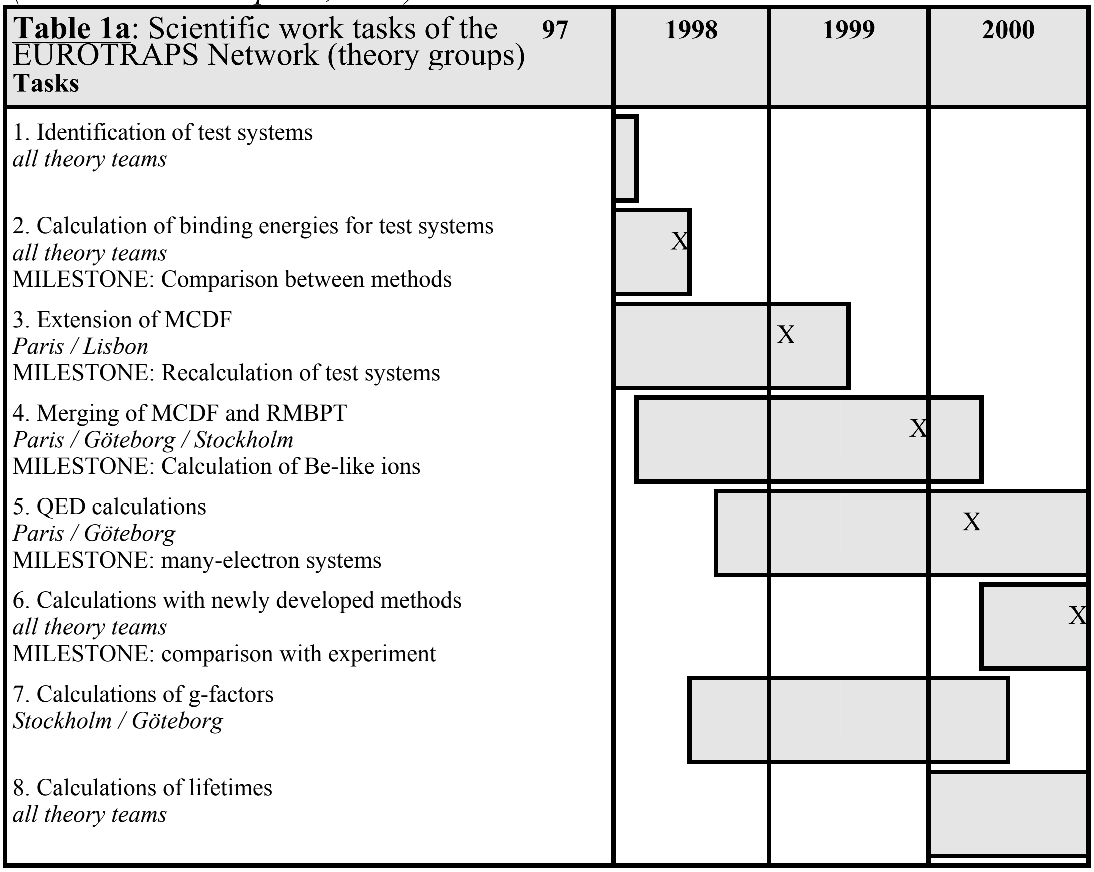

Table 1a: Scientific work tasks of the EUROTRAPS Network (theory groups) **Tasks**	**97**	**1998**	**1999**	**2000**
1. Identification of test systems *all theory teams*		▨		
2. Calculation of binding energies for test systems *all theory teams* MILESTONE: Comparison between methods		▨ X		
3. Extension of MCDF *Paris / Lisbon* MILESTONE: Recalculation of test systems		▨	▨ X	
4. Merging of MCDF and RMBPT *Paris / Göteborg / Stockholm* MILESTONE: Calculation of Be-like ions		▨	▨ X	▨
5. QED calculations *Paris / Göteborg* MILESTONE: many-electron systems		▨	▨	▨ X
6. Calculations with newly developed methods *all theory teams* MILESTONE: comparison with experiment				▨ X
7. Calculations of g-factors *Stockholm / Göteborg*		▨	▨	▨
8. Calculations of lifetimes *all theory teams*				▨

- Tasks 1+2: Identification of test systems *and* Calculation of binding energies for test systems
  all theory teams
  MILESTONE (1998): Comparison between methods
  Result: Tasks were fulfilled in due time.
  Comments: In the beginning of 1998 the cesium (Cs) ion was identified by the theory groups as an important test system for the calculation of atomic binding energies of highly charged ions because the measurement of the atomic mass of Cs with very high accuracy has been part of the experimental program of SMILETRAP in 1998. One of the motivations for the experimental and theoretical study of the cesium ion in different charge states is a better determination of the fine-structure constant α. In close collaboration the theory groups of Paris and Stockholm have calculated the electron binding energies for various charge states of Cs. From these calculations and mass measurements for different ions, one can deduce different atomic masses (i.e. masses of neutral atoms), the comparison of which enables to obtain an indication of the combined experimental and theoretical precision.
  The method of Multi-Configuration Dirac-Fock (MCDF) calculations was applied in Paris to the following closed-shell electron configurations of the Cs ion: heliumlike, berylliumlike, neonlike, argonlike, kryptonlike and neutral Cs. The results obtained with the MCDF method were compared to Relativistic Many-Body Perturbation (RMBPT) calculations performed in Stockholm. This comparison shows that the atomic binding energies can be predicted to within 10 eV for ions with closed-shell electron configurations. This theoretical uncertainty corresponds to one part in 10^{10} of the total Cs mass. The agreement between the different atomic masses deduced from the different ions is excellent. The comparison between different methods for the calculation of atomic binding energies was the milestone of the theory groups in 1998.

In addition to the calculation of the electron binding energies of the cesium ion the Lisbon, Paris and Stockholm theory groups decided to study also three- to ten-electron bismuth, thorium and uranium ions because for these test systems very accurate experimental results are available. A joint paper (Paris, Lisbon and Stockholm) about the results of these calculations was published. The Lisbon Group concentrated on the calculation of binding energies of several test systems, namely Li-like and Be-like ions with different nuclear charges Z, using the Multi-Configuration Dirac-Fock (MCDF) approach with a special emphasis on the assessment of the importance of electronic correlation. The Lisbon, Paris and Stockholm teams have also been studying the fundamental difficulties associated with the relativistic many-body problem. A long-standing problem has been associated with the non-relativistic limit of relativistic methods. The fine structure of some elements obtained by the MCDF method for example is incorrect because its non-relativistic limit is not zero. It was found that nine-electron (F-like) ions are the best candidates to study this problem. In this context the Stockholm theory group showed with the help of the RMBPT technique that the origin of the problem lies in the orbital relaxation. Adding diagrams of the same type as relaxation, but involving different orbitals (which were named generalized relaxation) enable us to recover a proper non-relativistic limit for the first time in 30 years since this problem has been identified.
The milestone to perform a detailed comparison between RMBPT and MCDF results for total binding energies was successfully completed and was published in Physical Review A. The methods we developed have also been used for an extensive compilation of X-ray transition energies, which has been submitted for publication in Review of Modern Physics. We have worked out the formalism for the merging of MCDF and RMBPT theory. This work is still an ongoing project. The endeavour for better many-body methods can probably never be considered a finished project. One unforeseen problem was that basis sets, which are generally considered to be very reliable, still show numerical difficulties in the relativistic case. A new basis set (a relativistic DVR method) has been developed during the stay of a Ph.D. student (Sung-Hwan Lee) from Stockholm in Paris.

- Tasks 3: Extension of MCDF
  Paris / Lisbon
  MILESTONE (1999): Recalculation of test systems
  Result: Tasks were fulfilled in due time.
  After a detailed discussion of the results of these binding energy calculations during the EUROTRAPS Network Collaboration Meeting in Estoril, Portugal, in October 1998 it was decided that the most promising route to extend the capability of the MCDF code is to add a Complete Basis Relativistic Configuration Interaction. This will make it possible to add thousands of electronic configurations including continuum states by using finite B-spline basis sets. The advantage of these calculations is their general applicability; however, they are very computer intensive. This method is very close to what has been developed for RMBPT by the theory group in Stockholm. Tests of both methods have been performed by the Paris and Stockholm groups on neutral He, and the agreement is very satisfactory.

- Task 4: Merging of MCDF and RMBPT
  Paris / Göteborg / Stockholm
  MILESTONE (1999): Calculation of Be-like ions
  Result: Task took longer than planned and was successfully completed in 2000.
  The second milestone of the theory teams for the year 1999, to perform a detailed comparison between RMBPT and MCDF results for total binding energies, was successfully completed in the beginning of 2000 and was published in Physical Review A (first issue 2001). We have worked out a formalism for the merging of MCDF and RMBPT theory. Several large-scale calculations have been completed with the assistance of the Lisbon team. E. Lindroth spent

one month working in Paris and we then started the next phase of our collaboration which is the work of combining the RMBPT and the MCDF methods for taking advantage of their complementary strengths. Significant progress was made. Many developments have been performed and a much better understanding of each others' methods has been reached. The computer code development has not been finished yet, due to the large effort required to improve code speed.

- Task 5: QED calculations
  Paris / Göteborg
  MILESTONE (2000): many-electron systems
  Result: Task was successfully completed in due time.
  One milestone for the year 2000 concerned QED effects in many-electron systems. In Göteborg, a method close to Relativistic Many-Body Perturbation Theory has been developed and applied to the two-photon interaction between electrons in heliumlike systems. In Paris, the other QED contribution of the same order (self-energy screening) has been evaluated, and another method for more general calculations has been developed. New parallel codes have been tested in Paris. The numerical difficulties and convergence problems were stronger than expected for two-electron self-energy.
  The methods of the g-factor calculations were transformed also into the only comprehensive QED predictions for the hyperfine-structure splitting (HFS) energy in heavy hydrogenlike systems which exist up to now. The discrepancies between experimental and theoretical results of the HFS energy led to a re-investigation of current values of magnetic moments (Gustavsson and Mårtensson-Pendrill, 1998). The QED calculations of the hyperfine structure of hydrogenlike ions has led to important new knowledge about the distribution of the nuclear magnetization in heavy nuclei (the Bohr-Weisskopf effect).

- Task 6: Calculations with newly developed methods
  all theory teams
  MILESTONE (2000): comparison with experiment
  Result: Task was fulfilled.
  The Göteborg and Paris teams have developed a new procedure, based upon a covariant form of the time-evolution operator, for evaluation of QED effects on closely spaced energy levels, so-called quasi-degenerate levels. This is an alternative to the two-times Green's-function technique, which has also been used within the network for similar purpose. The standard technique for bound-state QED, the S-matrix formulation with adiabatic switching, cannot be used in such calculations, because of the quasi-degeneracy. The covariant evolution-operator technique has been applied for the evaluation of the fine-structure splitting of the 1s2p level of heliumlike neon and argon. The results agree well with the experimental data, which have an accuracy of about 1×10^{-4}. This is the first time a numerical QED procedure has been applied to evaluate the separation of closely-spaced fine-structure levels. All those results have been presented in three contributions at the conference QED 2000 in Trieste, Italy, in October 2000.
  The second milestone of the theory teams concerned general calculations of binding energies. Large-scale coordinated efforts have been under way in Paris and Lisbon, which resulted in a complete database of binding energies for all charge states of all elements with nuclear between Z = 10 and 92, with an accuracy 40 times better than previously available. Particularly precise values are available for selected isoelectronic sequences. These important developments have only been possible through several meetings and a one-month visit of E. Lindroth (Stockholm) in Paris.

The calculations of binding energies are crucial for mass measurements on highly charged ions because the mass of a highly charged ion has to be corrected for the mass of the missing electrons and their binding energies. The electron mass is experimentally known with high accuracy but the binding energies can be an accuracy limitation for heavy atoms. They are obtained by summing up the accurately calculated ionisation energies for the missing electrons. For this purpose, the experimental team in Stockholm strongly collaborated with the theoretical groups of P. Indelicato in Paris and E. Lindroth in Stockholm. These were accurate to within 20 eV causing an atomic mass uncertainty of about 0.3 ppb. The results of these calculations have been indispensable for the mass measurements on atoms with Z>20. The calculations are in particular accurate for filled electronic shells and filled shells plus or minus one electron. Therefore, for the SMILETRAP mass measurements charge states were chosen which fulfil this condition.

- Task 7: Calculations of g-factors
  Stockholm / Göteborg
  Result: Task was fulfilled earlier than planned.
  Our numerical procedure for bound-state QED, previously applied mainly to Lamb-shift calculations of few-electron ions, have in this program been used to evaluate the g-factor (Zeeman effect) and hyperfine structure of hydrogenlike ions, which have also been studied experimentally within the EUROTRAPS Network. The results of the g-factor calculations agree well with the available experimental data. For hydrogenlike carbon the g-factor has been measured by the Mainz team within the network with an accuracy of about 1×10^{-9}, and when comparing this with theory one finds that the main uncertainty originates from the uncertainty in the electron mass. Therefore, the combination of the theoretical and experimental has led to a value for the mass of the electron, which is more accurate (about three times) than that obtained in the recent adjustment of the fundamental constants (CODATA 1998).
  During the Estoril meeting the difficulties associated with the current QED formalism have been discussed. This formalism, based on the adiabatic S-matrix and the Gellmann and Low theorem, is very difficult to use for second-order QED calculations and cannot be used for degenerate levels like $1s2p\,^3P_1$ and $1s2p\,^1P_1$. A new method, called the two-times Green's function method, has been developed by V. Shabaev a few years ago, but is not in wide use because it is not well understood. It was decided that the Paris and Göteborg groups will collaborate to study the fundamental aspects of this new method and develop it to study QED corrections on excited states of two-electron ions.

- Task 8: Calculations of lifetimes (transition probabilities)
  all theory teams
  Result: Tasks were fulfilled in due time.
  In close collaboration of the Lisbon and Paris theory groups a two-photon transition probability code for one-electron ions has been developed and tested, leading to a joint publication. This code was included in the MCDF code to calculate two-photon transition probabilities for ions with a single electron outside a closed core.
  A number of test systems were identified for one-photon transition-probability calculations. A particular emphasis has been set on systems for which the MCDF calculation method gives very imprecise results. The best candidates are systems with spin-forbidden transitions. Again the difficulties in these systems come from the fact that the transition probability in the non-relativistic limit which should be zero is not properly recovered. Be-like ions have been chosen as the best candidates and studied in details by the Lisbon and Paris groups, leading to a joint publication. Through the exchange of several Ph.D. students and short visits of senior

scientists, we developed a formalism for two-photon transitions in many-electron ions. A part of this work was published in 2001 in the European Journal of Physics D. We have also coordinated efforts to develop calculations of the dynamic properties of highly charged ions (line widths, transition probabilities, Auger rates), with applications to inner-shell transition widths and to the behaviour of plasmas and ion sources.

1.2.2 Comparison of Results: Experimental Groups

Table 1b: *Work plan of the experimental groups in the EUROTRAPS Network (Milestones are indicated by crosses, EUROTRAPS Proposal, 1997).*

Tasks	'97	**1998**	**1999**	**2000**
1. Mass measurements with SMILETRAP *Stockholm / GSI / Mainz / CERN* MILESTONE: mass accuracy $3\cdot10^{-10}$ and $1\cdot10^{-10}$, resp.	▨	▨ X	▨	▨ X
2. Improvement of vacuum and magnetic field, development of 100% ion detection *Stockholm / GSI / CERN / BFA*	▨	▨	▨	
3. Computer program development, FT-ICR detection: data acquisition, experiment control, trap design *CERN / Stockholm / Mainz / GSI / BFA*	▨	▨	▨	▨
4. Trap design and construction for weak interaction studies *Leuven / CERN / GSI*		▨	▨	
5. Connection to REXTRAP, test, weak interaction studies *Leuven / CERN* MILESTONE: Installation finished				▨ X
6. Development of electron/positron accumulator *Mainz / Aarhus / London / CERN / GSI*	▨	▨		
7. Test with electrons *Mainz / GSI / London*		▨		
8. Development of dc positron source *London / Mainz*		▨		
9. Operation, test of positron source at accumulator in Mainz *Mainz / London / Stockholm* MILESTONE: First accumulation of positrons			▨ X	
10. Positron – cluster collision studies *Mainz / London*			▨	
11. Set-up and test of positron beam line at Aarhus *Aarhus / London*		▨		
12. Design and installation of buncher, test of beam properties *Aarhus / London*		▨	▨	
13. Design of transfer optics and preparations for accumulator *Aarhus / London / Mainz / CERN / GSI*			▨	
14. Test of accumulator with intense positron pulses *Aarhus / London / Mainz* MILESTONE: Transfer of positron accumulator from Mainz				▨ X
15. Tests for positron cooling of protons and HCI *Aarhus / London / Mainz / GSI / Stockholm*				▨
16. Final tests, g-factor measurements with HITRAP at Mainz *Mainz / GSI* MILESTONE: g-factor measurement reaches 10^{-7} accuracy	▨	▨ X		
17. Design studies for deceleration of high-energy HCI *GSI / Stockholm / CERN*		▨	▨	
18. Construction and test of recoil ion source at GSI *GSI / Mainz*		▨		

19. g-Factor measurements by HITRAP using recoil ions at GSI, *GSI / Mainz* MILESTONE: g-factor measurements successful			X
20. Mass measurements with HITRAP using recoil ions at GSI *GSI / Mainz / Stockholm*			

- Task 1: Mass measurements with SMILETRAP
  Stockholm / GSI / Mainz / CERN
  MILESTONES (1998 and 2000): mass accuracy $3\cdot10^{-10}$ and $1\cdot10^{-10}$, resp.
  Result: Milestones were reached with slightly smaller accuracy.
  SMILETRAP is a Penning trap mass spectrometer connected to an electron beam ion source, CRYSIS, that can provide highly charged ions, located at Manne Siegbahn Laboratory, Stockholm University. CRYSIS can provide ions of all elements and isotopes having an abundance as low as 0.1 %. After one or two ions of the selected species are trapped in the hyperbolical precision trap, they are excited by applying a quadrupole RF-voltage. Atomic masses are measured by comparing the cyclotron frequencies of an ion whose mass is to be measured with that of a reference ion. The cyclotron frequency grows linearly with the charge of the ion and thus also the precision in mass measurements.
  In the first part of the funding period we reached a mass accuracy of better than 1 ppb, but there were some serious limitations in reproducibility. The proposed milestones of $3\cdot10^{-10}$ in 1998 and $1\cdot10^{-10}$ in 2000 were thus very ambitious. But at the end we almost reached this level of accuracy as illustrated by the summary of the results in the table below. As seen there all total mass uncertainties lie in the range 0.3-3 ppb. In the ^{4}He mass measurement a total mass accuracy of 0.3 ppb was reached which is close to the milestone set for 2000. In a dedicated investigation we tried the so-called Ramsey excitation and concluded that with 2 s excitation time we can reach an accuracy of 0.1 ppb as aimed for.
  Summary of relevant mass determinations made in SMILETRAP 1997 – 2001:

Isotope	**Charge state q+**	**Atomic mass (u)**
^{1}H	1	1.007 276 466 72(16)(89)
^{3}H	1	3.016 049 278 4(29)
^{3}He	2	3.016 029 323 5(28)
^{4}He	2	4.002 603 256 8(13)
^{20}Ne	9, 10	19.992 440 185(14)
^{22}Ne	9, 10	21.991 385 115(19)
^{28}Si	12, 13, 14	27.976 926 531 (29)
^{36}Ar	13, 14, 15, 16	35.967 545 105(15)
^{40}Ar	14, 16	39.962 383 122(40)
^{76}Ge	22, 23	75.921 402 758(96)
^{76}Se	24, 25	75.919 213 795(81)
^{86}Kr	26	85.910 610 729(110)
^{133}Cs	36, 37	132.905 45159(41)
^{198}Hg	52	197.966 768 40(60)
^{204}Hg	52	203.973 494 20(60)

Comments on the results

a) In mass consistency checks we discovered that the internationally accepted value for the ^{4}He mass was wrong by a relatively large amount. We therefore re-measured this mass. This inspired us to re-measure the tritium- and ^{3}He-mass yielding a Q-value for the interesting tritium beta-decay with an uncertainty of presently about 3 eV, corresponding to an mass uncertainty of 1 ppb.

b) Recently, we have measured the masses of ^{24}Mg and ^{26}Mg with a total uncertainty below 1ppb. These mass values are indispensable for the g-factor measurements on hydrogenlike ions, which take place in Mainz aiming at testing QED in strong electric fields. It is possible to observe the slight isotopic effect, since the electron wave function in ^{26}Mg is a little bit closer to the Mg-nucleus than in ^{24}Mg.

c) In the search for the double beta-decay of ^{76}Ge it is important to know its Q-value, which exactly gives the position of the electron peak in the $0\nu_e 2e$- decay which, if present, violates the Standard Model. We were able to determine this Q-value with an accuracy of 50 eV, which gives the position of the expected electron peak with a very high accuracy.

d) Physicists are searching for new ways of measuring the fine-structure constant α. One possible method which is independent of QED and requires an accurate value of the mass ratio $m(p)/m(^{133}Cs)$. We have determined this mass ratio with an uncertainty of 3 ppb, which is good enough for an improvement of our knowledge of the fine-structure constant α by a factor of two.

e) For two decades there has been a serious problem with the masses of mercury isotopes (atomic mass tables of Audi and Wapstra published in several issues of Nuclear Physics A). It was shown at SMILETRAP that likely some mass values used for the extrapolation are wrong.

- Tasks 2 and 3: Improvement of vacuum and magnetic field, development of 100% ion detection, computer program development, FT-ICR detection: data acquisition, experiment control, trap design
  Stockholm / GSI / CERN / BFA / Mainz
  Result: Tasks were fulfilled.
  The Stockholm team found in many tests that the main source of systematic cyclotron frequency shifts was due to a temperature effect. A change of ± 1°C can lead to a frequency shift as large as 600 ppb. Therefore, it was important to stabilise the pressure - and thus the temperature - in the helium dewar housing the superconducting coil. To improve the frequency reproducibility, we also connected the frequency synthesisers to GPS.
  The CERN team (ISOLTRAP) has continued to advance the international state of the art of Penning trap mass measurements of radioactive nuclei. The goal of such measurements is a precise determination of the total nuclear binding energy of the most exotic nuclei that can be produced in the laboratory. A difficulty is that these isotopes are generally very short-lived and are produced only in minute quantities. ISOLTRAP has succeeded in
    - reducing the minimum time it needs to store an ion for a mass measurement from more than one second to less than 100 milliseconds. This makes it possible to study isotopes with correspondingly short half-lives.
    - improving the sensitivity of Penning trap mass spectrometry by several orders of magnitude. The intensity needed for a mass measurement with 100 ppb accuracy was reduced from 10^5 ions per second to only 100 ions per second.
    - performing high-precision mass measurements important for a better understanding of fundamental interactions.

  Some major technical innovations were necessary to make these measurements possible. A carbon cluster ion source, developed by the Mainz team, was used to determine the accuracy potential of ISOLTRAP. Carbon clusters are ideal for the calibration of the Penning trap mass measurements but have never been used routinely before for this purpose. Using clusters of different sizes made it possible to perform a very thorough investigation of the accuracy limits of the ISOLTRAP mass spectrometer. The study showed that systematic errors were at least 10 times smaller than previously conservatively estimated. It was found that ISOLTRAP has the potential to perform measurements with an accuracy of at least 8 ppb.

The computer control of equipment on high voltage platforms is of interest for several trap projects. In this context the applicability of industrial field-bus systems was evaluated and 2 control systems were set up and put into operation by the CERN team. They were found to deliver high reliability and sufficient response time and to be easy to maintain. The data acquisition system used at ISOLTRAP has been the basis for a next step development. Based on the experience with a common control system for several quite similar experiments efforts have been started to develop a second-generation system based on recent programming techniques and newly available software as for instance LabView. Discussions with the network participants and incorporating their experience led to the concept of a very modular system that will be used at GSI-HITRAP and for controlling the Penning trap for weak interaction studies of the Leuven group. The later implementation at ISOLTRAP is under discussion and will benefit from the experience collected at the other two network partners.

- Tasks 4 and 5: Trap design and construction for weak interaction studies, connection to REXTRAP, test, weak interaction studies
  Leuven / CERN / GSI
  MILESTONE (2000): Installation finished
  Result: Tasks and milestone required more time than planned because a decision was made for a more complex design of the ion trap and detector apparatus.
  Ion and atom trapping techniques are of great interest for experimental studies of the weak interaction as a test of the Standard Model. Traps are especially well suited for the investigation of weak interactions as they allow for the detection of the decay products without interference from any supporting material. The clean detection of the beta particles and recoil ions emitted from stored and cooled ions in a trap makes it possible to investigate the beta-neutrino correlation in beta-decay with high precision. This allows to investigate the possible presence of scalar or tensor type components in the weak interaction, which is presently supposed to be of pure vector and axial-vector type. An ion trap was preferred over an optical trap because it is not as limited in the choice of elements that can be obtained and thus offers a wider range of possibilities as for the isotopes to be studied.
  A detailed study of different types of traps and their possible configurations in view of testing the electroweak standard model with high precision was carried out. Finally, it was decided to build a more complex apparatus than what was originally planned, but with no changes to the methodological approach described in the contract. It was decided that the best way to achieve the physics goal is provided by a system that is coupled to the REXTRAP ion accumulator at ISOLDE/CERN and consists of a deceleration section and a double Penning trap system, followed by a retardation spectrometer to probe the recoil energy of the ions resulting from beta decays in the second Penning trap. The physics information is contained in the shape of this recoil ion energy spectrum.
  The initial phase included a large number of computer simulations (for with a large PC-cluster was set up) and many discussions related to i) Penning trap technology - with the teams from GSI, Mainz and CERN - and to ii) the design of a superconducting magnet system that includes two large-bore magnets providing magnetic fields of 9 Tesla and 0.2 Tesla - with the companies Oxford Instruments Ltd. (England) and Magnex Scientific Ltd. (England).
  In the second phase a complete design for this new experimental apparatus, which combines for the first time electromagnetic ion traps with a retardation spectrometer, was realized. All components for the set-up are now either available or being manufactured. The installation of the set-up at ISOLDE/CERN has started in August 2001 and is still continuing. Major parts of the set-up were already installed and tested.
  As a consequence of the decision to build a much larger and also more complex set-up, the milestone (i.e. installation of the apparatus finished) was not reached within the period of the

network. The reason for this decision was two-fold: firstly, a higher precision can be reached with the more complex apparatus while secondly, the apparatus that is under construction now will not be restricted to weak interaction studies only but will also be very well suited for a number of investigations in nuclear and atomic physics which require detection of recoil ions or of low-energy (i.e. sub-keV) electrons (e.g. isospin impurities, Q-value measurements, in-trap spectroscopy, etc.).

- Tasks 6 to 9: Development of electron/positron accumulator, test with electrons, development of dc positron source, operation, test of positron source at accumulator in Mainz
  Mainz / Aarhus / London (later Swansea) / CERN / GSI
  MILESTONE (1999): First accumulation of positrons
  Result: Task was fulfilled in due time.
  In very close collaboration of the experimental groups at Mainz and Aarhus a cryogenic Penning trap for the accumulation of positrons from the Aarhus microtron was developed. The Penning trap, including a 6 Tesla superconducting magnet and ultra-sensitive detection electronics, was then shipped from Mainz to Aarhus. For technical reasons, the tests of the positron accumulator trap was not done in Mainz, but in Aarhus.
  The Swansea team has developed a radioactive source-based positron accumulator. First, a low-energy positron beam, based around a state-of-the-art solid-neon moderator was developed and its efficiency measured. The absolute yield of slow positrons was determined using a coincidence technique. The best efficiency has been found to be around 0.5%, giving a yield of approximately $7 \cdot 10^6$ low-energy positrons per second from a 560 MBq ^{22}Na source. This efficiency is similar to the best performance found by others using the same type of moderator. The positrons from this beam were used to feed the accumulator. The completion of this continuous positron source/beam was a **project milestone** which was achieved on schedule.
  Major progress with the Swansea positron accumulator has been made over the last two years. It is based around a buffer-gas capture and cooling method which now works routinely. We are able to capture around $2 \cdot 10^8$ positrons over a 5 minute period and hold them for extended periods. They form a plasma with a density of approximately 10^7 particles per cubic centimetre. One of the trapping electrodes has been split into 6 segments making it possible, by the application of a rotating electrical signal to the segments, to compress the plasma using the so-called “rotating wall” technique. The plasma density is increased roughly a factor of 10 over the figure given above. A novel feature is that the compression takes place during accumulation and helps reduce plasma loss by cross-field transport. The development of the positron accumulator was a **project milestone** which was achieved on schedule.
  The accumulator of the Swansea team is currently located at CERN, Geneva, in the hall containing the storage ring Antiproton Decelerator and it has been successfully operated there. The vacuum chamber housing the positron accumulator is coupled to an antiproton trapping experiment. Although positrons and antiprotons have yet to be merged, the Swansea team has successfully transferred positrons from our accumulator into the antiproton chamber where they were dynamically recaptured. Presently the transfer-plus-recapture efficiency is around 50%, and the re-trapped positrons can have very long lifetimes (greater than a few hours) in the extreme-high-vacuum and strong magnetic field conditions pertaining in the antiproton trap. The design and development of transfer optics for the positron accumulator was a **project milestone** which was achieved on schedule.

- Task 10: Positron – cluster collision studies
  Mainz / London (later Swansea)
  Result: Because the positron source was not tested in Mainz but in Aarhus (see task 9) the positron-cluster collision studies were not performed.

- Task 11 - 15: Set-up and test of positron beam line at Aarhus, design and installation of buncher, test of beam properties, design of transfer optics and preparations for accumulator, test of accumulator with intense positron pulses, and tests for positron cooling of protons and HCI
  MILESTONE (2000): Transfer of positron accumulator from Mainz
  Aarhus / London (later Swansea) / Mainz / GSI / CERN / Stockholm
  Result: The positron accumulator has been transferred from Mainz to Aarhus already in 1999. We have accumulated positrons from an intense source, namely the Aarhus Microtron. This completes the milestone for 2000.
  In Aarhus, a dedicated beam line for positrons produced at the Aarhus 100 MeV electron microtron accelerator via pair-production has been set up. A positron beam buncher has been developed and tested, which compresses the positron pulse-width to a few nanoseconds. After this work, a "positron accumulator" consisting of a Penning trap located in a superconducting magnet was transferred from Mainz to Aarhus, and connected to the positron beamline. This is one of the EUROTRAPS milestones, and was accomplished on schedule. Then we set out to catch positrons in the Penning trap, and this was first accomplished in the beginning of 2000. Since then we have been working on increasing the storage time and the number of trapped positrons. It was found that a larger than originally anticipated number of positrons has to be captured per microtron shot in order to obtain longitudinal cooling via the self-collision mechanism. Therefore, we have redesigned the Penning trap, which was ready for installation early 2001. With substantial help from Gerrit Marx of the GSI team we have identified a number of other technical problems, which have now been solved. We also computerized the whole facility for easier operation.
  Unfortunately, the Mainz superconducting magnet quenched in June 2001, without any apparent reason. We have since then taken it apart several times, but still we can cool down only to 10K. Clearly there is a mechanical problem with the magnet, most likely caused by the spontaneous quench, which we have not yet been able to identify. Therefore, the last point of our programme within EUROTRAPS, namely the demonstration of cooling of heavy ions, has to wait until the magnet is repaired.
  In Aarhus we have accomplished almost the entire scientific programme which was planned. One major goal for the network was to find ways to cool highly charged ions with cold positrons. Two methods were employed, one based on pair-production of positrons (Aarhus team) and the other on a radioactive source (London/Swansea team).

- Task 16: Final tests, g-factor measurements with HITRAP at Mainz
  Mainz / GSI
  MILESTONE (1998): g-factor measurement reaches 10^{-7} accuracy
  Result: In 1998, the g-factor measurements reached an accuracy of 10^{-6}. Meanwhile the accuracy was improved with an optimised measurement technique by three orders of magnitude to 10^{-9}.
  The experimental determination of the magnetic moment (g-factor) of the bound electron in hydrogenlike ions is an important test of the theory of Quantum Electrodynamics in strong nuclear Coulomb fields. In 1998, the experimental groups at Mainz and GSI performed the first measurement of the g-factor of the bound electron in a highly charged ion, with an experimental accuracy of 10^{-6}. This measurement is a breakthrough in the field of bound-state quantum electrodynamics (joint publications in PRL). The g-factor is measured by inducing spin-flip transitions of the bound electron with a single hydrogenlike ion stored in the

magnetic field of a Penning trap. The "test ion" in these measurements was hydrogenlike carbon ($^{12}C^{5+}$). In 1999, the experimental accuracy was improved by more than a factor of 1000 to 10^{-9} with an optimised measurement technique where the spin-flip transitions are induced and detected at two different positions in the Penning trap. The measured value of the g-factor of hydrogenlike carbon is $g(^{12}C^{5+}) = 2.001\ 041\ 597\ (4)$. The comparison of this experimental result with the also improved calculation of the Göteborg theory group shows excellent agreement. With the improved accuracies it is now possible, even for light hydrogenlike ions, to test the bound-state QED contributions. Our present experimental result confirms the bound-state QED terms in hydrogenlike carbon on the one-photon level with a fractional uncertainty of 1%.

Meanwhile, 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 $^{12}C^{5+}$ (Mainz and GSI teams) 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 by the EUROTRAPS Network is of great scientific importance (joint publication in PRL, Jan. 2002).

- Task 17: Design studies for deceleration of high-energy HCI
  GSI / Stockholm / CERN
  Result: The design studies are still going on.
  The HITRAP team at GSI submitted a Proposal in 1998 which was approved by the GSI scientific management. The approval of the HITRAP Proposal includes the allocation of the financial funds for the construction of the decelerator as well the ion-trap facility. For efficient capture and cooling in a Penning trap, the highly charged heavy ions extracted from the ESR must be decelerated from an energy of 3 MeV/u to below 10 keV/u. A combination of two different types of decelerators, i.e. an RFQ decelerator and an interdigital H-mode structure is planned. At a workshop in 1998 the advantages and disadvantages of this scheme were evaluated by accelerator experts from CERN, McGill University/Canada and GSI Darmstadt. Meanwhile, a RFQ decelerator for deceleration of antiprotons is in operation at CERN. It was tested at an accelerator in Aarhus with a proton beam. During several machine times during the last years, the accelerator team at GSI demonstrated that highly charged ions can be decelerated in the ESR storage ring to an energy below 10 MeV/u under stable conditions. This is an important step towards the goal of reaching an energy of 3 MeV/u which is required for the operation of the HITRAP Facility under the foreseen financial and technical boundary conditions. Meanwhile, the HITRAP Facility is the topic of a European RTD Network (HPRI-CT-2001-50036).

- Task 18 and 19: Construction and test of recoil ion source and g-factor measurements by HITRAP using recoil ions at GSI
  GSI / Mainz
  MILESTONE (2000): g-factor measurements successful
  Result: Because of the very positive experiences of the Mainz team the planned recoil-ion source was replaced by an electron beam ion source.
  In the workplan for the experimental groups it was planned to construct a recoil-ion source at GSI to extend the g-factor measurements to medium-heavy ions. However, this workplan was changed because of the positive experiences with the production of light hydrogenlike ions by electron-impact ionisation in the g-factor experiment at Mainz. Therefore, the **milestone "**g-factor measurements by HITRAP using recoil ions at GSI/Mainz, g-factor measurements

successful" is not directly applicable any more. Instead of the recoil-ion source a new version of the present Penning trap was constructed in a joint effort of the GSI and Mainz teams. With this new set-up it is possible to produce medium-heavy hydrogenlike ions up to Z ≈ 20 to 30 by electron-impact ionisation. The construction of the new trap was finished in 2000. g-Factor experiments on hydrogenlike oxygen ($^{16}O^{7+}$) ions were performed in 2000 and 2001. A single oxygen ion $^{16}O^{7+}$ was prepared in the trap, quantum jumps between the two electronic spin orientations were induced, and data of the g-factor of the bound electron in $^{16}O^{7+}$ were taken. A final experimental value for the g-factor of $^{16}O^{7+}$ was obtained in 2001.

- Task 20: Mass measurements with HITRAP using recoil ions at GSI
  GSI / Mainz / Stockholm
  Result: Test measurements for mass spectrometry will be performed by the Mainz team with highly charged ions from an electron beam ion source (see task 18). A resolving power of 10^9 was reached for light ions.

1.3 Networking and coordination activities

1.3.1 Business and Collaboration Meetings and Midterm Review Meeting

- The EUROTRAPS Business Meeting 1998 took place in Mainz on 28 March 1998 with representatives of each team (altogether 15 participants). An agenda of a Business Meeting is given below. This is typical for the other business meetings as well.
  Topics
  1. Approval of the minutes of the last Business Meeting
  2. Approval of the minutes of the last Collaboration Meeting
  3. Short progress reports of network participants
  4. Annual report for Brussels
  5. Milestones and person months: Can we fulfill our promises?
  6. Joint publications
  7. Working Groups
  8. Exchange of personnel, open positions
  9. Training of young researchers, school for students
  10. Financial situation of the teams: redistribution of money
  11. Next Business and Collaboration Meeting
  12. Any other business

- The EUROTRAPS Collaboration Meeting 1998 took place from 30 October to 1 November 1998 in Estoril, Portugal, and was organized by the Lisbon team. This meeting was held together with the Collaboration Meeting of EXOTRAPS, a European Network of nuclear physics groups working with ion traps, since there is common interest in ion trapping and cooling techniques. From the 82 participants, 44 were members of EUROTRAPS, 34 members of EXOTRAPS and three were invited as guests. All in all 44 young researchers participated.

- The EUROTRAPS Business Meeting 1999 took place in Leuven, Belgium, on 15 April 1999 with representatives of each team. The Business Meeting was held together with the Business Meeting of EXOTRAPS (altogether 18 participants).

- The EUROTRAPS Collaboration Meeting 1999 took place on 17-18 September 1999 in Neckarzimmern, Germany, and was organized by the GSI team. This meeting was held together with the Collaboration Meeting of the EXOTRAPS Network. From the 58 participants, 34 were members of EUROTRAPS, 21 members of EXOTRAPS and three were invited as guests. Altogether 28 young researchers participated.

- The EUROTRAPS Business Meeting 2000 took place in Paris, France, on 28-29 February 2000 with representatives of each team. The Business Meeting was held together with the EUROTRAPS Midterm Review Meeting and also together with the Business Meeting of EXOTRAPS (altogether 24 participants). All young researchers participated in the Midterm Review Meeting and gave reports on their work and experiences. The application of the EUROTRAPS Network for a prolongation by one year (until the end of 2001) was approved.

- The EUROTRAPS Collaboration Meeting 2000 took place on 24-26 October in Honfleur, France, and was organized by the Paris team. This meeting was held together with the Collaboration Meeting of the EXOTRAPS Network. From the 53 participants, 20 were members of EUROTRAPS, 29 members of EXOTRAPS and 4 were invited as guests. Altogether 24 young researchers participated.

- The EUROTRAPS Business Meeting 2001 took place in Munich, Germany, on 3 March 2001 with representatives of each team. The Business Meeting was held together with the EUROTRAPS Business Meeting (altogether 24 participants).

- The EUROTRAPS Collaboration Meeting 2001 took place on 11 - 13 October at CERN, Geneva/Switzerland, and was organized by the CERN team (31 participants were members of EUROTRAPS). This meeting was held together with the Collaboration Meeting of the EXOTRAPS Network and with first Business Meetings of the upcoming European Networks HITRAP, NIPNET and IONCATCHER (altogether 72 participants).

1.3.2 Workshops on Special Topics

The following working groups exist within the EUROTRAPS Network:

- Working group on rf-cooler: organized by the GSI team, 1 workshop in 1998

- Working group on computer control: organized by the CERN team, 1 workshop in 1998, 13 participants;

- For the preparation of the HITRAP Facility a workshop was held at GSI in December 1998 to discuss different schemes for the deceleration of highly charged ions. For efficient capture and cooling in a Penning trap, the highly charged heavy ions extracted from the ESR must be decelerated from an energy of 3 MeV/u to below 10 keV/u. During the workshop the advantages and disadvantages of three different deceleration schemes, i.e. an inverse cyclotron, a RFQ decelerator and an interdigital H-mode structure were compared and evaluated. Accelerator experts from CERN, McGill University/Canada and GSI Darmstadt showed great interest in the construction of such a decelerator. The workshop was organized by the GSI team, 14 participants;

- In June 1998 a workshop was held in Leuven on ion traps for weak interaction studies with members from the CERN, GSI, Leuven/Louvain-la-Neuve and Mainz teams, while members from the Leuven team have also visited on several occasions the CERN, GSI and Mainz institutes in order to discuss a number of key aspects of the set-up. This has led recently to a design that is now being worked out in detail using computer simulations.

- Working group on cooling of trapped ions: organized by the London team, 1 workshop in 1999 with 34 participants;
- Working Group on Penning Traps: organized by the CERN team, 1 workshop in 1999, 25 participants;
- Working Group on space-charge effects in ion traps: organized by the CERN team, 1 workshop in 2001, 22 participants;
- In addition, working groups on Penning traps and on computer control and theoretical working groups had meetings during each EUROTRAPS Collaboration Meeting. Also, members of EUROTRAPS participated in workshops organized by EXOTRAPS.

1.3.3 Schools for Students and Young Researchers

- The Collaboration Meeting 1998 was preceded by a 2.5-day school which took place at the University of Lisbon and included public lectures for faculty members.
- An ion trap school in Heidelberg was organized by the GSI team in March 2000. 64 participants, mostly students and young researchers, enjoyed a very attractive programme. It is planned to organize a similar school in the future.

1.3.4 EUROTRAPS Internet homepage

A homepage in the Internet was set up for the EUROTRAPS Network. The EUROTRAPS homepage provides information about the different teams, job offers for young researchers and Network Meetings. The address is:

http://www.gsi.de/eurotraps

1.3.5. Interaction with Industry: Visit to Bruker-Daltonik

In February 2000, EUROTRAPS organized a visit to the company Bruker-Daltonik in Bremen, Germany. 14 young researchers participated in the visit.

1.4 Benefits of working together at a Community level

All collaborators of the EUROTRAPS Network, including young researchers, students and senior scientists, experienced the network cooperation as very fruitful and inspiring. The scientific life on a Community level, in particular during Collaboration Meetings, workshops and conferences, made physics more attractive for young people.

Statements of some EUROTRAPS teams concerning the “benefits of working together” are listed below.

- Without the close collaboration of the experimental teams at Mainz/GSI with the theory group from Götheborg the test of bound state quantum electrodynamics by g-factor measurements on hydrogenlike ions would be much less significant than they now are. Particularly the new and improved value for the electron mass was obtained by a continuous direct interaction of members of the teams.

- Cooperation of the Stockholm team (SMILETRAP) with other groups within the network: The experimental team in Stockholm has collaborated with the theory teams in Paris (and in Stockholm). The calculations of binding energies has been very important for the applicability of our mass measurement on ions with Z>20; when an accurate value for the binding energy is available measurements on one charge state readily can be translated to other charge states. There has been several short term exchanges of personnel betweeen Stockholm and GSI and CERN which were very benificial for both sides as similar trap systems are used in these laboratories. Stockholm was first in employing a LabView operation system for their traps, one issue of mutual training. Several joint publications emerging from these collaborations have been submitted.

- Aarhus team: The benefits of collaborating in a European network have been absolutely crucial for the Aarhus team. Without the cooperation especially with the Mainz and the London/Swansea teams, we would not have been able to build the Aarhus positron facility. Apart from that, it has been a great advantage to be able to discuss and interact with the members of all the other teams.

- Swansea team: For the duration of the project the Swansea team has maintained strong connections with our colleagues in Aarhus, Denmark, particularly concerning various aspects of positron trapping and bunching technology. **Community support** has enabled the exchange of personnel at critical times during the development of the project. Together we have performed experimental tests of a positron bunching system and have supported this work with extensive numerical simulations of the behaviour of the device. The design and installation of the buncher and tests of the output beam properties was a **project milestone** which was achieved on schedule. We are currently preparing a joint publication on this work, which would not have been completed without **community support**.

- CERN team: The close collaboration with several EUROTRAPS teams definitively helped the CERN team (ISOLTRAP) to keep its world-wide leading role in Penning trap mass measurements on radioactive isotopes. The very efficient collaboration between the CERN team and the GSI team was decisive for accomplishing the above mentioned ISOLTRAP improvements in a short time. The exchange of personpower during online runs between the CERN, GSI and Leuven teams allowed for an intense measurement program and stimulated the exchange of ideas with the other partners. The large experience of the ISOLTRAP team in trapping radioactive species and mass measurements was efficiently transferred to the collaborating groups either by personnel exchange or via collaboration and working group meetings.

- Leuven team: Although the Leuven team has a long-standing tradition in high-precision weak interaction studies we had, at the start of the project, no experience in trap technology. We have therefore been working in close collaboration with the teams from GSI, Mainz and

CERN while, in addition, a former Ph.D. student of the GSI and Mainz teams was working as a postdoc in our team. This cooperation at a community level has provided an efficient transfer of advanced trap expertise to our team. At the start of the project a “Beta-decay trap” workshop was held in Leuven in order to explore the possibilities for weak interaction studies with both unpolarized and polarized ions in different types of ion traps. This was attended by members of the teams from GSI, Mainz, CERN and Leuven.

- Bruker team: During the whole period there has been a strong collaboration between Bruker and the Mainz Cluster team. Experiments on trapped fullerenes have been performed at Bremen which are not possible at the Mainz cluster trap. Finally, the experiments have been extended to small systems that are produced by the electro-spray technique which is not available at Mainz. A joint paper with the working title “Attachment of a second electron to stored metal cluster and fullerene anions” is in preparation. These experiments will be continued in 2002. A new MALDI source and a new designed ICR trap electronics will enable us to do more detailed investigations.

- Theory teams in Göteborg, Lisbon, Paris and Stockholm:
  The Paris and Stockholm theory teams have collaborated extensively during the whole period and several longer and shorter exchanges of personnel have taken place, of young researchers as well as of senior researchers. For example, E. Lindroth from Stockholm has been for two one-month-long visits to Paris in 2000 and 2001 as invited professor. We have today a good understanding of each others’ methods and have been able to use this knowledge to push the calculations of relativistic many-body systems towards higher accuracy and reliability in several cases. The collaboration will continue after the end of the present project. We are already working together on new projects.
  Many new activities and results where spawned from the interaction between the teams. The work of the team in Quantum Electrodynamics undoubtedly benefits from the collaboration with Göteborg. The enhancement of the collaboration with the Stockholm teams has been immensely valuable. The collaboration with Lisbon has motivated many developments. During the network program the Göteborg theory group has increased the collaboration with the GSI and Paris teams and also a group in Dresden. This collaboration has extended the field of research into new areas and has resulted in a number of joint publications. These collaborations will continue also after the closing of this program, particularly the collaboration between Göteborg and Paris concerning quasi-degenerate QED calculations. We have started to compare the two methods presently available for quasi-degenerate QED calculations, the two-times Green’s-function technique and the covariant evolution-operator technique, and interesting new results have appeared, which will be useful for future applications. The numerical procedures which we now have available for quasi-degenerate QED calculations have the potential for considerably higher accuracy than obtained so far, and there exist now also more accurate experimental data. The continuation of this work might therefore contribute to the future determination of the fine-structure constant α, for which there is presently serious disagreement between different evaluation procedures.
  The involvement with other scientists in new advances in physics is very important for researchers working in peripheral countries as Portugal. The EUROTRAPS Network was an invaluable instrument that allowed us to work in synchrony with leading research teams. We look forward for more programs of this kind to allow for a continuing involvement in advanced research in the field of atomic physics. The network gave a valuable contribution for incrementing in the Lisbon group the study of state-of-art methods of calculation of a broad range of atomic quantities, including binding energies and lifetimes, attracting more researchers to this field.

1.5 Interaction with Industry

In 1998 Bruker introduced the software for acquisition and evaluation of FT-ICR data for PC platform, so far only based on UNIX platform. This development made the Bruker software - and so the FT-ICR detection technique - available for a much greater community, in particular for the EUROTRAPS collaboration partners.

In parallel, Bruker developed a new generation of actively shielded superconducting magnets up to a field strength of 9.4 Tesla with horizontal bore and 16.4 Tesla with vertical bore. This shielded type of magnet provides much less influence on electronic devices in the laboratory as well as much less distortion of ion beams guided into the magnet field. Also influences from outside to the magnetic field are minimized. In addition, shielded magnets provide a much safer working environment in the laboratory. In the meantime, such a type of actively shielded 7 Tesla superconducting magnet with horizontal bore which is provided by Bruker for its FT-ICR mass spectrometer is used by the GSI group. A project aiming at the improvement of the sensitivity of the FT-ICR detection electronics together with L. Schweikhard from the Mainz Cluster team and the electronics workshop of the Physics department of the University of Mainz had to be cancelled since L. Schweikhard recently left Mainz for a new position at University of Greifswald.

Interaction of young researchers with the Bruker team:

- In November 1999, Bruker participated in the “FANTOM Study week” on “Physics with Trapped Particles” at the University of Leuven. An employee of Bruker, R. Jertz, gave a lecture about “Fourier Transform ICR mass spectrometry and its applications in biochemistry”. The contact had been established by N. Severijns, the leader of the EUROTRAPS Leuven team.

- In 2000, EUROTRAPS organized a visit to the company Bruker-Daltonik in Bremen, Germany. 14 young researchers participated in the visit. An FT-ICR training course was held including “hands on” measurements at the Bruker FT-ICR instrument.

- The Bruker team employed Ester Marotta, a doctoral student from University of Padua from April 1, 2001, for 9 months for an intensive training on the FT-ICR technique. Tomas Fritioff from the SMILETRAP team has been employed by Bruker from April 01, 2001, for 9 months. He participated in a new development of a filament for “Electron Capture Dissociation” which is a collaboration together with a customer from Uppsala (continued in 2002). This method will serve as a very important tool for the characterisation of biomolecules.

Statements of some EUROTRAPS teams concerning the interaction with industry:

- Leuven team: We have had intensive and regular contacts and exchange of information with the companies MAGNEX and Oxford Instruments regarding the design of the magnet system for the Penning trap and retardation spectrometer set-up which we are developing.

- The collaboration between the teams of Bruker and Mainz is still strong. We continued the joint experiments on fullerenes at Bremen which are not possible in the Mainz Cluster Trap and extended them to small systems that are produced by the electrospray technique which is not available at Mainz.

- Discussions have been going on between the Bruker team and the Aarhus team about a possible development of a positron-annihilation based mass spectrometer for biomolecules. Conclusions from this discussion are expected for the near future.

1.6 Training and mobility of young researchers

The following measures were taken to provide training and enhance mobility of young researchers.

- The g-factor experiment performed by the Mainz/GSI teams relied heavily on the cooperation of members from different European countries. 3 of 5 doctoral students actively involved in the experiment during the duration of the EUROTRAPS Network were from different countries of the European community. The scientific and technical trainining of these students on a high level will enable them to work as independent reseachers in the future.

- The young researchers of the EUROTRAPS Network were invited to participate in the annual Collaboration Meetings. These meetings were organised in a way which is attractive for young scientists. For example, introductory talks were given in special sessions by more advanced young researchers. Also, all speakers were asked to present their contributions such that they are understandable and pedagogical for young researchers who are new to the field.

- Young researchers were encouraged to visit other EUROTRAPS teams and to participate in their scientific activities. The young researchers have the possibility to use the scientific results which emerge from such a collaboration in their PhD thesis.

- The young researchers participated in the Euroconferences which were organised partly by team leaders of the EUROTRAPS Network. A series of three such conferences, entitled "Euroconference on Atomic Physics with Stored Highly Charged Ions", was held in Heidelberg/Germany (1995), Stockholm/Sweden (1996) and Ferrara/Italy (1997). A second series of conferences, entitled "Euroconference on Atomic Physics at Accelerators (APAC)", was held in Mainz/Germany (1999), in Cargese/France (2000) and in Aarhus/Denmark (2001).

- In February 2000, the Bruker team organised a two-day visit to the company in Bremen/Germany. Young scientists from all EUROTRAPS teams were invited to join this visit which was very interesting and fruitful according to the statement of the participating young researchers. Six different nationalities were represented at this visit.

- Concerning the exchange of scientific information between the young researchers the EUROTRAPS workshops are of great significance. At least one (often two or three) young researcher of each team is delegated to attend a workshop which is relevant for the team. A survey of each workshop is given to all teams by sending the minutes and copies of transparencies.

Here are some statements of the EUROTRAPS teams concerning the "training and enhance mobility of young researchers".

- It has been very fruitful for the young researchers and beneficial for their careers to be able to work in groups in foreign countries. The interaction with another culture is a plus in itself.

The Aarhus team has had young people from Germany and Ireland working for extended periods of time, and one of their students has likewise worked in Stockholm. Even for those students that did not join the other groups for a long period it was fruitful to meet all the EUROTRAPS teams at the collaboration meetings, workshops and conferences.

- The Swansea/Aarhus/Mainz aspect of the project has enabled one **young researcher** to develop and dramatically extend his PhD training by allowing him to tackle distinct, but related, projects which are both scientifically and technically demanding.

- The close international collaboration within the EUROTRAPS Network made the ISOLTRAP team more attractive to young researchers. The doctoral students and the post-doctoral researchers who worked during the project period at ISOLTRAP benefitted from the wide spectrum of physics carried out within the EUROTRAPS Network. It was possible for them to learn about the scientific goals of the various teams and to follow in detail the progress at other places. Vice versa many young researchers visited ISOLTRAP in order to collaborate or to gather information. This together with the regular coming together at special workshops and collaboration meetings triggered a lively communication between the young researchers at ISOLDE and those from other places, which was a key for the successful exchange of ideas throughout the network.

- Leuven team: The international context provided by the network in which this project was carried out has significantly contributed to the training of several young researchers in our team (i.e. not only those that were paid from the network) and has created new research contacts that will be continued.

- The Stockholm theory team has hosted one postdoc from France (Mohammed Ourdane), one from Germany (Josef Anton) and one from Spain (Jose Luis Sanz-Vicario). One of our graduate students (Sung-Hwan Lee) has further spent a whole year in Paris. In this way we have given several young researchers a possibility to continue with research and broaden their knowledge. In Stockholm they have especially been given training in many-body theories and methods. For our graduate student the year in the Paris group has been very valuable. He has been given the possibility to work in one of the best groups in the world in relativistic quantum mechanics and quantum electrodynamics and has there started up a completely new project. Tutorial lectures on many-body techniques have been given at the school organized by the network during the EUROTRAPS Collaboration Meeting 1998 in Lisbon.

- The Stockholm theory team has hosted one postdoc from France (Mohammed Ourdane), one from Germany (Josef Anton) and one from Spain (Jose Luis Sanz-Vicario). The experimental team has hosted one postdoc from France (Gulhem Douysset) and two postdocs from Denmark (Henrik Bluhme and Jens Jensen). One of our graduate students (Tomas Fritioff) has spent 9 months at the Bruker team and received training in FTICR detection technique. One of our graduate students (Sung-Hwan Lee) has further spent a whole year in Paris. He has been given the possibility to work in one of the best groups in the world in relativistic quantum mechanics and quantum electrodynamics and has there started up a completely new project. In this way we have given several young researchers a possibility to continue with research and broaden their knowledge. Tutorial lectures on many-body techniques have been given at the school organized by the network during the EUROTRAPS Collaboration Meeting 1998 in Lisbon.

- Ph.D. students from Göteborg, Lisbon and Stockholm have spent time in the Paris team, bringing in new expertise from their home team, or being trained in advanced computing technique. One of them, G. Rodrigues from Lisbon is now a Marie Curie fellow in Germany in theoretical ecology, exploiting his computing and differential equations skills, acquired during his three years in our team, in a completely different field. Tutorial lectures were given on QED at the school organized by the network in Lisbon.

- The Göteborg theory team has hosted Thomas Beier (Dresden, 24 months), providing him with training in our QED techniques. Eric-Olivier LeBigot (Paris), stayed 2 months in Göteborg, to learn our QED techniques and establish the link with the developments made in Paris. Björn Åsén, from Göteborg, visited Paris for 2 months to get training on the theoretical methods used there.

- Lisbon team: In our opinion, the network was useful for the training of a Portuguese young researcher in Paris, who otherwise would not have chosen this field, and for the training of a French young researcher in Lisbon. We organized a training school in Lisbon that was attended by many students, researchers and post-docs from the Lisbon University, as well as participants and young researchers from all teams in the network.s