2.1. Summary of the scientific program

In our scientific program we study different actual subjects, which are among those where large efforts (also financial) are currently made in theoretical and experimental physics. We are especially interested in problems, which are investigated, e.g., at PSI, CERN (SPS & LHC), GSI (especially FAIR), CEBAF (TJNAF), MSU (RIA) or at RHIC (BNL). The new experimental data obtained at these facilities ask for new theoretical descriptions or at least for an improvement of existing methods.

In atomic physics, we study mainly the excitation and ionization of atoms in ion-atom collisions, because the detailed knowledge of these processes is important, e.g., in plasma-, astro- or surface physics. We treat these reactions by using the semiclassical approximation, the Born-approximation in first or in higher order or in the Glauber approximation, but in all our calculations we use the full quantum mechanical description of the electronic states, e.g., relativistic hydrogenic wave functions or Dirac-Fock wave functions. For the ionization of electrons from outer shells, the intra-shell couplings become important, which are treated by us in a perturbative way. In strong collaboration with experimental groups worldwide we test our refined reaction model by comparing it with recent data and we make predictions and suggestions for new experiments to study, e.g., correlation effects. An important application of our methods developed in atomic physics is the calculation of excitation and breakup of exotic atoms and their propagation through matter. The detailed knowledge of these processes is crucial for the interpretation of the experiment DIRAC at CERN (and its possible continuation at J-PARC and/or GSI), which aims at measuring the lifetime of pionium and in the future also of other atoms like kaonium, thus testing some important prediction of quantum chromodynamics and chiral perturbation theory.

At new rare isotope facilities (especially FAIR at GSI or RIA) one produces exotic nuclei far from stability, close to the proton or neutron drip line. New phenomena like halos and pigmy resonances have been found. They present challenges for nuclear structure theory and are also of astrophysical importance. Our main focus is the Coulomb excitation of these nuclei as a main experimental tool to get more insight into their structure.

We study electromagnetic processes in the collision of relativistic heavy ions. Due to the strong electromagnetic fields photonuclear and photon-photon processes can be observed. RHIC (STAR and PHENIX) has an ongoing experimental program for these so-called ultraperipheral collisions. Our main interest is the study of interference effects in coherent vector meson production, of strong field effects of QED in e^+e^--pair production, the use of inelastic pair production for (deep) inelastic photon interactions and also the study of electroweak processes in pA collisions.

With the possibility of continuous electron beams, e.g., at TJNAF, exclusive electron scattering reactions can now be studied in detail. We investigate radiative corrections, going beyond the soft photon limit and the peaking approximation. Coulomb corrections in these processes are significant for the interpretation of the experimental results and calculations using the exact solution of the DIRAC equation are now possible.

RHIC-Spin will be the first polarized proton-proton collider and will be capable of copious production of jets, directly produced photons, and $W^{\pm}$ and Z bosons in the near future. Features will include direct and precise measurements of the polarization of the $\bar{u}$, $\bar{d}$, u and d quarks. Therefore, it is our intention to start a collaboration with the theory group of Prof. Gehrmann at the University of Zürich, with the aim to study how antiquark distributions in the proton can be extracted from the experimental data concerning spin asymmetries in the W boson decay at RHIC.

Based on our experience in the treatment of scattering processes, we also study the chaotic behavior of classical open (scattering) systems. Hereby we are especially interested in the correspondence between quantum mechanics and the chaotic behavior of classical systems. We concentrate on the investigation of Rydberg molecules which can be easily calculated quantum mechanically and which behave according to their highly excited states also nearly classically. So the structures seen in classical mechanics may show up there in the corresponding quantum mechanical expressions.

Key words:

Theory; atomic physics; hadronic atoms; nuclei far of stability; nuclear astrophysics; ultraperipheral collisions in heavy ion collisions; QED with strong fields; photon-photon and photonuclear processes; exclusive electron scattering; radiative and Coulomb corrections; high-energy hadron collider physics; semiclassic, chaotic scattering.

2.2. Scientific program

A - Atomic physics

SCA calculations of inner shell ionization

D. Trautmann, G. Lapicki (Greenville, NC - USA)

2.2.1.

The detailed knowledge of the ionization probability of inner-shell electrons in ion-atom collisions is important in many areas of physics, e.g., in plasma-, astro- or in surface physics, but also for the fundamental understanding of the atomic reaction mechanism, see, e.g., [D.H. Madison, Atomic Inner Shell Processes, Academic Press, New York, '75]. So, still a lot of experimental groups are measuring this process with increasing accuracy. Ionization from K-, L-, M- and N-shells is investigated and extensive data for total and impact parameter-dependent cross sections are available, see, e.g., [H. Paul & J. Muhr, Phys. Rep. 135 ('86), 47; J. Semaniak et al., Nucl. Instr. and Meth. B75 ('93), 63]. These data, especially for medium bombarding energies in very asymmetric systems can be fairly well described by the semiclassical approximation (SCA) using hydrogenic electronic wave functions, see, e.g., [J. Bang et al., Kgl. Dan. Vid. Selsk. Mat.-Fys. Medd. 31 ('59), 13; L. Kocbach, Z. Phys. A279 ('76), 233; F. Rösel et al., Nucl. Instr. and Meth. 169 ('80), 259].

2.2.2.

In our general computer code IONHYD, based on the SCA, we use relativistic hydrogenic, as well as, relativistic Hartree-Fock wave functions for the initial and final electronic states. Using this code for the description of inner-shell ionization, written several years ago, we were able to fit without free parameters not only the ionization data for the K- and L-shell in asymmetric collisions very well, but also the ionization from the higher shells and the ionization induced by heavier projectiles like Li-, C-, N- or O-ions, although with decreasing accuracy. This was a little bit a surprise since our approach is based on first order perturbation theory and the increasing (non-perturbative) influence of the disturbing projectile field is neglected [I. Bogdanovic et al., Nucl. Instr. Meth. B150 ('99), 18; Z. Halabuka et al., Z. Phys. D29 ('94), 151; M. Pajek et al., Nucl. Instr. Meth. B150 ('99), 33; A. Kubala-Kukus et al., Nucl. Instr. Meth. B152 ('99), 27]. Therefore we started to include these non-perturbative effects in a full coupled channel approach, at least in an approximate way, to obtain an even better accuracy for the analysis of the data.

Similarly successful for the description of total ionization cross sections is the ECPSSR-theory, developed in the last two decades [W. Brandt and G. Lapicki, Phys. Rev. A23 ('81), 1717, and further references therein]. This theory is based on the non-relativistic first order Born approximation and all additional physical important effects like screening, Coulomb deflection, relativistic effects and higher order perturbations of the wave functions are included by semi phenomenological correction factors. The great advantage of the ECPSSR model is that it allows a very easy calculation of total cross sections and therefore this approach is, e.g., very convenient for experimentalists for a first interpretation of their data.

2.2.3.

We will further analyze systematically very recent data on L-, M- and N-shell-ionization, using our general SCA-code with Dirac-Fock functions in strong collaboration with experimental groups, e.g., at Warsaw (Poland - M. Jaskola, D. Banas, M. Pajek et al.), at Erlangen (Germany - W. Kretschmer et al.) and at Mumbay (India - L. Tribedi et al.). By analyzing these total and differential ionization cross sections from the higher shells we have realized that it is necessary to include the coupling between the different subshells for an accurate analysis. Therefore we will modify our computer code IONHYD by using a full coupled-channel approach and using exact Dirac-Fock wave functions. Especially we are also interested in an approximate description of these very time-consuming coupled-channel calculations, which may then easily be applied in the analysis of the experiments. Some progress has already been obtained in this respect: comparing a simplified coupled channel calculation (by using straight line trajectories and non-relativistic wave functions as an approximation) with the corresponding first-order calculation, gives a correction factor which can then be used for the full first-order calculation, see [D. Banas et al., J. Phys. B35 ('02), 3421]. This method indeed works quite well for L-shell ionization and for light projectiles (i.e. lighter than C). Now we will improve this approximation, so that it may be used also for M-, N- and O-shell ionization and for heavier projectiles.

Finally we will incorporate these correction factors in the existing ECPSSR code thus extending this simple approach to the ionization from higher shells. This will be a great help for experimentalists being able to calculate also these ionization cross sections very easily. We will then prepare tables containing the parameters of these correction factors which can then be used for a simple estimate of the cross section. Also we will study if this simple method can be extended to the description of impact dependent ionization probabilities. Additionally, we will investigate the correction factors already being used in the ECPSSR and try to improve them by systematically comparing this model with full ab initio calculations.

Excitation and ionization of inner shells in relativistic heavy ion collisions

D. Trautmann

2.2.1.

In recent years there has been an increasing interest in excitation and ionization phenomena in relativistic ion-atom collisions, see, e.g., [J. Eichler and W. Meyerhof, Relativistic atomic collisions, Academic Press ('95)]. This is due to an increasing amount of data which are now available, e.g., from GSI (Darmstadt, Germany) and from CERN [H.F. Krause et al., PRA63 ('01), 032711 and references therein]. In these experiments ionization was measured at relativistic energies (e.g., $\gamma = 20$ at experiment DIRAC or $\gamma = 168$ at CERN-SPS). Theoretical calculations are mostly based on the first-order Born approximation (PWBA) [J. Anholt, Phys. Rev. A31 ('79), 1004] or on the semiclassical approximation (SCA) [G. Mehler et al., Z. Phys. D13 ('89), 193], but an analysis of the energy distribution of electrons after ionization was only partially successful. Besides the interest in itself of explaining these experimental results, the results are also interesting in connection with the breakup of pionium (see below), because the Z=82 system Pb^{81+}, investigated at CERN-SPS is similar to the pionium atom (with the pionium Bohr radius being 138 times smaller than the hydrogen radius). Therefore a theoretical analysis of these reactions gives also insight into the understanding of the electromagnetic excitation of the pionium system.

2.2.2.

For our treatment of the electromagnetic breakup of exotic atoms in relativistic heavy ion collisions (see discussion below) we have developed a general expression for excitation and ionization in the unified framework of SCA and PWBA and in the Glauber theory. The expressions can now also be used for the case of ionization of inner-shell electrons in relativistic ion-atom collisions. In our approach we used the full retarded projectile-target interaction and all magnetic interactions, but for the wave functions it was completely sufficient to restrict ourselves to non-relativistic hydrogenic wave functions.

2.2.3.

We will extend our code for the evaluation of the excitation and ionization of pionium to the case of ionization of electrons. Since we now, obviously, need a full relativistic description of the electron in the target, we have to express the radial form factor of the electron either analytically by using approximate relativistic hydrogenic electron wave functions or numerically if the atomic orbitals are generated in a relativistic Hartree-Fock potential. Having evaluated this form factor in this way it can then be immediately implemented in the existing code to calculate the wanted ionization cross sections. This code can then be used for arbitrary values of the momentum transfer and thus we can compare our calculations with the data taken quite recently, e.g., at GSI. First approximate calculations using our code with hydrogenic wave functions are quite promising if we compare these theoretical results with the experiments. Especially we are interested in very high bombarding energies, because in this case it can be expected that the cross sections will be quite sensitive to the detailed structure of the interior part of the electronic wave functions, which may then be studied uniquely in this way.

B - Nuclear physics

Coulomb excitation and breakup of rare isotopes

L. Pacearescu, D.Trautmann, K. Hencken and G. Baur (Basel and FZ-Jülich, Germany)

2.2.1.

Rare isotopes are those nuclei that exist close to the neutron or proton drip line, that is, far from stability. In some of them the last one or more bound nucleons decouple from the system and the nucleus can be seen as a core plus one or more nucleons, the so-called halo. As the binding energies of these nucleons are rather small, they have a large spatial extent. A number of well known halo nuclei exist by now: beside single-neutron and single-proton halos like ^{11}Be, ^{19}C and ^{8}B, systems with two or more loosely bound neutrons like ^{11}Li, ^{12}Be, ^{6}He or ^{8}He are known.

Another phenomenon occurring in neutron-rich nuclei is the presence of low lying dipole strength in the form of a so-called 'pigmy resonance', which is in analogy to the well known giant dipole resonance, which consists of the motion of the protons against the neutrons. In the pigmy resonance only a few neutrons, building up the halo or skin of the nucleus, oscillate against the core. These resonances are found at much smaller excitation energies and are therefore of great importance for nuclear astrophysics.

Especially in view of the FAIR facility planed at the GSI (Darmstadt) it is of interest to study the possibilities of investigating these exotic nuclei by reactions. Higher rates allow for more detailed studies and at the high energies found especially at the GSI relativistic effects need to be taken into account. The main reaction mechanism used to study halo nuclei is their breakup when reacting with light and heavy targets. In collisions with light target nuclei, the nuclear interaction dominates, leading to a spectrum of diffractive breakup and stripping reactions. For heavy targets, due to their large charge, the Coulomb interaction and therefore Coulomb breakup dominates. Both types of reactions allow the study of different properties of these systems.

The case of Coulomb excitation is also of special interest for nuclear astrophysics. With the help of the EPA (equivalent photon approximation), one can use the Coulomb excitation to derive cross sections of photon-induced reactions, which by detailed balance are then related to the (n,γ)-, (p,γ) - or (α,γ)-reactions. These reactions are important in different astrophysical reaction chains. Of course for this to be viable, one relies on the accuracy of the EPA. This simple relation can, e.g., be spoiled by higher order Coulomb effects or nuclear interaction. Numerical calculations have been done by several groups especially for the breakup of ^{8}B, which is important also in connection with the solar neutrino problem. Whereas higher order effects were found to be rather unimportant at high energies, their theoretical as well as experimental status is less clear at lower energies.

2.2.2.

The Coulomb breakup of the deuteron, which is with its small binding energy the prototype of all halo nuclei, has been formulated within the DWBA (distorted wave Born approximation) by using the zero range approximation some time ago [G. Baur and D. Trautmann, Nucl. Phys. A191 ('72), 321]. This model has the advantage of taking the Coulomb interaction between the different components and the target into account in all orders. In addition it is analytically solvable in terms of hypergeometric functions. This model has been used successfully in numerical calculations for different halo systems [R. Shyam et al., Nucl. Phys. A540 ('92), 341; P. Banerjee et al., Phys. Rev. C65 ('02), 064602; G. Baur, K. Hencken and D. Trautmann, Proc. of ENAM2001].

We have written an invited review article on 'Coulomb dissociation in hadron- and astrophysics' for 'Progress in Particle and Nuclear Physics' [G. Baur, K. Hencken and D. Trautmann, Prog. Part. Nucl. Phys. 51 ('03), 487]. This article gives an overview of the possibilities of Coulomb interaction for the radioactive beam facilities, in operation (RIKEN, MSU, GANIL), to be built (FAIR/GSI) and planned (RIA). Besides discussions on nuclear structure information also the use of Coulomb interaction to investigate key reactions in nuclear astrophysics, like the r- or rp-process were studied. Also a detailed discussion of the importance of higher order effects and the nuclear interaction was given.

As an alternative to the derivation of the cluster sum rule, which gives the total strength in a 'pigmy resonance' starting from the Thomas Reiche Kuhn sum rule, we have given a derivation starting from the

Gellmann-Goldberger-Thirring (GGT) sum rule [K. Hencken, G. Baur and D. Trautmann, Nucl. Phys. A733 ('04), 200]. Whereas the final result is formally identical to the already known 'cluster sum rule' from the TRK, different assumptions are made in both cases. In addition the GGT cluster sum rule can easily be extended to more complex configurations, e.g., a nucleus consisting of three clusters.

2.2.3.

We plan to study in the framework of an analytically solvable model — the post-form CWBA solution — the importance of higher order Coulomb interaction with the target, especially the so-called 'post-acceleration'.

We have already derived an expression of this analytically solvable model in the limit of small angle scattering, which shows an agreement with the semiclassical limit for arbitrary charges, in analogy to the bremsstrahlung case [G. Baur et al., Proc. ENAM 2001; P. Banerjee et al., Phys. Rev. C65 ('02), 064602]. We want to study this limit further by using a confluence in the hypergeometric function therefore avoiding the restriction on small scattering angles. This study of the parameter space will be extended in order to see its relation to other models like the PWBA (plane wave Born approximation), the CDCC (continuum discretized coupled channel) approach or the SCA (semiclassical approximation). Especially in the framework of the SCA a simple closed expression is available for our model and thus may help to understand the physics of this process even better. Also the accuracy of the far field approximation (FFA) which is normally used and with was challenged in [H. Esbensen et al., Phys. Rev. Lett. 94 ('05), 042502] could be addressed.

It is an interesting and difficult task to specify more clearly the ranges of validity of the post and prior formulations. In the simplest high energy limit (sudden limit) we have found that there are regions where both approaches agree with each other. A scaling behavior depending on two universal parameters x and y was found [S. Typel and G. Baur, Nucl. Phys. A583 ('94), 486 & Phys. Rev. C64 ('01), 024601]. For low energy deuteron breakup the post-form CWBA is very reasonable, whereas the prior form is a very bad approximation [F. Ribycki and N. Austern, Phys. Rev. C6 ('71), 1525]. At high energies this has not been studied systematically. Deviations from the high energy scaling would be of interest to be studied. It would also be extremely interesting to apply in this context the three-body methods [E. O. Alt et al., Phys. Rev. C71 ('05), 024605] to this model. In this work, the post-acceleration of the fragments is studied using genuine three-particle wave functions for the final state. In their case there are three charged particles in the final state, but the problem is non-trivial even for only two (out of three) charged particles in the final state.

From a more practical point we want to study up to which energies the semiclassical approach can still be used. Post-acceleration is important in studying and interpreting these photo-induced reactions in order to explore the nuclear structure of exotic nuclei as well as to deduce cross sections of astrophysical interest. The interpretation in terms of the EPA is easy only in those cases where higher order effects are small. If the higher order effects are important a direct and model independent extraction of photon cross sections is not possible anymore and one has to rely on calculations within a specific model.

Radiative corrections in $(e, e'p)$-scattering

F. Weissbach, A. Aste, D. Trautmann, K. Hencken and G. Baur (Basel and FZ-Jülich, Germany)

2.2.1.

Electron scattering off nuclei and nucleons is an essential tool in nuclear physics. Experiments probe the nuclear structure as well as the structure of the nucleons and their excited states in various energy domains. They shed light on single-particle properties, few-nucleon system dynamics, systematics of electromagnetic excitations, and decay mechanisms of resonance states. However, these scattering experiments are subject to energy- and momentum losses due to bremsstrahlung (external radiative corrections). The momentum and energy transferred from the incident electron to the struck proton in the target nucleus are concealed because both the electron and the proton undergo bremsstrahlung before and after the impact. The background constituted by this bremsstrahlung constrains the accuracy of the data analysis in nuclear structure experiments. Bremsstrahlung can be produced in the field of the same nucleus from which the electron scattered off (in which case it is referred to as 'internal bremsstrahlung') or by the field of another nucleus ('external bremsstrahlung'). This discussion is concerned with the internal bremsstrahlung, which is also called 'radiative corrections' or 'radiative tails'.

Radiative corrections have already been investigated by [H. A. Bethe and W. Heitler, Proc. Roy. Soc. A146 ('34), 83], who restricted themselves to electron scattering off a Coulomb potential. The full treatment of the first-order radiative corrections was done by [J. Schwinger, Phys. Rev. 76 ('49), 790]. For soft-photon emission, lowest order perturbation theory is inadequate and [D. R. Yennie, S. Frautschi and H. Suura, Ann. Phys. 13 ('61), 379] calculated this process to higher orders, showing how to include higher-order soft-photon emission. Later, explicit formulae for radiative corrections to the inclusive elastic scattering of electrons off protons were derived in [Y. S. Tsai, Phys. Rev. 122 ('61), 1898; N. T. Meister and D. R. Yennie, Phys. Rev. 130 ('63), 1210]. Two review articles by [L. M. Mo and Y. S. Tsai, Rev. Mod. Phys. 41 ('69), 205] and by [L. C. Maximon, Rev. Mod. Phys. 41 ('69), 193] summarized the different approaches and approximations of the radiative corrections used to correct the available data. Mo and Tsai also discussed the advantages of the approach of Y. S. Tsai compared to the one of N. T. Meister and D. R. Yennie. More recently another approach of radiative corrections for coincidence $(e, e'p)$ reactions, based on the work of L. M. Mo and Y. S. Tsai was given by [N. C. Makins, PhD-thesis, MIT ('94), unpublished; R. Ent et al., Phys. Rev. C64 ('01), 054610] and by [J. A. Templon et al., Phys. Rev. C61 ('00), 014607]. Finally in [C. de Calan, H. Navelet and J. Picard, Nucl. Phys. B348 ('91), 47] another (different) set of formulae was given disagreeing with the results given by Y. S. Tsai. Recently [L. C. Maximon and J. A. Tjon, Phys. Rev. C62 ('00), 054320] also for the first time incorporated the nuclear (proton) dipole form factor in the calculation of the radiative tails.

2.2.2.

Up to now most data analysis computer codes for radiative corrections employed in $(e, e'p)$ experiments make use of the SPA (soft photon approximation) and the peaking approximation. The latter one assumes that the bremsstrahlung photons are predominantly emitted along the momentum directions of the radiating particles and is currently used for experimental data analysis in an $(e, e'p)$ scattering experiment at the Thomas Jefferson National Accelerator Facility (TJNAF) and at MAMI in Mainz by the group of I. Sick [I. Sick et al., TJNAF-proposal, ('98); D. Rohe et al., Eur. Phys. J. A17 ('03), 439]. The peaking approximation, originally developed for inclusive electron scattering experiments, breaks down especially in those cases where photons are emitted by the proton and it cannot appropriately deal with photons emitted between the direction of the incoming beam and the outgoing electron.

In a first step we have replaced the peaking approximation by a full angular Monte Carlo simulation of the radiative processes. We have shown [F. Weissbach et al., nucl-th/0411033] that this is possible at reasonable computing power expenses. These corrections have been incorporated in two of the current MC analysis codes (SIMC and mceep) and a re-analysis of a TJNAF experiment (E97-006) was done, showing that this approach is able to reproduce the photon distribution between the directions of the incident beam and the scattered electron. Multi-photon processes have also been included within the soft photon approximation, where multi-photon radiation is feasible due to the factorization of the different processes and the Poisson distribution of the photon energies. Inserting a full angular multi-photon bremsstrahlung treatment into the $(e, e'p)$ data analysis codes has never been done before.

In a second step we have investigated the accuracy of the soft photon approximation by implementing an exact single-photon emission Monte Carlo routine, starting from our existing SPA routine. The two approaches were compared and differences between the two were found to be of importance predominantly at large photon energies. For the angular distribution of the photon the inaccuracies due to the SPA were found to be smeared out by other sources of errors like limited detector resolution [F. Weissbach et al., nucl-th/0411033].

Our new approach takes into account the exact kinematics of the single-photon bremsstrahlung process, in contrast to the Borie-Drechsel formalism [E. Borie and D. Drechsel, Nucl. Phys. A167 ('71), 369]. The Borie-Drechsel formalism is based on both the peaking approximation and the SPA and has predominantly been used for $(e, e'p)$ analysis until now.

2.2.3.

A Monte Carlo simulation of the full angular distribution of the bremsstrahlung photons has been implemented by us. This can be seen as a first step in overcoming the limitations of the currently existing analysis codes. The second step should clearly be an improvement going beyond the SPA. Following this direction we have performed an exact calculation (not relying on the SPA) for single-photon bremsstrahlung by looking at exact single-photon emission cross sections. But multi-photon bremsstrahlung cannot be incorporated in this way efficiently. We therefore want to combine the two approaches (multi-photon SPA and exact single-photon treatment) in the following way: After generating multi-photon bremsstrahlung events in the SPA, we can identify one photon which we are able to treat as 'hard' and which we are going to treat exactly. All other photons are then assumed to be soft and are again added in the SPA limit. Given the typical $1/\omega$ dependence of the energy of the bremsstrahlung photons it is clear that predominantly only one photon will be hard. In addition we can treat again the kinematics much better in this way, as the modifications of the energies and momenta of the electron and proton due to the hard photon are treated exactly and the influence of the soft photon is expected to be weak.

We want to implement this treatment in a computer routine and then incorporate it into existing analysis programs like SIMC, which would allow to improve the data analysis of both old and future experiments considerably. We will compare several strategies to choose the 'hard' photon from the multi-photon bremsstrahlung events.

While theoretical calculations for electron scattering bremsstrahlung have gone beyond the peaking approximation and the SPA, our combined SPA background plus exact hard photon treatment would yield the first $(e, e'p)$ data analysis code ever with radiative correction treatment going beyond the SPA.

Radiative corrections also play an important role in the determination of the nucleon form factor. The proton electric form factor $G_E(Q^2)$ can be extracted using two different experimental techniques. One is the so-called Rosenbluth separation or L-T separation. The other one is the polarization transfer method which has become available recently. These two methods are apparently disagreeing. While the Rosenbluth method yields a scaling behavior of $G_E(Q^2)$ with Q^2, the polarization transfer method suggests that $G_E(Q^2)$ becomes smaller for larger values of Q^2. A re-analysis of the world Rosenbluth data plus the so-called Super-Rosenbluth measurements confirmed the discrepancy [J. Arrington, Phys. Rev. C 68 ('03), 034325]. Theoreticians have tried to explain this deviation mostly in terms of second-order corrections (the QED box diagrams), which are difficult to calculate with precision in this case due to the structure of the intermediate proton [P. Blunden, W. Melnitchouk and J. Tjon, Phys. Rev. Lett. 91 ('03), 142304].

The Rosenbluth method is very sensitive to systematic changes of the reduced cross section as a function of the scattering angle. The polarization transfer method is much less sensitive to radiative corrections than the Rosenbluth technique. We want to investigate the influence of the SPA and the peaking approximation used in the analysis of the Rosenbluth separation, as we expect that even small changes (like the small contributions from the second-order amplitudes) in the bremsstrahlung treatment can have a systematic effect on the reduced cross section and thus on the determination of G_E. By using our improved bremsstrahlungs routine, which does not make use of the peaking approximation and which also improves considerably the SPA, we want to study the influence of these two effects on the Rosenbluth analysis in order to see whether the much debated discrepancy can partially be removed this way.

Coulomb corrections in (e, e')-scattering

A. Aste, D. Trautmann, Z.-E. Meziani and J. P. Chen (Thomas Jefferson National Accelerator Facility, VA - USA), S. Choi (Seoul, South Korea), J. M. Udias (Madrid, Spain)

2.2.1.

In August 2005, the Jefferson National Accelerator Facility Proposal E01-016, entitled 'Precision measurement of longitudinal and transverse response functions of quasi-elastic electron scattering in the momentum transfer range 0.55 GeV $\leq |\vec{q}| \leq$ 1.0 GeV' (Spokespersons: Z.-E. Meziani, J. P. Chen and S. Choi, Theory support: J. Udias and A. Aste) was approved with A-rating such that the experiments will be performed in 2007 at JLab in Hall A. This fact necessitates further efforts to solve the issue of Coulomb correction in inclusive (e, e') scattering off heavily charged nuclei, since in the experiments, ^{4}He, ^{12}C, ^{56}Fe and ^{208}Pb will be used as target nuclei.

Nucleon knockout by electron scattering provides a powerful probe of the electromagnetic properties of nucleons and of the momentum distributions in nuclei. The transparency of the nucleus with respect to the electromagnetic probe makes it possible to study the entire nuclear volume. For light nuclei, the weakness of the electromagnetic interaction allows one to separate the soft Coulomb distortion of the electron scattering process due to the charged nucleus from the hard scattering event in which, to a very good approximation, a single virtual photon transfers energy and momentum to the nuclear constituents. Since the kinematic conditions of electron scattering can be varied easily, different aspects of the reaction mechanism can be tested. Under conditions in which a single nucleon receives most of the energy and momentum transfer, the quasifree electron-nucleon scattering process is emphasized.

Due to the small size of the elemental charge it is for most electromagnetic elementary particle reactions fully sufficient to calculate only in Born approximation. But this is no longer true when heavy nuclei are involved, like e.g. lead, where the relevant perturbation expansion parameter $Z\alpha$ is of the order of one. It is then possible that the ratio of the (calculated) exact and the Born cross section for electron scattering differ significantly from unity due to the distortion of the electron waves by the long range Coulomb potential of the highly charged nucleus. This important fact needs to be accounted for, if one aims at a quantitative interpretation of the presently available measured data.

We mainly concentrate our work on the inclusive quasielastic scattering process (e, e') where only the scattered electron is observed, but not the knocked out nucleons. Inclusive scattering provides information on a number of interesting nuclear properties:

-The width of the quasielastic peak allows a dynamical measurement of the nuclear Fermi momentum [R.R. Whitney, I. Sick, J.R. Ficenec, R.D. Kephart and W.P. Trower, Phys. Rev. C9 ('74), 2230].
-The tail of the quasielastic peak at low energy loss and large momentum transfer gives information on high-momentum components in nuclear wave functions [O. Benhar, A. Fabrocini, S. Fantoni and I. Sick, Phys. Lett. B343 ('95), 47].
-The integral strength of quasielastic scattering, when compared to sum rules, tells us about the reaction mechanism and eventual modifications of nucleon form factors in the nuclear medium [J. Jourdan, Nucl. Phys. A604 ('96), 117].
-The scaling properties of the quasielastic response allows to study the reaction mechanism [D. Day, J.S. McCarthy, T.W. Donnelly and I. Sick, Ann. Rev. Nucl. Part. Sci. 40 ('90), 357].
-Extrapolation of the quasielastic response to A=infinite provides us with a very valuable observable of infinite nuclear matter [D.B. Day et al., Phys. Rev. C40 ('89), 1011].

For the heavier nuclei, all these informations obviously can only be addressed once the Coulomb distortion of the electron wave is properly dealt with. A problem is the fact that the exact electron wave functions have to be calculated numerically and then are available only as an expansion in partial waves, and for high energies also a summation over a large number of terms is necessary in order to compute the exact matrix elements. This approach has been used by Yanhe Jin et al. [Y. Jin, D.S. Onley and L.E. Wright, Phys. Rev. C45, ('92), 1333; [K.S. Kim, L.E. Wright and Y. Jin, Phys. Rev. C54, ('96), 2515]. Their calculations were performed on supercomputers due to the necessary large computational effort. Due to this disadvantage, experimentalists still use the effective momentum approximation (EMA) to include Coulomb corrections in their data analysis, a method which is based mainly on classical considerations. There, it is often assumed that the Coulomb corrected cross sections can be obtained basically by calculating the Born cross section, but with the asymptotic electron momenta replaced by their classical value in the center or at the surface of the nucleus.

Heavy nuclei are complex objects which have to be described as accurate as possible. Jin et al. used a single particle shell model, where the nucleon wave functions were obtained by solving the Dirac equation for each shell nucleon with phenomenological S-V-potentials. Comparison of measured data and the calculations seemed to justify this simplified picture of the nucleus within certain kinematical regions. At high energy transfer, correlation effects and pion productions become increasingly important, and the shell model is no longer a sufficient physical model for the scattering process.

It would a great advantage if one could find a general, model independent method which makes it possible to include the Coulomb distortion effect in the analysis of experimental data (e.g., an improved version of the EMA). The calculations which have been performed so far used exact electron wave functions, but it would lead to even more involved problems from the computational point of view to go beyond a single particle nuclear shell model.

2.2.2.

In the initial phase of this proposal, we adopted the eikonal distorted wave Born approach for the calculation of Coulomb corrections in (e, e') scattering. The advantage of this method is that a simple analytic description of the electron wave function is directly accessible, and the method has proven its validity in many theoretical cases. An approximate formula for the electron wave function in the vicinity of the nucleus, which is strongly related to the eikonal description, was derived already in 1971 from a high energy partial wave expansion by Lenz and Rosenfelder [F. Lenz and R. Rosenfelder, Nucl. Phys. A176 ('71), 513]. The method has been applied to $(e, e'p)$ scattering, but not in a very extensive way due to the restricted available computational power at that time. Additionally, reliable calculations of $(e, e'p)$ cross sections require an accurate description of initial and final proton states, i.e. of the nucleon current.

In this spirit, we performed extensive calculations in the same kinematical regions as in the works of Jin et al., mainly for ^{208}Pb. The bound state proton and neutron wave functions were calculated from a self-optimizing Woods-Saxon potential approach, where the potential parameters were fixed such the rms (charge) radius of the nucleus and the experimentally well-known upper nucleon binding energies were reproduced correctly. The knocked out nucleons were described only by an effective momentum approach, where the energy dependence of the optical potential for the nucleons was taken into account. One peculiarity of this approach is that one works mainly in real space, and matrix elements were calculated for the $(e, e'p)$ process by performing numerical integrations over the contributing nuclear volume. The total cross section was then obtained by a further integration over all proton scattering angles.

The results were indeed in good agreement with those obtained by Jin et al., although we used a relatively poor model for the electromagnetic nucleon current due to the effective momentum approximation for the protons. This seems to indicate that the inclusive cross section is not so sensitive to finer details of the nuclear structure as in the exclusive $(e, e'p)$ case. The results were published in [A. Aste et al., Nucl. Phys. A743 ('04), 259]. Further results for positron scattering off heavy charged nuclei were published in [A.Aste and J. Jourdan, Europhys. Lett. 67 ('04), 753].

However, we continued to refine our model by implementing exact Coulomb wave functions in our calculations during the last few months. We found that the eikonal approximation that was used in our previous calculations provides a very good description of the distortion of the phase of electron wave function (i.e., the modification of the electron momentum inside the nucleus due to the attractive Coulomb potential), but the generally adopted expression for the focusing turned out to be too large. This is indeed a very important insight, since a preliminary correction of the eikonal results with a reduced focusing factor obtained from exact electron wave function calculations hints at the possibility that the calculations of Kim and Jin contain an error and that the effective momentum approximation is a viable method for the analysis of Coulomb distortion, even though in a slightly modified form.

2.2.3.

As a next step, we will investigate in detail how the effect of Coulomb distortions on the inclusive cross section can be described with an EMA-like strategy. We are currently using simple harmonic oscillator wave functions or wave functions obtained from a self-optimizing Woods-Saxon potential for the bound nucleons, but first results seem to indicate that the influence of the Coulomb distortion on cross sections calculated with exact electron wave functions exhibits a typical behavior which can be described in a nuclear-model independent manner. Similar observation have been reported from preliminary calculations by J. Udias (Madrid) at the 'Joint Jefferson Lab/Institute for Nuclear Theory Workshop Precision ElectroWeak Interactions' which took place at the College of William and Mary (Williamsburg, VA) on August 16, 2005 shortly before the submission and subsequent approval of the E01-016 experiment. Therefore, the Basel and the Madrid group are quite confident that a consensus on how to apply Coulomb corrections to the experimental data can be reached until the new experiments will start.

We will perform extensive calculations for (e, e') scattering for the kinematical regions relevant for the experiment E01-016. Additionally, J. Udias will provide us with a FORTRAN code that calculates the nuclear current in a relativistic optical potential model. This will also clarify how strongly the Coulomb corrections depend on the nuclear model. We have discussed in detail which precautions must be taken in order combine our programs. The use of the more refined nuclear current models will also open the door to the analysis of Coulomb correction for the case of exclusive scattering.

The analysis will also be applied to positron scattering off heavy nuclei. After an experiment in 1999 at the 700 MeV Saclay Linear Accelerator ALS [P. Guèye et al., Phys. Rev. C60 ('99), 044308)], the authors concluded from the comparison of their inclusive positron scattering data to inclusive electron scattering data that had been taken earlier at Saclay in 1993, that the EMA is a reliable method for the analysis of Coulomb corrections. However, there has been some discussion concerning the accuracy of the measurements, and preliminary calculations performed by the Madrid university group have cast some doubts on the interpretation of positron scattering data especially for positron energies below 300 MeV.

We finally point out that the modifications of the nucleon properties by the nuclear medium is a key issue in nuclear physics which is yet unresolved. Since the charge and magnetic responses of a single nucleon are quite well studied from elastic scattering experiments, measuring the same response from quasi-elastic scattering off nuclei and comparing with a single nucleon are likely to shed light on the problem. Especially, a Rosenbluth separation of the charge and magnetic responses of the nucleus can be used to test the Coulomb sum rule (CSR). This sum rule states that the integration of the charge response of a nucleus over the full range of energy loss of the scattered electrons should correspond to the total charge Z of the nucleus. However, this simple picture becomes more complicated due to various effects inside the nucleus. First of all, at very small momentum transfer, considering only Pauli blocking on a system of freely moving nucleons will produce a quenching of the CSR, leading it not to reach the full value of Z. As the momentum transfer increases, the long range and then the short range correlations play a similar role. They have been estimated by various theoretical calculations using different nucleon-nucleon forces and were found to be responsible for at most 10% quenching of the CSR integral. As a result, further quenching of this quantity at sufficiently high momentum transfer may indicate the possibility of modified nucleon properties inside the nucleus. It is therefore desirable that a reliable method for the analysis of Coulomb corrections is found which can be used by experimentalist, and mandatory that such a simplified strategy can be validated by exact calculations.

As an outlook we mention that Coulomb corrections may also play a role in strangeness physics, e.g. in kaon electromagnetic production $A(e,e'K)YB$, where A is the target nucleus, Y the produced hyperon and B the recoil. This problem has not been tackled so far and it is planned that this will be investigated when the calculations on Coulomb corrections have been completed.

Determination of the kaon form factor

A. Aste and P. Guèye (Hampton, VA - USA)

2.2.1.

Since the mid-90s, kaon electromagnetic production experiments have attracted renewed interest from nuclear physics at both experimental [B. Zeidman et al., CEBAF Experiment E91-016/1996 , R. Mohring et al., Phys. Rev. Lett. 81 ('98), 1805] and theoretical [M. Vanderhaeghen et al., Phys. Rev. C57 ('98), 1454, C. Bennhold and T. Mart, Phys. Rev. C61 ('99), 012201] level. To completely describe the cross sections of these reaction - $A(\gamma,K)YB$ and $A(e,e'K)YB$, where A is the target, Y the produced hyperon and B the recoil - 36 observables are necessary and need to be measured using both unpolarized and polarized beam, target and recoil asymmetry experiments [G. Knochlein et al., Z. Phys. 352 ('95), 327].

The main ingredients for the description of electromagnetically induced kaon production are embedded in the so-called Chew, Goldberger, Low and Nambu (CGLN) scattering amplitudes. The expression of the electron induced unpolarized differential cross section in terms of its longitudinal, transverse and interference terms can be expressed as a function of the three Mandelstam variables s,t, and u. In the case of the longitudinal component, the reaction mechanism is dominated by the t-diagram, and (in certain kinematic conditions) the differential cross section can be factorized basically as [R.A. Williams, Phys. Rev. C46 ('92) 1617]: $\sigma_L = k \cdot F(Q^2)G(W)H(t)$, where k is a kinematic factor. F,G, and H are functions of the virtual photon 4-momentum transfer Q^2, the invariant mass W and the Mandelstam variable t. The function $H(t)$ contains the information about the electromagnetic form factor of the K-meson. Knowledge of this quantity is of fundamental importance for a realistic and accurate description of the reaction mechanism. Similarly, the hyperon form factor could be extracted in principle from the u-diagram.

To date, the electromagnetic kaon form factor is very poorly known and only measured at very low Q^2 (below 0.2 GeV$^2/c^2$). The status for the (quasi-free) Lambda and Sigma hyperons is worst, i.e. there are no experimental data. Basic quantities like the leading strong coupling constant $g_{K\Lambda N}$ and $g_{K\Sigma N}$ derived from purely hadronic processes or theoretical considerations are not well established and must be considered adjustable.

Recently, however, there appeared quite large and precise data sets on photo-production of Kaons from the SAPHIR (ELSA) [K.H. Glander et al., Eur. Phys. J. A19 ('04), 251], CLAS (CEBAF) [J.W.C. McNabb et al., Phys. Rev. C69 ('04), 042201(R)], and LEPS (SPring8) [R.G.T. Zegers et al., Phys. Rev. Lett. 91 ('03), 092001] collaborations. There are also new data on electro-production of positive kaons from experiment E98-108 at CEBAF, which are being analyzed at the moment.

Currently, the procedure used to extract hadronic form factors is based on the so-called Chew-Low extrapolation method. There one first performs a successive collection of data in kinematical regimes where the t-diagram dominates in the longitudinal component of the cross section [J. Vollmer et al., Phys. Rev. Lett. 86 ('01), 1713], i.e. proper kinematical constraints are imposed on the electron beam scattering off the virtual meson within the proton target. Each experimental data point within the experimental acceptance is then scaled to a given central value (typically the center of the experimental acceptance). This is to ensure extraction of a single value of the cross section for a fixed kinematical setting. The technique utilizes known scaling functions that represent the dependencies of the cross section in Q^2, W, and t [R. Mohring et al., Phys. Rev. C67 ('03), 055205]. A Rosenbluth separation is then used to separate the measured cross section in its longitudinal and transverse components [M. N. Rosenbluth, Phys. Rev. 79 ('50), 615]. The data collected this way are in the time-like region, the assumed t-dependence dominance is finally used to extrapolate the longitudinal cross section to the pole of the hadronic mass in order to extract the form factor of the studied meson (kaon). Since Q^2, W and t are not independent from each other, it is of course experimentally impossible to keep two variables constant while changing the kinematical settings. The whole procedure described above is flawed by the large inaccuracies in the result induced by the scaling and the extrapolation procedure. The extrapolation of any function depends on how far from the explored domain the function is extrapolated to. Hence it is believed that the current procedure is a fairly good technique for pion production, but one may argue about the validity of the technique for heavier masses.

2.2.2.

Due to the unsatisfactory status of data analysis in the case of electromagnetic hadron electroproduction, we were asked by P. Guèye (Hampton University, Virginia, USA), who has been involved in several experiments during the last decade at Saclay and the Jefferson National Accelerator Facility TJNAF in Newport New, USA, for theoretical support concerning the problem exposed above. For additional expertise concerning algorithms and software used in signal processing (see below), we are in contact with I. Cissé, who is currently with the Laboratoire 'Mathématiques pour l'Industrie et la Physique', Université Paul Sabatier, Toulouse, France.

We decided to investigate the feasibility to extract hadronic form factors by using numerical algorithms from a different field of research, i.e. signal processing. The fact that the measured cross section can be factorized into a product of factors describing different properties of the particles involved in the hadronic reaction and effects that are due to the measurement process has a strong similarity to the convolution problem posed by the fact that many measurements are distorted by filtering effects which modify the true signal. A typical problem of this type in signal processing is, e.g., the restoration of blurred images. Finding a general algorithm for the analysis of the new data sets which will become available in the near future will be an appreciated instrument for the hadronic physics community.

A first check of the validity of this method was performed at Jefferson Lab in the group of P. Guèye using kaon electro-production data. The preliminary results were obtained by generating artificial data sets (since only few measured data are available until now), which are based on theoretical expressions for kaon electroproduction cross sections. These data were blurred by a diffusion process which mimics the effects of the detectors used in the experiment. Subsequent deconvolution has shown that a satisfactory reconstruction of the initial data is indeed possible.

2.2.3.

The naive mathematical convolution problem $g = f{*}h$ with given g has a unique solution if both components f and h are irreducible. However, in practice, the measured quantity g is known only for a limited data set, and additionally, the measurements are never exact (there is a 'noise' n, such that we have $g = f * h + n$). There are many numerical algorithms known for the defactorization or deconvolution of signals [D. Kundur and D. Hatzinakos, IEEE Trans. Sig. Proc. 46 ('98), 2918]. However, due to the incomplete information about the 'blurring function' h and noise, the factorization algorithms are always model dependent. In our case, we have rather detailed constraints concerning the analytic structure of the functions F,G etc. introduced above (from Feynman rules and strong interaction models). It is our aim to find a valid numerically stable algorithm which can be used to extract the kaon form factor from the experimental data in a most general way (where hadronic masses, coupling constants and the basic structure of form factors may serve as an additional input). The stability and global convergence of (iterative) deconvolution algorithms is a non-trivial task but can be studied in the framework of Lyapunov stability theory [A. Lyapunov, Int. J. of Control ('98), 531]. All experimentally measured data points within the spectrometer acceptance will be used to generate a representation of the data in a hyper-volume with coordinates Q^2, W, ant t. Then we will investigate in which way the measured cross section can be deconvoluted according to a product ansatz $\sigma_{exp} = \sigma(Q^2, W, t) * h(Q^2, W, t) + n$, with the constraint that the true cross section σ depends only on two independent kinematical variables.

An associated program lead by P. Guèye is intended to be submitted to the Program Advisory Committee (PAC) of Jefferson Lab in 2006 that will be driven by results from our effort.

C - High energy physics

Photon-photon and photonuclear processes in ultraperipheral collisions at RHIC and LHC

U. Dreyer, D. Trautmann, K. Hencken and G. Baur (Basel and FZ-Jülich, Germany)

2.2.1.

The main physical interest of heavy ion colliders like the running RHIC at Brookhaven and the currently built LHC at CERN is the study of the transition of nuclear matter to a new state of matter, that is the Quark Gluon Plasma, in central hadronic collisions of the two ions. 'Ultraperipheral collisions' is a term coined to denote those collisions of the heavy ions, where they do not meet and therefore cannot interact directly by the hadronic interaction. Only the long range part of the interaction, which is predominantly the electromagnetic field is able to give rise to interactions. In this way both photon-photon and photonuclear interactions can be studied at high energies, beyond the possibilities of LEP and HERA [G. Baur, K. Hencken and D. Trautmann Topical Review, J. Phys. G24 ('98), 1657; G. Baur, K. Hencken, D. Trautmann, S. Sadovksy and Yu. Kharlov, Phys. Rep. 364 ('02), 359; C.A. Bertulani, S.R. Klein and J. Nystrand, nucl-ex/0502005, submitted to Ann. Rev. Nucl. Part. Sci.].

In recent years this field has developed itself into a program which is investigated at both STAR and PHENIX at RHIC [C. Adler et al., Phys. Rev. Lett. 89 ('02), 272302; S. Timoshenko et al., nucl-ex/0501010; D. d'Enterria, Contribution to QM'05; S. White et al., to be published ('05)] and which is also a part of the heavy ion programs of the detectors ALICE, ATLAS and CMS at CERN ['ALICE Physics Performance Report' CERN/LHCC/2003-049; 'Detector and Physics Performance Technical Design Report' ATLAS Collaboration, CERN/LHCC 1999-14; S. N. White, arXiv:nucl-ex/0505020, 'Heavy Ion Physics at the LHC', CMS-NOTE-2000-060]. First results have been published on coherent vector meson production (ρ and also J/Ψ) [S. Klein et al., Heavy Ion Phys. 15 ('02), 369; C. Adler et al., Phys. Rev. Lett. 89 ('02), 272302; S. White, to be published] and electron-positron pair production at small impact parameter [J. Adams et al., Phys. Rev. C70 ('04), 031902; V. Morozov, Ph. D. thesis, ('03), unpublished].

At CERN a 'peripheral collisions working group' was formed (in which we play a leading role) with the aim to write a CERN Yellow Report. This document, which discusses the possibilities for this physics at the different detectors at the LHC is currently being finished. In addition this group has also contributed to a proposal to study ultraperipheral collisions also at $p + A$ at LHC.

The measurement of the gluon distribution function inside the nucleus is of interest in order to investigate nuclear modification effects and their origin. It has been well known that quark pdfs inside nuclei do deviate from those of free nucleons. Especially for small x different mechanisms have been proposed as a source of this modification. One possibility of measuring this gluon distribution is through the coherent production of heavy vector mesons, especially of J/Ψ but also of Υ, which is proportional directly to the square of the gluon distribution [L. Frankfurt, M. Strikman and M. Zhalov, Acta Phys. Polon. B34 ('03), 3215]. Another possibility to measure the gluon pdf is photon-gluon fusion and the production of two jets (with the additional possibility to tag on heavy quarks) [R. Vogt, hep-ph/0407298; M. Strikman, R. Vogt and S. White, hep-ph/0508296]. The quark pdfs could in principle also be studied in ultraperipheral photonuclear collisions by looking for photon and single jet production with large transverse momenta in $\gamma + quark$ collisions, as these events are predominantly coming from deep inelastic photon scattering on the quark.

It has been pointed out that in the production of vector mesons there is the possibility of an interference, as the role of the two ions as either emitting the target or acting as target can be exchanged. This interference has been calculated in a simplified model [S.R. Klein and J. Nystrand, Phys. Rev. Lett. 84 ('00), 2330; S.R. Klein and J. Nystrand, Phys. Rev. C60 ('99), 014903] and there are experimental indications that this has been seen at STAR [S.R. Klein, nucl-ex/0402007]. As the analysis of these experiments is rather sensitive on the shape of the transverse momentum distribution and as the interference might influence also the total cross section for heavy vector meson production at the LHC, a more refined analysis starting from first principles should be done.

An interesting process is the electron-positron pair production in relativistic heavy ion collisions due to the strong Coulomb fields acting for a short time. Whereas the lowest order calculations seem to be rather well understood in the meantime by several groups, the role of Coulomb corrections, that is, higher order electromagnetic interactions, especially at small impact parameter is still an open question. Several groups have found a way to solve the single particle Dirac equation for the two fields in the high energy limit [B. Segev and J.C. Wells, Phys. Rev. A57 ('98), 1849; A.J. Baltz and L. McLerran, Phys. Rev. C58 ('98), 1679; U. Eichmann et al., Phys. Rev. A61 ('00), 062710]. This single particle approach needs to be interpreted then within a many-body field theoretical interpretation. One of the predictions of this approach was the absence of Coulomb corrections for the total cross section, in contradiction to the Bethe-Maximon result for pair production by real photons. In a series of papers starting either from different approaches or carefully analyzing the original derivation, a quite sizable Coulomb correction, e.g., at RHIC of about 15%, in agreement with the Bethe-Maximon result was found [D. Ivanov and K. Melnikov, Phys. Rev. D57 ('98), 4025; D. Ivanov et al., Phys. Lett. B454 ('99), 155; R.N. Lee and A.I. Milstein, Phys. Rev. A61 ('00), 032103]. In the meantime the discrepancy between the two results is understood [R. Lee et al., hep-ph/010801; A. Baltz, Phys. Rev. C68 ('03), 034906 & Phys. Rev. C71 ('05), 024901 & Erratum-ibid. C71 ('05), 039901]. It can be attributed to the wrong regularization of an integral treating the Coulomb interaction at large distances from the nuclei. These results are only true for the electron-positron cross section, which are dominated by large impact parameters. In this case predominantly processes with one photon emitted by one ion and a large number of photons by the second ion are of importance. A still open question is the pair production at small impact parameter, where multiphoton exchange from both ions should play a more dominant role.

2.2.2.

We have studied the physics potential of ultraperipheral collisions in relativistic heavy ion collisions in an invited review article for Physics Reports [G. Baur, K. Hencken, D. Trautmann, S. Sadovsky and Y. Kharlov, Phys. Rep. 364 ('02), 359], the state of this field from a more theoretical perspective is summarized in [G. Baur, K. Hencken and D. Trautmann, J. Phys. G24 ('98), 1657]. In addition we have contributed to a number of experimental proposals in connection with UPC at LHC.

Multiphoton processes, where more than one inelastic process occurs in a single collision, are of importance in order to be able to trigger on ultraperipheral collisions and also as they offer the possibility to trigger on small impact parameter. E.g., the experiments at RHIC have used the ZDC on either one or both sides to search for a photonuclear reaction (coherent vector meson production or electron positron pair production) together with the electromagnetic excitation of both ions. The analysis was based on a factorization ansatz [K. Hencken, G. Baur and D. Trautmann, Z. Phys. C68 ('95), 473] for each process in the semiclassical approximation. In a recent article we have studied the validity of this factorization in more detail, showing where deviations from it could be expected and have also pointed out the possibility to use correlations in either the impact parameter range or angular correlation between different processes [G. Baur et al., Nucl. Phys. A729 ('03), 787].

We have studied the interference between the vector meson production of the two ions starting from the semiclassical approximation. We found that the interference phenomenon is more complex than originally anticipated, as the phase between the two amplitudes is not fixed but depends on both the transverse momentum of the produced meson as well as on the impact parameter. We have calculated distributions for both ρ meson production at RHIC and J/Ψ production at the LHC within a schematic model, where also an analytic expression can be found [K. Hencken, G. Baur and D. Trautmann, submitted to Phys. Rev. Lett.].

Pair production processes, where one of the leptons is emitted with a large transverse momentum, have been investigated by us as an alternative to measure the quark pdfs in heavy ions [U. Dreyer, T. Baier, K. Hencken and D. Trautmann, submitted to Eur. Phys. J. C]. Such deep inelastic processes can be intuitively seen not as photon-photon collisions, but within the framework of the ELA (equivalent lepton approximation). A general plane wave approach for the inelastic pair production process was developed and differential distributions were compared with the ones of either the EPA (equivalent photon approximation) or the ELA. Whereas the EPA was found to be in good agreement with the full calculation, the ELA deviates rather strongly. Nuclear modifications have been included and it was found that they could be measured by looking, e.g., at the rapidity distribution of the quark.

In the case of electron pair production, the fields are strong enough to produce more than one pair in a single collision. We have calculated both single and multiple pair production cross sections within a lowest order calculation [A. Alscher, K. Hencken, D. Trautmann and G. Baur, Phys. Rev. A55 ('97), 396] and also by using the the high energy limit, as discussed above [K. Hencken, D. Trautmann and G. Baur, Phys. Rev. A59 ('99), 841]. Whereas the single pair production cross section is insensitive to these higher order corrections in this limit, the multiple pair production cross section is reduced considerable.

In order to interpret the recent experimental results of e^+e^--pair production with electromagnetic excitation of the two ions at STAR, we have calculated this process based on the pure QED lowest order calculation, within the external field approach. The results agree quite well with the experimental findings of STAR. Good agreement was also found with the EPA, which is expected under the experimental conditions of the experiment. One exception is the transverse momentum distribution of the pair, where the EPA results are too narrow compared to the experimental results as well as the QED calculation [K. Hencken, G. Baur and D. Trautmann, Phys. Rev. C69 ('04), 054902.]

2.2.3.

The production of vector mesons in photon-nucleus collisions has been calculated recently by us including interference phenomena coming from the vector meson production on either ion within a schematic model for the production process on the ion. Using this approach starting from the semiclassical approximation we want to investigate this phenomenon in more detail. The interference phenomenon could also be studied in pp and $p\bar{p}$ collisions at the LHC and the TEVATRON. As the antiproton has a different charge, but the production process of the vector meson is charge symmetric, one expects a different sign for the interference in both cases. We want to use our model to study the shape of the production process in both cases and compare them also with the simplified model as discussed in [S.R. Klein and J. Nystrand, Phys. Rev. Lett. 84 ('00) 2330 & hep-ph/0310223; S.R. Klein for the STAR Collaboration, nucl-ex/0402007]. In addition we want to study also the interference away from the central rapidity. This is of interest, as in this case the strength as well as the phase of the production process will be different for the two cases. Whereas this on the one hand may allow to study the size of the phase, it is on the other hand a nuisance if one wants to extract high energy photoproduction data at very forward rapidity. In addition a more careful analysis of the accuracy of the equivalent photon approximation that can be achieved in this case is needed in order to be able to disentangle the two processes at LHC energies.

The inelastic lepton production as a tool for inelastic lepton-nucleus collisions has been investigated already by us for the scattering on the quarks as a way to study the quark pdf. We want to extend this approach also to other processes. Nuclear excitation (predominantly to the GDR) and quasielastic scattering on individual nucleons have been estimated already as a possible additional loss process. At HERA one has also studied vector meson production with virtual photons. As the equivalent photons in ultraperipheral collisions are always quasireal, with a virtuality limited by $q^2 \leq 1/R^2$, with R the nuclear radius, they cannot be used directly. Inelastic lepton production is therefore a promising alternative to study these processes also at the LHC. We plan to investigate both light and heavy vector meson production and their q^2 dependence in order to see whether such processes can be studied within the detectors at the LHC.

In both pp and pA collisions at the LHC one has in addition to photonuclear processes also the possibility to look for photon-proton collisions. Especially pA collisions have a luminosity which is two to three orders of magnitude larger than what can be achieved in either pp or AA collisions. This offers the possibility to study also electroweak processes. Since it has been proposed by Brodsky in 1999, the W-production of a nucleus has been one possible process of interest [S. Brodsky, Talk at the HIF at CERN ('02)]. In this case the production on the proton would be directly an advantage. Inclusive W production has been searched for at HERA with about 3 candidate events found [J. Breitweg et al., Phys. Lett. B471 ('00), 411]. We want to study the possibility whether this can be improved at the LHC. In addition it is of interest to look also at the exclusive process $\gamma + p \rightarrow W^+ + n$, which would have the advantage that the neutron can be detected and one has a very clean way to measure the $WW\gamma$ coupling [U. Baur and D. Zeppenfeld Nucl. Phys. B325 ('89), 253; K. O. Diener et al., Eur. Phys. J. C25 ('02), 405]. Unfortunately it is expected that this process is rather small, but it has not been estimated in the literature up to now.

An open question in electron-positron pair production in relativistic heavy ion collisions is the importance of Coulomb corrections especially at small impact parameter. Whereas the single pair production cross section is dominated by large impact parameter, where the Bethe-Maximon approach is applicable, the case of multiple pair production is dominated by the small impact parameter and therefore not very well understood. We will tackle the problem from the theoretical as well as from the calculational side. From the theoretical point of view it seems quite clear to us that it is necessary to investigate a class of Feynman diagrams which probably can only be neglected in the case of highly relativistic electron scattering off two heavy nuclei, but not for the crossed process of electron-positron pair production. We plan to calculate the pair production within Magnus theory, that is, in a systematic expansion in the interaction time. The derivation of this cross section has already been done and the interpretation in terms of diagrams looks promising, but numerical calculations still need to be done.

Finally we have been invited to write a review article for Physics Reports on the pair production process in heavy ion collisions. Whereas we have started already on this article, work will clearly continue in the next year. We will focus especially on the calculations in lowest order but also how to incorporate the higher order corrections: multiple pair production and also Coulomb corrections. In a third section we will then look at practical applications not only at heavy ion colliders but also for cosmic rays.

Coulomb excitation and breakup of $\pi^+\pi^-$-atoms at high energies

M. Longhitano, D. Trautmann, V. Yakhontov, T. A. Heim, K. Hencken and G. Baur (Basel and FZ-Jülich, Germany)

2.2.1.

The experiment DIRAC at CERN is currently measuring the lifetime of the pionium atoms, i.e., $\pi^+\pi^-$-pairs forming a hydrogen like bound state through the Coulomb interaction. The purpose of the experiment is a test of predictions of this lifetime from the pion scattering length to a high precision, as the lifetime is predominantly determined from the decay $\pi^+ + \pi^- \rightarrow \pi^0 + \pi^0$ [B. Adeva et al., J. Phys. G30 ('04), 1929; G. Colangelo, J. Gasser and H. Leutwyler, Nucl. Phys. B603 ('01), 125].

First results, in agreement within error bars with the prediction of chiral perturbation theory, have already been published [B. Adeva et al., Phys. Lett. B619 ('05), 50], but the main part of the data analysis is still under way, as the required accuracy is not yet reached. CERN has also in the meantime accepted the addendum to the DIRAC proposal [CERN-SPSC-2004-009 (SPSC-P-284 Add. 4)]. Therefore it is clear that data taking will continue throughout the next years. DIRAC aims to improve their current limits on the pionium lifetime but also to investigate new exotic atoms, in particular the $K-\pi$ atom, but also kaonium, that is, the K^+K^--atom. Also it is planned to investigate excited pionium atoms and their fine structure as a way to a different combination of the scattering lengths a_0 and a_2. In addition there are plans for future experiments of the DIRAC collaboration as DIRAC/J-Parc in Japan or as DIRAC/GSI at the FAIR facility in Germany. There the accuracy can be improved again substantially, but also other hadronic systems like kaonium and $K\pi$-atoms can be studied in more detail.

A peculiarity of the DIRAC experiment is that the lifetime is measured indirectly. The $\pi^+\pi^-$-atoms normally already decay within the target material. But due to the electromagnetic excitation of the pionium with other target materials there is also the possibility for the atoms to be excited and to break up. The experiment therefore doesn't measure the π^0's from the pionium decay but instead the π^+ and π^- from the breakup. By comparing this with the number of pionium atoms produced the part which has decayed and therefore the lifetime can be inferred [L.G. Afanasyev et al., Phys. Lett. B338 ('94), 478]. As an essential ingredient for this analysis both the electromagnetic cross sections and also the propagation of the atom through the target (where it undergoes a number of transitions to different states) need to be known to high precision. It has been shown that the overall uncertainty of the computed electromagnetic cross sections for these scattering processes (where both target and projectile possess complex internal structure) must not exceed 1% in order to qualify as input data for the analysis of the experiment to achieve the design goal of 10% of the lifetime.

Concerning kaonium and also the $K\pi$ atom this is of interest in order to test chiral perturbation theory in its extension to SU(3). At the moment DIRAC is in the process of studying how these atoms can be analyzed within the existing detector.

2.2.2.

To be able to determine the electromagnetic cross sections of the pionium interacting with the target matter to such a high accuracy requires the inclusion of a number of effects, which are normally not taken into account in calculations of these cross sections and also in normal atomic physics. We have addressed most of these contributions in a series of papers and have also sent extensive tabulations of the cross section for transitions up to principal quantum number $n = 10$ to the DIRAC collaboration for their analysis.

We have started from our formulation of the electromagnetic excitation and breakup of $\pi^+\pi^-$-atoms in the framework of first-order perturbation theory using the semiclassical and the distorted-wave Born approximations and have calculated the lowest order cross section for the Coulomb interaction with an accuracy far better than the required 1%, studying also the effect of different elastic form factors for the target atoms [Z. Halabuka et al., Nucl. Phys. B554 ('99), 86]. The next part then dealt with the inclusion of additional effects on the target atoms: instead of analytically given screening models we have used atomic form factors and also scattering functions calculated within the framework of Dirac-Hartree-Fock theory. This allows us to include target inelastic processes, where the target atoms are also excited. Our results showed that simplifying models for this are not accurate enough for our purpose. Our approach with scattering functions determined from individual orbitals allowed us to study how each atomic shell contributes to the electromagnetic cross section of pionium interacting with the target. From our analysis we concluded that solid state effects of the target are adequately treated in our formalism [T. Heim et al., J. Phys. B33 ('00), 3583]. In [T. Heim et al., J. Phys. B34 ('01), 3763] we have then also calculated the magnetic term in the interaction and discussed corrections coming from the relativistic treatment of the Coulomb interaction, where new contributions, e.g., the diamagnetic term as well as a contribution from a seagull graph, were found. The magnetic terms were found to be of some minor importance to reach the required accuracy, while other corrections were too small to be of importance at the current level.

As a next step we have gone beyond the lowest order Born approximation and we have studied the importance of higher order Coulomb effects. Within the framework of the sudden or Glauber approximation numerical calculations were done in Basel [M. Schumann et al., J. Phys. B35 ('02), 2683 & Proc. HadAtom02; M. Schumann, Ph. D. thesis, ('03), unpublished]. Total cross sections as well as differential ones were tabulated and also compared with those which were already known in the literature [L.G. Afanasyev et al., J. Phys. G25 ('99), B7].

As a last step in the process of providing the DIRAC experiment with results for their analysis a Monte Carlo code to describe the (classical) propagation of the pionium through the target matter was developed [C. Santamarina et al., J. Phys. B36 ('03), 4273]. Detailed studies for different target materials were made and the achieved accuracy for different sets of cross sections was checked.

As it has been discussed that the simple approach to treat the propagation of pionium on a classical level by a rate equation is not sufficient, we have developed an approach were the effect of the lowest energy degenerate states has been incorporated (3s/3d, 4s/4d and 4p/4f states). By using an optimal mixture of the two states based on the feeding mechanism we found a change of the cross sections of about 0.5% [M. Schumann et al., Contribution to HadAtom03], much less than what had been estimated from using two different basis sets as explored in [L. Afanasyev, contribution to HadAtom99].

2.2.3.

With the improved precision that can be reached in future runs of DIRAC it is crucial to do a more thorough analysis of the uncertainties of the existing calculations. An accuracy of less than 1% will be required in the future in order that the experimental result is not limited by this theoretical uncertainty. Whereas we have always shown that our results are better than 1% the final accuracy that can be obtained (in terms of uncertainties of, e.g., the atomic structure or by terms not included at the moment, like higher order inelastic contributions) have not been discussed up to now. We intend to analyze our approach with the aim to give limits of the current approach and point out possible approaches to overcome these limitations.

There are current plans to continue the DIRAC experiment in a different form also for the measurement of the lifetime of the kaonium atom as well as the $K\pi$ atom. With our expertise acquired in the context of the calculations for the pionium experiment it is a rather straightforward task to determine also electromagnetic cross sections for this system. Besides a replacement of the mass of the meson in our codes, one also needs to revisit carefully the assumption about certain selection rules, which are no longer valid in the unsymmetric $K\pi$ system and also the integration ranges as the binding energies are stronger. In addition one needs to extend the MC simulation of the propagation to this case also.

In the case of the kaonium we want to investigate in addition the influence of the shift in the binding energy and the width of the ground state on the excitation cross sections. Whereas they are expected to be small in the pionium case, it is less clear how large their influence is in the kaonium case. This part of the work is planned together with R. Lemmer (Univ. of Witwatersrand, South Africa), who already did an analysis of the energy shift and width of kaonium within a meson model [S. Krewald, R. Lemmer and F.P. Sassen, Phys. Rev. D69 ('04), 016004]. The inclusion of decaying states in the Coulomb excitation formalism has already been studied in nuclear physics and we plan to use these results here.

Finally DIRAC plans to measure also energy shifts of excited states of pionium within the current experimental program. For this one needs calculations of the different states in a decaying beam, but also cross sections for atom-laser interactions, on which we intend to work as well.

Spin physics via W boson production at RHIC

A. Aste, C. von Arx, D. Trautmann and T. Gehrmann (University of Zürich)

2.2.1

Colliding beams of 70% polarized protons at up to $\sqrt{s}$ =500 GeV and reaching a high luminosity of $L = 2 \cdot 10^{32}\text{cm}^{-2}\text{sec}^{-1}$, will represent a new and unique laboratory in the forthcoming years ($\geq$ 2006) for studying the proton at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, where the charged weak vector bosons $W^{\pm}$ will be produced by colliding bunches of protons spinning alternatively left- (+) and right- ($-$) handed.

Since W bosons are produced through pure V-A interaction (within the standard model), the helicity of the participating quark and antiquark are fixed in the reaction. In addition, the W couples to a weak charge that correlates directly to flavors, if ones concentrates on one generation. Indeed the production of Ws in pp collisions is dominated by $u, d, \bar{u}$, and $\bar{d}$, with some contamination from $s, c, \bar{s}$, and $\bar{c}$, mostly through quark mixing. Therefore W production is an ideal tool to study the spin-flavor structure of the nucleon.

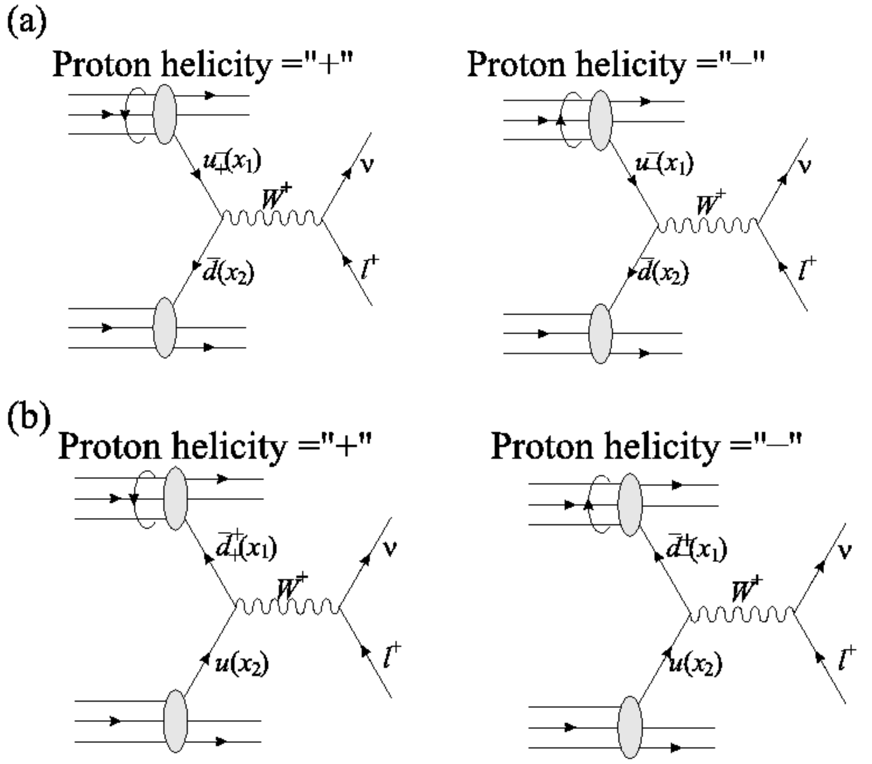
The $W^{\pm} \to l^{\pm}\nu$ charge asymmetry has been studied at leading order (LO) and next-to-leading order (NLO) in connection with the measurement by the CDF collaboration at the Fermilab $p\bar{p}$ collider, or more precisely the asymmetry of the rapidity distribution of the charged leptons

$$A(y_l) = \frac{d\sigma(l^+)/dy_l - d\sigma(l^-)/dy_l}{d\sigma(l^+)/dy_l + d\sigma(l^-)/dy_l},$$

with $d\sigma(l^{\pm})/dy_l$ being the differential $p\bar{p} \to W^{\pm}X \to l^{\pm}\nu X$ cross sections for producing $l^{\pm}$ leptons of rapidity y_l [S. Kretzer et al., Phys. Lett. B348 ('95), 628)]. The asymmetry probes the d/u ratio, since the dominant contribution to W^+ (W^-) producton in $p\bar{p}$ collisions comes from the $u\bar{d}$ ($d\bar{u}$) annihilation process. The NLO predictions where based on a pre-existing program (DYRAD, W. T. Giele et al., Nucl. Phys. B403, ('93), 633].

Since RHIC is a pp and not a $p\bar{p}$ collider, the focus is on the antiquark densities inside the proton. Experiments in recent years have shown [K. Ackerstaff et al. (HERMES Collaboration), Phys. Rev. Lett. 25 ('98), 5519] that there is a strong SU(2) symmetry breaking in the antiquark sea, with a ratio $\bar{d}/\bar{u}$

rising to 1.6 or higher. It is also very attractive to learn whether the polarization of $\bar{u}$ and $\bar{d}$ is large and asymmetric as well.



The leading-order production of Ws, $u\bar{d} \to W^+$, is illustrated in the figures above. A longitudinally polarized proton at the top of each diagram collides with an unpolarized proton, producing a W^+. The parity-violating asymmetry is defined as the difference of left-handed and right-handed production of Ws, divided by the sum and normalized by the beam polarization:

$$A_L^{W^+} = \frac{1}{P} \times \frac{N_-(W^+) - N_+(W^+)}{N_-(W^+) + N_+(W^+)} \quad . \tag{1}$$

One can construct this asymmetry from either polarized beam, and by summing over the helicity states of the other beam. The production of the left-handed weak bosons violates parity maximally. Therefore, if for example the production of the W^+ proceeded only through the diagram in figure (a), the parity-violating asymmetry would directly equal the longitudinal polarization asymmetry of the u quark in the proton:

$$A_L^{W^+} = \frac{u_-^-(x_1)\bar{d}(x_2) - u_+^-(x_1)\bar{d}(x_2)}{u_-^-(x_1)\bar{d}(x_2) + u_+^-(x_1)\bar{d}(x_2)} = \frac{\Delta u(x_1)}{u(x_1)}. \tag{2}$$

Similarly, for figure (b) alone,

$$A_L^{W^+} = \frac{\bar{d}_-^+(x_1)u(x_2) - \bar{d}_+^+(x_1)u(x_2)}{\bar{d}_-^+(x_1)u(x_2) - \bar{d}_+^+(x_1)u(x_2)} = -\frac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}. \tag{3}$$

In general, the asymmetry is a superposition of the two cases [C. Bourrely and J. Soffer, Phys. Lett. B314 ('93), 132], expressed with the corresponding scale M_W and as a function of the vector boson rapidity:

$$A_L^{W^+}(y) = \frac{\Delta u(x_1, M_W^2)\bar{d}(x_2, M_W^2) - \Delta\bar{d}(x_1, M_W^2)u(x_2, M_W^2)}{u(x_1, M_W^2)\bar{d}(x_2, M_W^2) + \bar{d}(x_1, M_W^2)u(x_2, M_W^2)}, \tag{4}$$

The asymmetry for W^- is obtained by interchanging u and d.

By identifying the rapidity of the W boson relative to the polarized proton, one can obtain direct measures of the quark and antiquark polarizations, separated by quark flavor. $A_L^{W^+}$ approaches $\Delta u/u$ in the limit $y \gg 0$, whereas for $y \ll 0$ the asymmetry becomes $-\bar{d}/d$. In practice one can probe, e.g., the polarized antiquark distributions at RHIC for $x \leq 0.12$ from $A_L(y \leq 0)$ [T. Gehrmann, Nucl. Phys. B534 ('98), 21].

The rapidity of the W is related to the lepton rapidity in the W rest frame (y_l^*) and in the laboratory frame (y_l^{lab}) by $y_l^{lab} = y_l^* + y$, where $y_l^* = (1/2)\ln[(1+\cos\theta^*)/(1-\cos\theta^*)]$, with θ^* the decay angle of the lepton in the W rest frame, and $\cos\theta^*$ can be determined from the transverse momentum of the lepton with an irreducible uncertainty of the sign. In this reconstruction, the p_T of the W is neglected. In reality, it has a p_T, resulting from higher-order contributions such as $gu \to W^+d$ and $u\bar{d} \to W^+g$, or from primordial p_T of the initial partons. This is the point where work has to be done.

2.2.2

This is a project which includes the aim to establish a collaboration with the particle physics theory group of T. Gehrmann at the University of Zürich. T. Gehrmann is an expert in the field of hadron collider physics and our group will greatly benefit from his knowledge. It is intended that C. von Arx will focus on the problems described in this proposal as the main subject of his PhD thesis work.

2.2.3

As a first step, we will rederive the LO results given in [S. Ketzer et al., Phys. Lett. B348 ('95), 628] and generalize the results to the LO polarized case. The kinematics of W production and Drell-Yan production of lepton pairs is the same, and the momentum fraction carried by the quarks and antiquarks can be determined from the W boson rapidity. This picture is valid for the predominant production of Ws at transverse momentum $p_T = 0$. The experimental difficulty is that the W is observed only through the charged lepton in its decay $W \to \mathrm{l}\nu$, and usually W production is identified by requiring charged leptons with high p_T. Therefore, we will as a second step implement the polarized LO lepton rapidity numerically and, from the theoretical side, calculate and include the virtual QCD NLO corrections (i.e. corrections of order $\mathcal{O}(\alpha_s)$, which are indeed sizeable) to them.

To obtain NLO results for the lepton rapidity distribution valid without kinematical restrictions, we will study the $2 \to 3$ massless particle phase space for NLO in $d = 4$ dimensions numerically, and examine its properties in collinear limits. Additionally, we will include $gu \to W^+d$ and $u\bar{d} \to W^+g$ matrixelements at order $\mathcal{O}(\alpha_s)$ in order to implement them using an appropriate regularization method.

D - Chaotic physics

Correspondence of classical and quantum chaos

D. Salem, D. Trautmann, C. Jung and T.H. Seligman (Cuernavaca, Mexico)

2.2.1.

In the last two decades, the interest in nonlinear systems has increased enormously. The investigations done in very different fields of science have lead to the understanding that nonlinear behavior and chaotic dynamics are the rule rather than the exception. For some time only the chaotic behavior of classical bound states were investigated, but in the last decade open systems, i.e. chaotic scattering, have attracted particular attention. Chaotic scattering denotes hereby the general behavior of a physical system that evolves from a state that was stationary in the far past to another state that will be stationary in the far future [B. Eckhard, Physica 33 ('98), 89]. The benefits from the study of chaotic scattering systems are therefore not restricted to a limited area in physical research but can produce results that help to understand a wide range of physical processes [L. Benet et al., Celest. Mech. 66 ('97), 203; C. Jung et al., J. Phys. A25 ('92), 3929; R. Guantes et al., Phys. Rev. E56 ('97) 378; E. Doron et al., Phys. Rev. Lett. 65 ('90), 3072; W. Dorfman et al., Phys. Rev. E52 ('95), 28]. Furthermore there exists very extended work on two-dimensional chaotic scattering [C. Lipp and C. Jung, J. Phys. A28 ('95), 6887; W. Breymann et al., Phys. Rev. E50 ('94), 1994], while only little is known about higher dimensional scattering [F. Ezra, J. Chem. Phys. 94 ('91), 2648; K.M. Atkins and J.M. Hutson, J. Chem. Phys. 103 ('95), 9218; Z. Kovacs and L. Wiesenfeld, chao-dyn98/10006; S. Wiggins, Phys. Rev. Lett. 86 ('01), 5478; D. Sweet et al., Phys. Rev. Lett. 86 ('01), 2261; U. Jaffe et al., Nonlinearity 15 ('02), 957].

Recently now, there has also been a considerable amount of discussion about the correspondence between quantum mechanics and the chaotic behavior of classical low dimensionality systems. In this context Rydberg molecules, where the loosely bound outer electrons are highly excited, are a perfect laboratory to study this correspondence.

2.2.2.

The goal of every scattering experiment is to reveal as much information as possible of the hidden scattering region. The only informations available are the asymptotically stable states in the far past and in the far future of the scattering event and how they are transformed from one into the other. The quest is then to make statements on the scattering process based on this restricted information. A very important ingredient in the transient chaotic dynamics of chaotic scattering are the unstable periodic orbits, since they strongly influence the phase flow. Recently, we have developed a method, that finds periods, stability exponents and symmetries of unstable periodic orbits only from scattering data. The results are given in [T. Buetikofer, C. Jung and T.H. Seligman, Phys. Lett. A265 ('00), 76]. This method has been successfully applied to scattering off a magnetic dipole, to the three-disk billiard and to periodically kicked systems [O. Merlo, PhD-thesis, Basel ('05), unpublished].

Furthermore we concentrated on systems with an explicit time-dependence, i.e. systems in which the kinetic energy is not a constant of motion. As a special model L. Benet et al. have investigated the dynamics of rotating targets, e.g. they have studied the case where the target rotates with constant angular velocity, which implies the existence of a constant of motion (the Jacobi integral), and also the case, where the rotating target consists of two rotating stars of given masses attracted by means of the gravitational force, thus moving on Keplerian orbits [N. Meyer et al., J. Phys. A28 ('95), 2529; L. Benet et al., loc. cit. & Celest. Mech. 73 ('98), 167]. We found a great stability of the structure of the scattering against external perturbations and we could give a sufficient condition for the periodic orbits to remain after this perturbation.

We also investigated the classical and quantummechanical chaotic behavior of Rydberg molecules. Using the so called 'multi channel quantum defect theory' (MQDT), it is possible to describe such Rydberg molecules as a quantum system in a finite space, as was shown by [B. Dietz, M. Lombardi and T.H. Seligman, Ann. of Phys. 312(2) ('04), 441] and with the interpretation of the MQDT as a quantum Poincaré map (QPM) [F.Leyvraz, R.A. Méndez-Sánchez, M. Lombardi and T.H. Seligman, Phys. Lett. A268 ('00), 309; T.Prosen, Physica D91 ('96), 244; M.Lombardi and T.H. Seligman, Phys. Rev. A47 ('93), 3571], a comparison of the quantum and classical system becomes accessible. So the statistics for the quantum case for nearest-neighbour spacing distribution was studied and a first comparison between the Quantum Poincaré Map (QPM) and the classical Poincaré Map (PM) showed, that the basic structure of classical chaos also shows up in the quantum system.

2.2.3.

We plan to study now further the structure of classical chaos in the quantum system for these Rydberg molecules. The goal there is to to analyze the detailed structure in the QPM and especially to extend our studies for the situation with the energies of the bound state near the ionization threshold. For this system we have on the one hand its quantum mechanical spectrum and the corresponding eigenstates as a function of the interaction parameter, and on the other hand the classical Poincaré map as a function of the interaction parameter and the total energy. For the quantum states we can also compute Husimi functions and compare them with structures in the classical map.

In the classical map, the rotation numbers of the important (basic) fixed points change as a function of the parameters. They suffer bifurcations where they create new fixed points or absorb old ones. The new fixed points move from one basic point to the other through the domain of the map. These events repeat themselves almost periodically if the energy is varied continuously.

We will now investigate how the connection between the classical and quantum dynamics can be established. In particular, this implies that one has to find the changes in the quantum states which reflect the classical development scenario. As mentioned, it is very promising that in the structure of the quantum spectrum we already observed an approximate repetition of the patterns in parallel to the approximate repetition in the classical scenario. This parallelism has now to be demonstrated and described in detail.