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HadAtom03

Workshop on Hadronic Atoms,
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edited by

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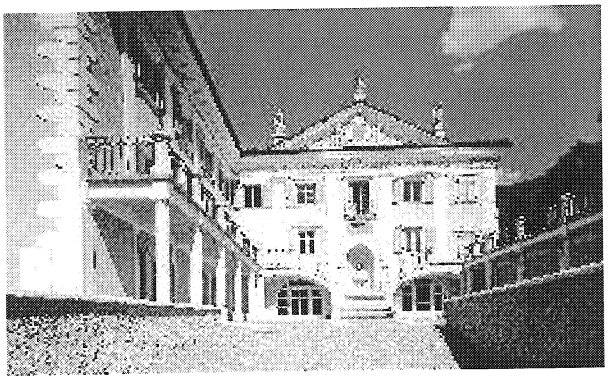

ABSTRACT

These are the proceedings of the workshop "HadAtom03", held at the European Centre for Theoretical Nuclear Physics and Related Studies (ECT*), Trento (Italy), October 13 - 17, 2003. The main topics discussed at the workshop were the physics of hadronic atoms and in this context recent results in experiment and theory. Included here are the list of participants, the scientific program and a short contribution from each speaker.

1 Introduction

The HadAtom03 workshop was held on October 13-17, 2003 at the European Centre for Theoretical Nuclear Physics and Related Topics (ECT*), Trento (Italy). This was already the fifth regular workshop of the HadAtom series, which originally have been inspired by latest experimental and theoretical progress achieved in the investigation of the bound states of strongly interacting particles – hadronic atoms. The previous workshops were held in Dubna (1998), Bern (1999,2001), and at CERN (2002). At this time, the topics of the workshop included:

- Hadronic atoms, in particular their
  - Production
  - Interaction with matter
  - Energy levels
  - Decays
- Meson-meson and meson-baryon scattering
- Experiments
  - DIRAC at CERN
  - DEAR at DAFNE
  - Pionic Hydrogen Collaboration at PSI
  - Experiment on deeply bound pionic atoms at GSI
  - Others
- Lattice calculations and effective theory of QCD
- Chiral Perturbation Theory and nuclear many-body systems
  - Nuclear Matter
  - Finite systems
  - π-nucleus, K-nucleus bound states: spectrum and decays

More than 40 physicists took part in the workshop, and 35 talks were presented. For the first time during the workshop we allocated free slots for informal discussions, particularly useful for not being restricted with time limits and a detailed program. The topics and the coordinators of the discussions were announced in advance. In total, three discussions took place during the workshop:

Topic	*Coordination*
πK interaction and three-flavour ChPT	Stern
The single arm results from DIRAC: pion propagation in the medium	Nemenov and Wirzba
Spectrum and decays of the KN atom	Petrascu and Rusetsky

As after the previous workshops [1,2,3,4], we publish a collection of abstracts of the presentations, containing relevant references. In addition, we display the list of the participants with their e-mail addresses.

Acknowledgments.
We wish to thank all participants for travelling to Trento and for making "HadAtom03" an exciting and lively meeting. We want to thank our secretary Ines Campo for the excellent performance, and the staff of the ECT*: Corrado Carlin, Cristina Costa, Barbara Curro-Dossi, Tiziana Ingrassia, Mauro Meneghin, Donatella Rossetti, Rachel Weatherhead and Gianmaria Ziglio for their help. Last but not least, we thank our colleagues from the program panel: Leonid Afanasyev, Valery Lyubovitskij, Leonid Nemenov, Hagop Sazdjian and Dirk Trautmann, for their invaluable contribution in structuring the meeting.

The "HadAtom03" workshop was partially supported by the ECT*, and by RTN, BBW-Contract No.01.0357 and EC-Contract HPRN–CT2002–00311 (EURIDICE). It was a topical workshop of the EURIDICE collaboration.

Bern/Bonn, January 26, 2004

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3 Contributions

Atoms consisting of $\pi^+\pi^-$ and πK mesons

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Using experience obtained in the DIRAC experiment at CERN [1] the new experimentis proposed for the PS CERN and J-PARC in Japan [2] to perform a crucial check of the precise predictions of the low energy QCD. The DIRAC Collaboration plans to upgrade the setup: 1) improving the detector shielding, 2) adding aerogel counters in combination with existing Cerenkov counters to identify K-mesons and protons and 3) modernising part of the electronics.

The proposed experiment aims to measure the lifetime of $\pi^+\pi^-$-atom ($A_{2\pi}$) with precision better then 6% and the determination of the difference S-wave pion-pion scattering lengths $|a_0 - a_2|$ at the level of 3%. Simultaneously with investigation of $A_{2\pi}$ with the same setup the observation of atoms consisting of πK-mesons ($A_{\pi K}$) and their lifetime measurement with precision of ~20% and the evaluation of the difference S-wave πK scattering lengths $|a_{1/2} - a_{3/2}|$ with precision ~10% is planned.

The observation of the long-lived (metastable) states of $A_{2\pi}$ is also planned with the same setup. This will give the possibility to measure the difference ΔE_n between energy of nS and nP states and to evaluate in a model independent way the value $2a_0 + a_2$. The measurements of the $A_{2\pi}$ lifetime and ΔE_n allow to obtain in a model independent way values for a_0 and a_2, separately.

Low energy QCD [3] predicts for the pion-pion scattering lengths with an accuracy about 2% [4,5] and about 10% of the pi-K scattering lengths [6,7]. The pion-pion and pion-kaon scattering lengths have never been verified by the experimental data with the same accuracy as the theoretical prediction.

These theoretical results have been obtained assuming strong condensation of the quark-antiquark pairs in the vacuum. On this reason the proposed experiment will be a crucial check of the low energy QCD predictions and our understanding of the nature of QCD vacuum [8].

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Observation of $\pi^+\pi^-$ atoms at DIRAC and its lifetime estimation

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The Chiral Perturbation Theory (ChPT) relies on the 2-loop corrections and Roy equations to give an accurate prediction of the difference between the S-wave $\pi\pi$ scattering isospin 0 and 2 lengths, a_0 and a_2. $|a_0 - a_2|$ is predicted with an accuracy of 1.5%: 0.265 ± 0.004 [1]. The dominant mode of $\pi^+\pi^-$ atom ($A_{2\pi}$) decay is $A_{2\pi} \to \pi^0\pi^0$, whereas the partial width of the second decay mode $A_{2\pi} \to \gamma\gamma$ is 0.4%. The relationship between the decay width $\Gamma_{2\pi^0}$ and the $\pi\pi$ scattering lengths is $\Gamma_{2\pi^0} = C \cdot |a_0 - a_2|^2$ [2,3]. The next-to-leading order correction for the isospin breaking gives: $\Gamma_{2\pi^0}^{NLO} = \Gamma_{2\pi^0}(1 + \delta_\Gamma)$, with $\delta_\Gamma = (5.8 \pm 1.2)\%$ [1]. This yields the value of the $A_{2\pi}$ lifetime $\tau = (2.9 \pm 0.1) \times 10^{-15}$ s. A measurement of the latter with an accuracy of 10% allows one to determine the corresponding $\pi\pi$ scattering length difference with a 5% precision.

The following method is used for the lifetime measurement by the DIRAC experiment. A $\pi^+\pi^-$ pair are generated from the short-lived sources as a result of the proton-target interaction. Final state $\pi^+\pi^-$ Coulomb interaction may lead to the creation of an atom $A_{2\pi}$ [5,6]. Once created, the $A_{2\pi}$ propagates through the target and may break up due to interaction with target matter, producing so-called "atomic pairs". These pairs are characterized by small relative momenta $Q < 3$ MeV/c in the pair c. m. system. A further process competing with the breakup is the $A_{2\pi}$ annihilation into $\pi^0\pi^0$. Additional $\pi^+\pi^-$ pairs originating from the short lived sources can form free "Coulomb pairs" [6], e.g. pion pairs in a free or continuous state. The number "Coulomb pairs" is related to the number of produced $A_{2\pi}$'s. With the definition of the breakup probability P_{br} as the ratio of the number of dissociated atoms n_A to the number of produced atoms, a lifetime vs. breakup probability relationship may be established by solving a set of differential transport equations. Then P_{br} can be derived with an accuracy of better than 1% [7].

The DIRAC spectrometer was designed specifically for detecting $\pi^+\pi^-$ pairs with small relative momenta [8]. The setup is located in the T8 beam area of the CERN PS accelerator. Three detectors are installed upstream of the magnet, and six detectors in two identical arms downstream of the magnet. The setup resolution for the relative c. m. momentum Q for $\pi^+\pi^-$ pairs is better than 1 MeV/c.

The method of extracting "atomic pairs" is explained in more detail in [9]. The accuracy of this method is defined not only by the statistical errors, but also the systematic one. There are two main sources of the latter. The first one is the accuracy of the description of multiple scattering in the target and detectors and the second one is the scintillating fiber detector response for two close tracks. To this end we have dedicated portions of our runs in 2002-2003 to the investigation of the systematic errors. During 2002-2003 runs, two Ni targets, single and multilayer, were also used. Single and multilayer target event distributions are identical in all respects but one: the multilayer target yields a lower number of dissociated pairs due to the annihilations in the interlayer gaps. This allows one immediately obtain the atomic pair signal from the difference between the single and multilayer target distributions.

It is possible to decrease the systematic error by a factor of 2 if only the longitudinal momentum component Q_L is taken into consideration [9]. An alternative approach for the

signal extraction is to make use of the downstream detectors only. This method allows us to get a more realistic number of "atomic pairs" due to absence of all criteria on hit occupancy and inefficiency in upstream detectors. In Fig. 1 we present the Q_L distributions of "atomic pairs" with and without the information from the upstream detectors.

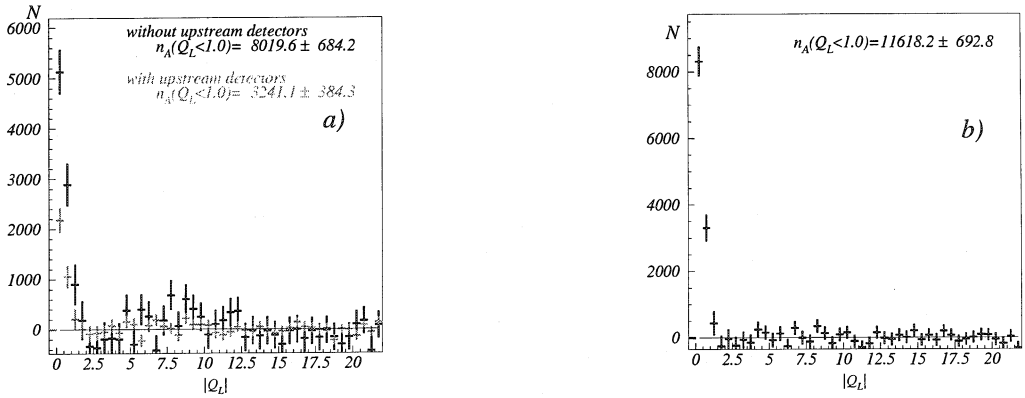

Figure 1: "Atomic pair" signals: a) for the combined Ni 2000 and Ti 2000-2001 statistics (~30% of all statistics) with and without upstream detectors and b) for the combined Ni 2001-2003 statistics (~70% of all statistics) with upstream detectors.

The total number of "atomic pairs" collected during 2000-2003 runs is more than 20000 in the case of identification using downstream detectors only.

The data analysis procedure has not been finalized. Taking into account the best understood part of the Ni 2001 data statistics with about 5200 "atomic pairs", a preliminary estimate for the lifetime yields the value: $\tau = [3.1^{+0.9}_{-0.7}(stat) \pm 1(syst)] \times 10^{-15}$ s. The analysis of the data collected in 2000 and 2003 allows us to reduce the overall error down to 12-14%.

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Pion-nucleon scattering

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The meson factories at Los Alamos (LAMPF), Vancouver (TRIUMF) and Villigen (PSI) have produced a lot of pion-nucleon scattering data at low and medium energies. Most of these data were not yet available at the time of the Karlsruhe-Helsinki partial wave analysis [1], but are included in the data dase of the SAID analysis [2]. The new data are expected to change the low-energy pion-nucleon partial wave amplitudes. It is our aim to perform a pion-nucleon partial wave analysis in the spirit of the Karlsruhe-Helsinki approach by making use of the expansion method of Pietarinen and to include the data of the meson factory era.

Examples of recent data sets at low energy are the data of Pavan et al. [3] on differential cross sections, Hofman et al. [4] on polarization, Alekseev et al. [5] on spin rotation parameters and Kriss et al. [6] on integrated cross sections. In addition, there are precise measurements of the level shift and width of the pionic hydrogen. Also, the CHAOS collaboration at TRIUMF has measured elastic scattering at the Coulomb-nuclear interference region providing information for the forward extrapolation [7].

The electromagnetic corrections will be treated in the manner of Tromborg et al. [8] eventhough the approach is known to have shortcomings [9].

Currently we are still testing the analysis programme with theoretical "data" from the KA85 analysis [10].

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Moliere multiple-scattering theory revisited

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We have derived the rigorous relation between the values of the screening parameters (angle) θ_a of the Moliere multiple scattering theory [1], calculated in the Born and WKB approximations, instead of the approximate one obtained in the original paper by Moliere.

Our result reads:

$$\ln(\theta_a^{\mathrm{WKB}}) - \ln(\theta_a^{\mathrm{Born}}) = \mathrm{Re}\,[\psi(1+i\alpha) - \psi(1)]$$

$$\alpha = \frac{Z}{137\beta} \qquad \psi(x) = \frac{d}{dx}\ln\Gamma(x)\,.$$

Here Z is the atomic number of the target atom and β is the charged particle velocity.

References

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Interaction of Pionium with atoms at relativistic energies and propagation of Pionium through matter

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In order to be able to measure the pionium ($A_{2\pi}$) lifetime with an accuracy of 10%, the experiment DIRAC at CERN needs as theoretical input the electromagnetic excitation and ionization cross sections of this exotic atom with 1% accuracy. This is due to the fact, that DIRAC determines the lifetime indirectly by measuring the number of pionium atoms breaking up (in contrast to being annihilated to $\pi^0\pi^0$) and the number of produced atoms. From this breakup ratio, together with its theoretical calculation as a function of the lifetime of pionium, the lifetime is estimated, see Fig. 3(A) below.

In order to achieve the required accuracy of 1% for the cross section needed for the analysis, a number of effects need to be incorporated in the calculations. Starting from the Born cross section within the semiclassical approach, target inelastic effects, magnetic terms and relativistic corrections have been calculated and included in the tabulation of the cross section, where needed, see [1,2] and references therein. Within a Glauber calculation it was found that the higher order photon exchange is important, as the excitation cross sections change relative to the lowest order results by up to 20%, see Fig. 1. An independent test of the Glauber results by using a coupled channel approach for some important transitions is currently under way. We have found already that transitions to the continuum are important and cannot be neglected. We are including them either within a discretization of the continuum ("Weyl states") or by a perturbative coupling to the continuum only.

It has become clear in the meantime, that the density formalism used to describe the propagation of pionium through the target needs to be tested more thoroughly. By choosing two different decompositions (spherical and parabolic coordinates) for degenerate states, it was pointed out in [3] that changes of the predicted life time of the order of a few percent can be found. More recently a full quantum mechanical approach to the propagation within a density matrix approach has been proposed [4]. We have employed an "optimal mixture" approach. The idea is to stay within the density formalism, but to use optimal linear combinations of degenerate states that maximize the transition from the dominant feeding states into them, see Fig. 2. Due to m-number conservation and z-parity, the important cases are the $3s/3d$, $4s/4d$ ($m = 0$) and the $4p/4f$ ($m = \pm 1$) states. The optimal linear combination was found for a mixing angle of about 161^o ($3s/3d$), 155^o ($4s/4d$) and 170^o ($4p/4f$). The resulting new basis states are therefore close to the spherical one. Using these new states within the density formalism, and adapting production and annihilation cross sections to incorporate their mixed nature, we find a deviation from the pure spherical basis of about 0.2%, see Fig. 3. A test of the possible error within this approach was made by dropping the transitions to the "small component" altogether, which gives a change of about -0.5%. As a different approach we assume that the whole cross section to the degenerate states goes to s or p states only. With this we find good agreement with the "optimal mixture" model. From this we conclude, that the accuracy of our approach is of the order of 0.5% with a deviation from the density formalism up to now of 0.2%.

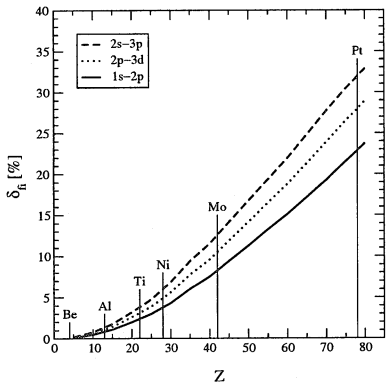


Figure 1: The relative difference between the lowest order and the Glauber results $\delta_{fi} = (\sigma_{LO} - \sigma_{GL})/\sigma_{LO}$ is shown for different transitions as a function of the charge number of the target.

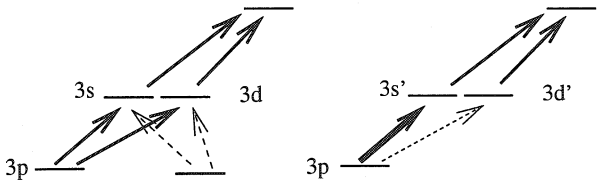
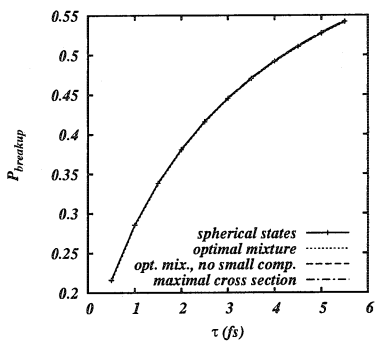
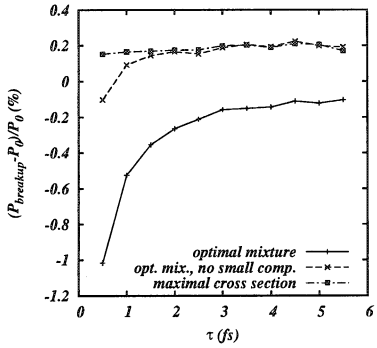


Figure 2: In the optimal mixture approach a linear combination (of the $3s$ and $3d$ ($m = 0$) in the case depicted here) is chosen, which maximizes the transition to one of the new set of states ("$3s'$") from the dominant feeding state, which in this case is $3p$, $m = \pm 1$. The propagation of pionium through matter is then done employing this new set of states.



(A)



(B)

Figure 3: In (A) the change of the breakup ratio $P_{\rm br}$ as a function of the pionium lifetime τ is shown for the four different models, see the text for detail. (B) shows the relative difference of the three new models compared to the one using spherical states. In the calculation, a 95 μm Ni target and a pionium momentum of $p = 4.7$ GeV/c were used.

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Production of the long-lived excited states of $\pi^+\pi^-$ atoms in view to perform an experiment on their observation and measurement the Lamb shift

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Measurement of the $\pi^+\pi^-$ atom lifetime in the DIRAC experiment will allows one to obtain in the model independent way the value $|a_0 - a_2|$, the difference of the s-wave $\pi\pi$ scattering lengths with the isotop spin 0 and 2 correspondently [1]. To get the values of a_0 and a_2 separately basing on the $\pi^+\pi^-$ atom data, one may use the fact that the energy splitting between levels ns and np, $\Delta E_n = E_{ns} - E_{np}$, depends on the the another combination of scattering lengths: $2a_0 + a_2$. Thus the measurement the energy splitting coupled with the lifetime measurement would provide a determination of a_0 and a_2 separately [1,2].

The lifetimes of the np states are significantly, 3–5 order, higher in compare with the ground state [2]. For that reason atoms in np states have the mean paths of teens centimeters. Methods of ΔE_n measurement proposed in papers [3] and [4] based on observation of the interference between ns and $np(m = 0)$ states in the external electro-magnetic fields.

Production of $\pi^+\pi^-$ atom in the np states have been considered for different target materials and thicknesses with the intent to optimize the experimental conditions for their observation. It have been shown that for the DIRAC experiment usage of thiner targets with smaller Z provides increase of yield of np states and a better ratio to the atom break-up. In the following table a set of targets providing the highest yield of $\pi^+\pi^-$ atom states with the magnetic quantum number $l \geq 1$ are shown.

Target Z	Thickness μm	Break-up	$\sum(l \geq 1)$	$2p_0$	$3p_0$	$4p_0$	$\sum(l = 1, m = 0)$
04	50	2.63%	5.86%	1.05%	0.54%	0.20%	1.93%
06	50	5.00%	6.92%	1.46%	0.51%	0.16%	2.52%
13	20	5.28%	7.84%	1.75%	0.57%	0.18%	2.63%
28	5	9.42%	9.69%	2.40%	0.58%	0.18%	3.29%
78	2	18.8%	10.5%	2.70%	0.55%	0.16%	3.53%

The experimental data already collected in the DIRAC experiment with single and multi-layer nickel targets confirm existence of the excited states of $\pi^+\pi^-$ atom with the mean paths much longer than 1 mm.

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The quantum-mechanical treatment of pionium internal dynamics in matter

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The quantum-mechanical consideration of a passage of fast dimesoatoms through matter is given. A set of quantum-kinetic equations for the density matrix elements describing their internal state evolution is derived. It is shown that probabilistic description of internal dynamics of hydrogen-like atoms is impossible even at sufficiently low energies because of the "accidental" degeneracy of their energy levels.

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On radiative decay channels of pionic and kaonic hydrogen

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In [1] we have developed a quantum field theoretic, relativistic covariant and model–independent approach to the description of the energy level displacements of the ground and excited $n\ell$ states of pionic and kaonic hydrogen A_{h^-p}, where $h^- = \pi^-$ or K^-. In order to estimate of the contribution of the radiative decay channels of pionic and kaonic hydrogen we apply a soft–pion and soft–kaon technique [1] (nucl–th/0310081). For the Panofsky ratio we get the result [1] (nucl–th/0310081)

$$\frac{1}{P} = \frac{\sigma(\pi^- p \to n\gamma)}{\sigma(\pi^- p \to n\pi^0)} = \frac{\Gamma_{1s}(A_{\pi^- p} \to n\gamma)}{\Gamma_{1s}(A_{\pi^- p} \to n\pi^0)} = 0.681 \pm 0.048 \quad (1)$$

agreeing well with the experimental value $1/P_{\rm exp} = 0.647 \pm 0.004$ [2]. As it is shown in [3] the agreement with the experimental data can be improved accounting for the form factor of the axial–vector current, the matrix element of which defines the amplitude of the reaction $\pi^- p \to n\gamma$ in the soft–pion limit, i.e. at leading order of ChPT (Gasser & Leutwyler). For the Panofsky ratio of kaonic hydrogen we get [1] (nucl–th/0310081)

$$\frac{1}{P} = \frac{\Gamma_{1s}(A_{K^- p} \to \Lambda^0\gamma) + \Gamma_{1s}(A_{K^- p} \to \Sigma^0\gamma)}{\Gamma_{1s}} = (3.97 \pm 0.47) \times 10^{-3}, \quad (2)$$

where $\Gamma(A_{K^- p} \to \Lambda^0\gamma) = (0.82 \pm 0.04)\,{\rm eV}$, $\Gamma_{1s}(A_{K^- p} \to \Sigma^0\gamma) = (0.08 \pm 0.01)\,{\rm eV}$ and $\Gamma_{1s} = (227 \pm 27)\,{\rm eV}$. Thus, the contributions of the radiative decay channels of kaonic hydrogen can be neglected for the theoretical analysis of experimental data on the energy level displacement of the ground state of kaonic hydrogen by the DEAR Collaboration: $\epsilon_{1s}^{\rm exp} = (183 \pm 62)\,{\rm eV}$ and $\Gamma_{1s}^{\rm exp} = (213 \pm 138)\,{\rm eV}$ (see M. Cargnelli, *DEAR–Kaonic Hydrogen: First Results*, hep–ph/0311212, p.125).

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Deser-type formula for pionic hydrogen

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The decay width of the ground state of pionic hydrogen is dominated by the two decay channels $(\pi^- p)_{1s} \to \pi^0 n$ and $(\pi^- p)_{1s} \to n\gamma$. Using δ as a common counting for the light quark mass difference $m_u - m_d$ and for the fine-structure constant α, the leading term of the former (latter) decay channel is of order $\delta^{7/2}$ (δ^4). The decay width through these two channels can be expressed by a Deser-type formula

$$\Gamma_{1s} = 4\,\alpha^3 M_r^2 q_0 \left(1 + \frac{1}{P}\right) [a_{\pi^- p \to \pi^0 n}(1 + \delta_\Gamma)]^2 \,. \tag{1}$$

Since the Panofsky ratio $P = \sigma(\pi^- p \to \pi^0 n)/\sigma(\pi^- p \to n\gamma)$ is about 1.5, the $n\gamma$ channel amounts to a 60% correction. To the best of my knowledge, this formula was first established in the framework of potential models [1,2]. I want to verify its validity in QCD + QED, using the technique of non-relativistic effective field theories [3,4,5]. Constructing the effective Lagrangian and solving the master equation, one encounters the obstacle that the photon in the intermediate state carries a hard momentum of order M_π. To circumvent this problem, I do not incorporate $n\gamma$ intermediate states with effective fields. Instead I introduce a non-hermitian contact term [3] (cf. also [6]) in the Lagrangian with the coupling $d_1^R + i d_1^I$,

$$\mathcal{L}_1^{n\gamma} = (d_1^R + i d_1^I)\, \psi^\dagger(x)\psi(x)\, \pi_-^\dagger(x)\pi_-(x) \,. \tag{2}$$

The imaginary part d_1^I replaces the imaginary part generated by the intermediate $n\gamma$ state. With this contact term, I can prove that formula (1) is valid at order δ^4. It remains[1] to evaluate Γ_{1s} at order $\delta^{9/2}$ and to determine δ_Γ in equation (1).

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Electromagnetic corrections to scattering lengths from hydrogenic atoms applied to the π^-p system

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Motivated by the accurate measurements of strong interaction 1s shifts and width in pionic hydrogen, we explore the atomic corrections to the leading order Born relation of the (complex) scattering length a^h to the (complex) strong interaction level shift $\epsilon_{1s} - i\Gamma_{1s}/2$. In terms of the reduced mass μ and the deviation δ_{1s} from the Born relation:

$$\epsilon_{1s} = -\frac{4\pi}{2\mu}\,\Phi_B(0)^2\ \mathrm{Re}\ a^h(1+\delta_{1s}) = 4\mu\alpha\ \mathrm{Re}\ a^h(1+\delta_{1s})\ E_B\ , \qquad (1)$$

where $\Phi_B(r)$ and $E_B = -\mu\alpha^2/2$ are the Bohr wave function and Bohr energy, respectively. To display the physical mechanisms at work, we first consider an oversimplified model with the merit of an explicit solution. It is later realistically generalized [1]. The hadronic scattering length a^h is taken to result from a zero range interaction. The charge distribution is approximated by concentrating the charge to a spherical shell of radius R with the scattering interaction at its center. The solution to order $\alpha^2 \ln\alpha$ for a single channel is:

$$\delta_{1s} = -2\frac{R}{r_B} + 2\frac{a^h}{r_B}\,[2 - \gamma - \log(2\alpha m R)] = \delta_{1s,1} + \delta_{1s,2}. \qquad (2)$$

An energy dependent amplitude with a threshold expansion $a^h(q^2) = a^h + b^h q^2 + ..$ gives the additional term $\delta_{1s,3} = (2\mu\alpha/R)\mathrm{Re}b^h/\mathrm{Re}a^h$. These three generic contributions have simple physical interpretations. The linear term in R represents the change of the wave function at the origin of the extended charge with $\delta\Phi(0)/\Phi_B(0) = -\alpha\mu R$; the term proportional to $1/R$ expresses that the relevant kinetic energy is the depth of the extended charge Coulomb potential and not the small binding energy. The term proportional to the scattering length $\delta_{1s,2}$ is a renormalization induced by consistency of the strong energy shift with the scattering length producing it. A realistic generalization to the $\pi^-p \to \pi^-p$ channel in the coupled channel πN system with the empirical charge distribution and mass difference gives in percent: $\delta_{1s,1} = -0.853(8); \delta_{1s,2} = 0.701(4); \delta_{1s,3} = -0.95(29); \delta_{1s} = -0.62(29)$. These results correspond to an interpretation of the energy shift in terms of a scattering length in the absence of an external, removable Coulomb field. We have made no corrections for the internal e.m. contributions to the masses. Our relation cannot therefore be readily compared to the EFT expansion based on the QCD Lagrangian [2].

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Ground-State Shift in Pionic hydrogen

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The measurement of ground–state transitions in pionic hydrogen allows to determine the isoscalar and isovector scattering lengths a^+ and a^-, which describe the πN s–wave interaction [1,2,3]. In addition, the πN coupling constant can be extracted by applying the Goldhaber–Miyazawa–Oehme sum rule [4,5]. To improve on the accuracy achieved by previous measurements [6], a thorough study of the atomic cascade has been started at the Paul–Scherrer–Institut using the new cyclotron trap, a cryogenic target, and a Bragg spectrometer equipped with spherically bent silicon and quartz crystals and a large–area CCD array [9] (PSI experiment R–98.01 [7,8]) .

At first, the possibility of radiative de–excitation of the πH atom – when bound into complex molecules formed during collisions $\pi^- p + H_2 \rightarrow [(pp\pi^-)p]ee$ [10] – was studied by searching for a density dependence of the πH(3p-1s) transition energy. No density effect was found in a pressure range from 3.5 bar to liquid and, consequently, the measured line shift ϵ_{1s} can be attributed exclusively to the strong interaction. The value of $\epsilon_{1s} = 7.120 \pm 0.013$ eV (preliminary) measured in this experiment [8,11] was found to be in good agreement with the result of the previous experiment [6]. The experimental error was improved by more than a factor of two. The precise value for ϵ_{1s} from πD, which has been used for the determination of a^+ and a^- because of the poor knowledge of Γ_{1s} [5], may be questioned because radiative de–excitation should be enhanced considerably.

At present, the accuracy for Γ_{1s} (7%) is limited by the not sufficiently well known correction for the Doppler broadening of the X–ray lines [6], which is is caused by conversion of de–excitation energy into kinetic energy during collisions (Coulomb de–excitation) [12]. The efforts in the extraction of the strong–interaction broadening are dicussed by L. Simons [13].

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Cascade model predictions: K^-p, K^-d, and π^-p

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The extended standard cascade model [1] has been used to study the atomic cascade in exotic hydrogen atoms. The model is based on cross sections for the collisional processes: Stark transitions, elastic scattering, nuclear absorption during collisions, Coulomb deexcitation, and external Auger effect. The X-ray yields, cascade times, and kinetic energy distributions in exotic hydrogen atoms have been calculated and compared with experimental data. Cascade model predictions are important for the analysis of experimental data and for planning future experiments. The following three experiments are of particular interest:

- The DEAR Collaboration has measured the K X-ray spectrum in kaonic hydrogen and results for the $1s$ shift/width and the X-ray yields are in progress [2]. The K yields depend strongly on the $2p$ strong interaction width so cascade model predictions can be used to determine it.
- The SIDDHARTA Collaboration plans to measure the K X-ray spectrum in kaonic deuterium from which the $1s$ shift/width can be extracted [3]. The experiment depends crucially on the K X-ray yield which is reduced by absorption from the ns and np states. Our cascade calculations show that absorption from ns states does not make X-ray measurements infeasible. The poorly known np state absorption could, however, reduce the yields significantly.
- The pionic hydrogen $1s$ shift/width experiment at PSI is in progress [4]. In order to extract the strong interaction width from the measured line profiles corrections due the Doppler broadening must be taken into account–*i.e.* the kinetic energy distributions at the instant of the radiative transitions are needed. At present, the calculated cross sections which are used as input by the cascade program are not accurate enough for an *ab initio* calculation of the Doppler correction to the required precision. Until improved results for the collisional processes become available a combination of cascade model constraints and a fitting procedure is the best option.

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Experimental determination of the strong interaction ground state width in pionic hydrogen

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The importance of the measurement of the ground state shift and width from a measurement of X-rays from pionic hydrogen atoms has been addressed at this workshop by D. Gotta [1]. Whereas first results could be obtained for the shift from recent measurements the extraction of the width is still subject of investigations. Two main difficulties are withstanding a direct extraction of the width. The first difficulty is inherent to the method of the measurement as a crystal spectrometer is used in order to achieve high resolution. The response function of this device is a complicated function of crystal and imaging properties and has to be determined in an independent measurement. Such a measurement has been performed in the meanwhile by using an ECR (electron cyclotron resonance) source [3,4]. This source produces an extended source of quasi-monoenergetic X-rays in the energy range of the pionic hydrogen X-rays. Astonishingly the measurements showed no sizeable deviation of the resolution function from the theoretical values [5]. This fact allows to produce response functions for each of the transition energies and crystal types (α quartz(10-1) and Si(111)) as well and served as a basis for the analysis of the measured spectra.

The second not yet solved difficulty is caused by the fact that the pionic hydrogen atoms are not at rest at the instant of X-ray emission. This leads to a Doppler broadening which renders the extraction of the strong interaction width to be very difficult. The theory of the different processes changing the state of the velocity of the pionic hydrogen atoms is discussed by T. Jensen in a contribution to this workshop [2]. Especially kinetic energies of about some 10 eV will result in a Doppler broadening faking a strong interaction broadening of about 900 meV. A thorough understanding of the acceleration processes is therefore indispensable to reach the goal of an accuracy of about 1% required in the proposal [6]. From a preliminary evaluation of the 3-1 and the 4-1 transition, however, even now a safe upper limit for the strong interaction broadening of 850 meV can be extracted.

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Calculating πK atom properties in the constraint theory approach

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The constraint theory approach reduces the Bethe–Salpeter equation to a covariant three-dimensional equation. It has been applied recently to the calculation of the pionium lifetime with its relativistic corrections. The method can also be applied to the evaluation of the lifetime and energy splittings of excited states of the πK hadronic atoms, for the observation of which experimental projects are being prepared. The calculations can be done in covariant arbitrary gauges for the photon propagator present in the QED type diagrams that contribute to the evaluation of part of the electromagnetic corrections. Observable quantities should be independent of the gauge parameter. Cancellation of infra-red singularities between various off-mass shell scattering diagrams and effective three-dimensional diagrams, resulting from the three-dimensional reduction procedure, should occur in order to render the interaction potentials free of such singularities. In that case, the potentials that are present in the bound state equation can be analytically continued to the πK threshold and identified with the real parts of the infra-red regularized on-mass shell πK scattering amplitudes at threshold, including isospin breaking and electromagnetism at leading order. The expressions of those amplitudes can then be used for the evaluation of the various physical quantities.

On the precision of the theoretical predictions for $\pi\pi$ scattering

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In two recent papers [1], Peláez and Ynduráin evaluate some of the low energy observables of $\pi\pi$ scattering and obtain flat disagreement with our earlier results [2]. The authors work with unsubtracted dispersion relations, so that the outcome of their calculation is very sensitive to the poorly known high energy behaviour of the scattering amplitude. They claim that the asymptotic representation we used in [2,3] is incorrect and propose an alternative one. We have repeated [4] their calculations on the basis of the standard, subtracted fixed-t dispersion relations, using their asymptotics. The outcome fully confirms our earlier findings. Moreover, we show that the Regge parametrization proposed by these authors for the region above 1.4 GeV violates crossing symmetry: Their ansatz is not consistent with the behaviour observed at low energies.

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Energy shift and decay width of the πK atom

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Nearly fifty years ago, Deser et al. [1] derived the formula for the width of pionic hydrogen at leading order in isospin symmetry breaking. Similar formulas also hold for pionium and the $\pi^- K^+$ atom. These Deser-type relations allow to extract the scattering lengths from measurements of the decay width and the strong energy shift. The DIRAC collaboration at CERN [2] aims to measure the pionium lifetime to 10% accuracy which allows to determine the S-wave $\pi\pi$ scattering lengths difference $|a_0^0 - a_0^2|$ at 5% precision. New experiments are proposed at CERN PS and J-PARC in Japan [3].

To determine the scattering lengths from such precision measurements, the theoretical expressions must be known to an accuracy that matches the experimental precision. We evaluated the width and the energy shift for the ground state of the $\pi^- K^+$ atom within the non-relativistic effective Lagrangian framework [4]. The result reads at next-to-leading order in isospin symmetry breaking, where both $\alpha \simeq 1/137$ and $m_u - m_d$ count as small quantities of order δ,

$$\Gamma_{\pi^0 K^0} = 8\alpha^3 \mu_+^2 p^* \mathcal{A}^2 \,(1+K)\,, \quad \mathcal{A} = -\frac{1}{8\sqrt{2}\pi}\frac{1}{M_{\pi^+}+M_{K^+}} \mathrm{Re}\, A_{\rm thr}^{00;\pm} + o(\delta), \tag{1}$$

with

$$\begin{aligned} p^* &= \left[\frac{M_{\pi^+}\Delta_K + M_{K^+}\Delta_\pi}{M_{\pi^+}+M_{K^+}} - \alpha^2\mu_+^2 + \frac{(\Delta_K - \Delta_\pi)^2}{4(M_{\pi^+}+M_{K^+})^2}\right]^{\frac{1}{2}}, \\ K &= \frac{M_{\pi^+}\Delta_K + M_{K^+}\Delta_\pi}{M_{\pi^+}+M_{K^+}} a_0^{+2} - 4\alpha\mu_+ \left[\ln\alpha - 1\right](a_0^+ + a_0^-) + o(\delta). \end{aligned} \tag{2}$$

Here $\Delta_\pi = M_{\pi^+}^2 - M_{\pi^0}^2$, $\Delta_K = M_{K^+}^2 - M_{K^0}^2$ and μ_+ denotes the charged reduced mass. The quantity $\mathrm{Re}\, A_{\rm thr}^{00;\pm}$ is determined as follows. One evaluates the relativistic $\pi^- K^+ \to \pi^0 K^0$ amplitude at order δ near threshold, see Refs. [5,6]. The real part of this matrix element contains a singularity $\sim 1/|\mathbf{p}|$ at threshold ($\mathbf{p}$ denotes the c.m. momentum of the charged pion and kaon). The constant term in the threshold expansion corresponds to $\mathrm{Re}\, A_{\rm thr}^{00;\pm}$. Further, $\mathcal{A}$ is normalized such that in the isospin symmetry limit it coincides with the isospin odd scattering length a_0^-. The isospin even and odd πK scattering lengths[1] a_0^+ and a_0^- are defined in QCD at $m_u = m_d$ and $M_\pi \doteq M_{\pi^+}$, $M_K \doteq M_{K^+}$.

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Roy–Steiner equations for πK scattering

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πK scattering is the most simple $SU(3)$–process involving strange quarks. It is therefore an ideal place to test chiral predictions with non–vanishing strangeness. While this process is interesting by itself, a detailed knowledge of πK scattering also contributes to the understanding of the flavour dependence of the order parameters of Chiral Perturbation Theory (ChPT) [1]. In our work we use Roy–Steiner equations to analyze the available experimental πK and $\pi\pi \to K\bar{K}$ data and to explore the low energy region where no such data are available [2].

Taking the higher partial waves and all S– and P–waves above the energy region from threshold to $\approx$ 1 GeV. Our solutions for the low–energy region turn out to be in general poor agreement with the available experimental data. Hence, the mass for the $K^*(892)$ is shifted by $\approx$ 10 MeV from the published value to 905 MeV. The solutions of the Roy–Steiner equations also yield predictions for the scattering lengths $a_0^{1/2}$ and $a_0^{3/2}$. In contradiction to $\pi\pi$ scattering the allowed values are strongly constrained by the data, so that there is no universal band for the two scattering lengths. We find $m_\pi a_0^{1/2} = 0.224 \pm 0.022$, $m_\pi a_0^{3/2} = -0.0448 \pm 0.0077$ Finally, the matching of the sub-threshold parameters in the chiral and the dispersive framework yields the following estimates for the low–energy constants (at the scale $\mu = m_\rho$ in units of 10^{-3}): $L_1^r = 1.05 \pm 0.12, L_2^r = 1.32 \pm 0.03, L_3^r = -4.53 \pm 0.14, L_4^r = 0.53 \pm 0.39$ and $2L_6^r + L_8^r = 3.66 \pm 1.52$.

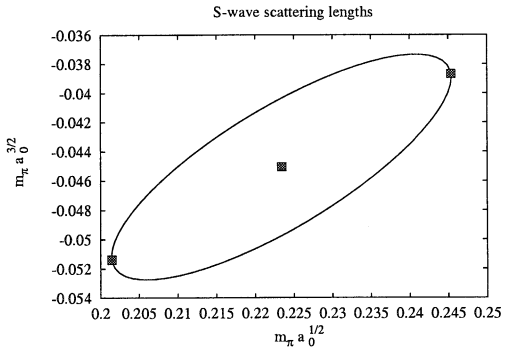

Fig: 1–σ error ellipse for the scattering lengths $a_0^{1/2}$ and $a_0^{3/2}$.

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The impact of $\pi\pi$ scattering data on SU(3) chiral dynamics

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Recent $\pi\pi$ scattering data from the E865 experiment at Brookhaven [1] have confirmed the standard scenario of large condensate in the limit of two massless flavours [2,3]. The theoretical interest has therefore focused on the SU(3) chiral dynamics. Actually one realizes that the order parameters appearing in the SU(3) ChPT are experimentally observable quantities the most directly related to chiral symmetry breakdown. The same is not true for the two-flavour order parameters, defined with the strange quark kept at its physical mass, which is not large enough to decouple from the theory. In this case massive $\bar{s}s$ pairs, which are abundant in the vacuum, induce e.g. an SU(2)×SU(2) breaking condensate, through OZI rule violating correlations, which adds up to the genuine condensate. The determination of the two main three-flavour order parameters, $\Sigma(3)$ and $F^2(3)$, respectively the quark condensate and the pion decay constant in the $N_f = 3$ chiral limit, is a delicate issue because the fluctuations of massive $\bar{s}s$ pairs induce instabilities in the SU(3) chiral series. In Ref. [4], a possible cure for such instabilities is explained (see also J. Stern's contribution to these proceedings), which amounts to a non-perturbative resummation of vacuum fluctuations encoded in the low-energy constants L_4 and L_6. A suitable class of observable is expressed in terms of $\Sigma(3)$, $F^2(3)$ and the quark mass ratio $r = 2m_s/(m_u + m_d)$. Uncertainties due to higher chiral orders and theoretical constraints coming from first principles (vacuum stability and paramagnetic inequalities [5]) can be suitably accounted for in the framework of Bayesian statistical inference when fitting to data. It is shown that, while present $\pi\pi$ data [1] are not accurate enough to constrain the three-flavour order parameters, they yield a lower bound on the quark mass ratio, $r \geq 14$ at 95% confidence level.

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Formation of Meson-Nucleus Systems

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Mesic atoms and mesic nuclei are the useful laboratory for studying the meson-baryon interactions and the meson properties in nuclear medium. Among others, pionic atoms have been long utilized for such studies, since they would provide valuable information on the behavior of "real" pions in the interior of the nucleus. Deeply bound pionic states were found experimentally for the first time in (d,^{3}He) reactions on ^{208}Pb [1,2] and the observed spectrum showed an excellent agreement with our calculation made before the experiment [3]. This agreement between theoretical results and data provides a strong confidence on the predictability of the theoretical model used. Hence, we can investigate other exotic meson-nucleus systems using the same model. In this presentation, we reported recent developments of the theoretical studies in our group for the structure and formation of the meson-nucleus systems. Following subjects were included.

(1) Formation of the deepest and, thus, most interesting 1s pionic states in heavy and medium heavy nuclei [4]. Especially, we consider the excellent data obtained by K. Suzuki et al . [5] and the attempts to deduce a clear evidence for partial restoration of chiral symmetry from the data.

(2) Residual interaction effects in the deeply bound pionic atoms [6]. Since the experimental data of Sn isotopes are so accurate ($\Delta E \sim$ 20keV), the residual interaction effects could be important and should be evaluated. The results will be obtained soon [6].

(3) Structure and formation of K-mesic atoms [7]. We reported several theoretical results for the Kaonic atom formation by (K,p) reactions [7].

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η-Nucleus interactions and in-medium properties of $N^*(1535)$ in chiral models

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We investigate the properties of η-nucleus interaction and their experimental consequences [1]. The strong coupling of ηN to $N^*(1535)(N^*)$ makes the use of this channel particularly suited to investigate this resonance and enables us to consider the η-mesic nucleus as one of the doorway to investigate the in-medium properties of N^*.

In this study, we investigate the N^* properties in the nuclear medium using two kinds of chiral effective models: the chiral doublet model and the chiral unitary model. The chiral doublet model is an extension of the SU(2) linear sigma model for nucleon sector [2,3]. In this model, a reduction of the mass difference of N and N^* in the nuclear medium is found [4,5]. We should stress that this reduction yields a curious shaped potential of η-nucleus system. On the other hand, in the chiral unitary model [6], N^* is introduced as a resonance generated dynamically by meson-baryon scattering. Since this theoretical framework is quite different from the chiral doublet model, it is interesting to compare the consequences of these 'chiral' models for N^* and η mesic nucleus.

For this purpose, we calculate the (d,^{3}He) and (γ,p) spectra for the formation of the η-nucleus systems in the final states [1]. This (d,^{3}He) spectroscopy is an established experimental method in the studies of the pionic bound systems. We conclude that we can deduce the new information of η-nucleus interaction from these experiments, and by knowing the nature of the η-nucleus optical potential, we will be able to study the in-medium properties of the N^*. We believe that this research helps much the experimental activities for the studies of the η-nucleus systems, and the understanding of the baryon chiral symmetries and its medium modifications.

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Precise measurement of deeply bound pionic 1s states of Sn nuclei

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A goal of this work is to measure the degree of chiral symmetry restoration in a nuclear medium through the determination of the isovector πN interaction parameter in the pion-nucleus potential by studying deeply bound 1s states of π^- in heavy $N > Z$ nuclei. We performed a systematic experimental studies of 1s π^- states in a series of Sn isotopes, which were produced with the Sn(d,^{3}He) reactions. One of the advantages of using Sn isotopes is that we can produce the 1s π^- states as the most dominant quasi-substitutional states, $(1s)_{\pi^-}(3s)_n^{-1}$, because of the presence of the 3s orbital near the Fermi surface, as theoretically predicted [1]. Another merit is to make use of isotopes over a wide range of $(N-Z)/A$ to test the isospin dependence [2].

We observed spectra, $d^2\sigma/(dEd\Omega)$, on mylar-covered ^{116}Sn, ^{120}Sn, ^{124}Sn targets as function of the ^{3}He kinetic energy [3], from which we determined precisely the 1s binding energies (B_{1s}) and widths (Γ_{1s}) as summarized in the table 3 below.

Isotope	B_{1s} [MeV]	ΔB_{1s} [MeV]	Γ_{1s} [MeV]	$\Delta\Gamma_{1s}$ [MeV]
^{115}Sn	3.906	$\pm$0.024	0.441	$\pm$0.087
^{119}Sn	3.820	$\pm$0.018	0.326	$\pm$0.080
^{123}Sn	3.744	$\pm$0.018	0.341	$\pm$0.072

The obtained data of binding energies and widths of the 1s π^- states in ^{115,119,123}Sn combined with those of symmetric light nuclei (^{16}O, ^{20}Ne and ^{28}Si) yielded $b_1 = -0.116 \pm 0.007\ m_\pi^{-1}$ [3]. The error includes both statistical and systematic errors. One of the main sources of the systematic error originates in uncertainty of neutron density distributions. The new, yet unpublished, pp-scattering data from RCNP/Osaka [4] are in complete agreement with the antiprotonic atom data we use.

The magnitude of the $|b_1|$ is significantly enhanced over the free πN value, which translates into a reduction of ${f_\pi}^2$ [5] as $R = \frac{b_1^{\rm free}}{b_1} = 0.78 \pm 0.05 \approx \frac{b_1^{\rm free}}{b_1^*(\rho_e)} \approx \frac{f_\pi^*(\rho_e)^2}{f_\pi^2} \approx 1 - \alpha\rho_e$, with an effective density $\rho_e \approx 0.6\rho_0$. This hence implies that the chiral order parameter, $f_\pi(\rho)^2$, would be reduced by a factor of ≈ 0.64 at the normal nuclear density $\rho = \rho_0$.

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DEAR - Kaonic Hydrogen: First Results

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The DEAR[1] experiment [1] measures the energy of X-rays emitted in the transitions to the ground states of kaonic hydrogen. The shift ϵ and the width Γ of the 1s state are related to the real and imaginary parts of the complex S-wave scattering length by the Deser Trueman formula.

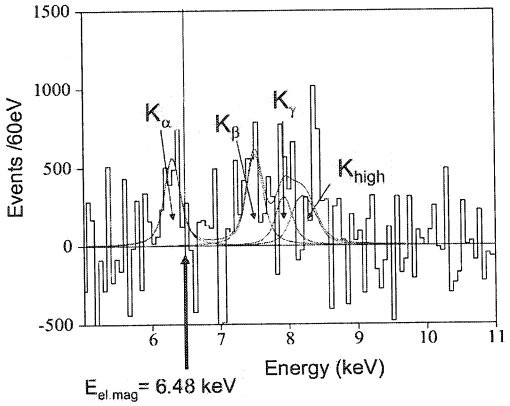

Figure 1: Background subtracted energy spectrum of kaonic hydrogen X ray transitions.

The preliminary results are: ϵ= - 202 $\pm$ 45 eV and Γ= 250 $\pm$ 138 eV. Both values are smaller then those from the previous experiment [2] and consistent with recent theoretical studies [3].

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[1]DAΦNE Exotic Atom Research, conducted at the Frascati electron positron collider

Chiral dynamics and pionic states of Pb and Sn isotopes

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In recent papers [2,3] we have re-investigated the issue of missing repulsion in pionic atoms from the point of view of the distinct explicit energy dependence of the pion-nuclear polarization operator. The starting point is the energy- and momentum-dependent polarization operator $\Pi(\omega, \vec{q}; \rho_p, \rho_n)$. In the limit of very low proton and neutron densities, $\rho_{p,n}$, the pion self-energy reduces to $\Pi = -(T^+ \rho + T^- \delta\rho)$ with $\rho = \rho_p + \rho_n$ and $\delta\rho = \rho_p - \rho_n$, where $T^\pm$ are the isospin-even and isospin-odd off-shell πN amplitudes. Terms of sub-leading orders in density are incorporated within in-medium chiral effective field theory, following [3]. Double scattering corrections are fully incorporated at 2-loop order. Absorption effects and corresponding dispersive corrections appear at the 3-loop level and through short-distance dynamics parameterized by contact terms, not explicitly calculable within the effective low-energy theory. The imaginary parts associated with these terms are well constrained by the systematics of observed widths of pionic atom levels throughout the periodic table. The real part of the s-wave absorption term ($\Re B_0$) is still the primary source of theoretical uncertainty. As suggested also by the detailed analysis of the pion-deuteron scattering length we utilize $\Re B_0 = 0$. The canonical parameterization of p-wave parts is included as well. We solve the Klein-Gordon equation (KGE) $[(\omega - V_c)^2 + \vec{\nabla}^2 - m_\pi^2 - \Pi(\omega - V_c; \rho)]\phi = 0$ in the local density approximation. The explicit energy dependence of Π requires that the Coulomb potential V_c must be introduced in the canonical gauge-invariant way. With input specified in details in [2], we have solved KGE with the explicitly energy dependent pion self-energy. The results for the binding energies and widths of $1s$ and $2p$ states in pionic ^{205}Pb are shown in Fig. 1 in comparison with the outcome of "standard" phenomenological calculations using a energy independent s-wave optical potential (empty circles). The explicit energy dependence in $T^\pm$ results in considerably batter agreement with experimental data. The replacement $\omega \to \omega - V_c > m_\pi$ increases the repulsion in T^- and disbalances the "accidental" cancellation between the πN sigma term σ_N and the range term proportional to ω^2 in T^+, such that $T^+(\omega - V_c) < 0$ (repulsive). The combined effect from uncertainties in $\Re B_0$, in the radius and shape of the neutron density distribution falls within the experimental errors. Using the same scheme we have predicted binding energies and widths for pionic $1s$ states bound to a chain of Sn isotopes. Results are shown in Fig. 1 in comparison with the experimental data [1]. This figure also gives an impression of the sensitivity with respect to variations of the πN sigma term.

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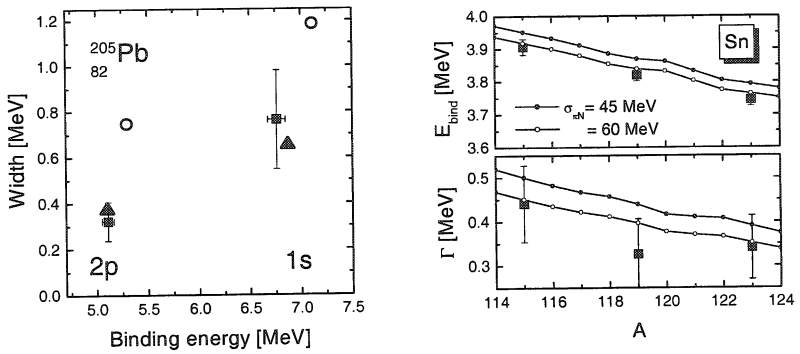

Figure 1: Left panel: Binding energies and widths of pionic $1s$ and $2p$ states in ^{205}Pb isotopes for the energy-dependent (full triangles) and energy-independent (open circles) s-wave polarization operator. Right panel: Curves show binding energies and widths of pionic $1s$ states in Sn isotopes. for different values of the πN sigma term. Data are from [1]

Chiral restoration from pionic atoms

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A major component of the so-called anomalous s-wave repulsion in pionic atoms, as extracted from fits of optical potentials to pionic atom data, is due to the isovector s-wave πN amplitude b_1 which comes out too repulsive compared to the free πN amplitude [1]. Average values of b_1 with added uncertainties due to neutron distributions are summarized in the table, for the standard Ericson-Ericson model, including double-scattering and angle-transformation terms. The free pion-nucleon value is $b_1^{\rm free} = -0.0885^{+0.0010}_{-0.0021}\ m_\pi^{-1}$. 'Deep' refers to deeply bound $1s$ states in ^{115,119,123}Sn and ^{205}Pb.

data	'global 2' ^{12}C to ^{238}U	'global 3' ^{20}Ne to ^{238}U	light $N=Z$ + light $N>Z$ $1s$ only	light $N=Z$ +'deep' $1s$ only	'deep' $1s$ only
points	120	100	22	20	8
$b_1(m_\pi^{-1})$	-0.108 ± 0.007	-0.104 ± 0.006	-0.099 ± 0.014	-0.104 ± 0.013	-0.130 ± 0.036

It is obvious that only *large* data sets provide conclusive evidence for the modification of b_1 in the nuclear medium.

The in-medium s-wave interaction of pions has been discussed recently by Weise [2] in terms of partial restoration of chiral symmetry, leading to a density-dependent $b_1(\rho)$ which essentially removes the anomaly [3]. Alternatively, Kolomeitsev et al. [4] imposed the minimal substituion $E \to E - V_c$ using energy-dependent chirally expanded amplitudes for $\mathbf{q}$=0. We have found [5] this approach to disagree with the data, for large data sets, and with the value of the free πN amplitude b_1, whereas good agreement is obtained using the empirical on-shell energy dependence as suggested long ago by Ericson and Tauscher [6].

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Introduction to the ChPT for Heavy Nuclei

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Recent accurate measurements of deeply bound ($1s$) states of pionic atoms formed with Pb and Sn isotopes [1] have triggered renewed interest in the underlying mechanisms governing S-wave pion-nucleus interactions, raising the quest for "fingerprints of chiral restoration" [2]. Latest theoretical investigations [3] based on ChPT, have focused on the calculation of the in-medium shift of the pion mass. Alternatively, the energy-dependent pion self-energy operator has been extrapolated, using ChPT input and the local density approximation, to calculate directly the pionic $1s$ and $2p$ level shifts and widths [4]. In order to have the reliable predictions, however, all these analyzes should be carefully reexamined in a ChPT framework, where the nucleus is consistently treated as a finite system.

In our paper [5] we give a systematic formulation of ChPT in a non-uniform fermionic background, which corresponds to the (finite) nucleus. The construction of the relativistic field-theoretical counterpart of the multiple-scattering theory on the static nuclear target is described in detail. It is shown, that in this framework chiral symmetry plays a crucial role, leading to the suppression of the non-local effects in the nuclear matrix elements.

Using the formulated framework, we present a systematic derivation of the pion-nucleus optical potential at $O(p^5)$ in ChPT, including a full pattern of electromagnetic and strong isospin-breaking effects. In the future, we plan to perform similar calculations at $O(p^6)$ – beyond the linear density approximation for the optical potential.

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ChPT in the nuclear medium - the generating functional approach

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We report on a systematical study of the properties of pions in nuclear matter under the presence of external sources [1]. For this purpose the methodology of the generating functional formalism of ChPT is applied which originates back to Ref. [2] and which has been transcribed to nuclear matter by Oller [3]. The corresponding in-medium lagrangian is non-covariant as well as non-local and involves solely pions and external sources.

Within this approach the derived (chiral) power counting rules separate for the standard and the non-standard scenario where either the residual nucleon energies are of the order of the pion mass or of the nucleonic kinetic energy, respectively. The scales of applicability of these two perturbative expansions are established as $\sqrt{6\pi} f_\pi \simeq 0.7\,\mathrm{GeV}$ and $3\pi^2 f^2/M_N \simeq 0.27\,\mathrm{GeV}$, respectively, instead of the vacuum scale $4\pi f_\pi \simeq 1.2\,\mathrm{GeV}$.

We present a systematic analysis of the in-medium contributions to the quark condensates, pion propagators, pion masses, and pion couplings to the axial-vector, vector and pseudoscalar currents for symmetric and non-symmetric nuclear matter. In particular, it is found that the chiral symmetry-breaking contributions to the quark condensate are subleading, and that the upward-shift of the in-medium mass of the π^- can be traced back to the Weinberg term which, however, is amplified by a factor of two by a corresponding reduction in the wave-function renormalization coefficient.

The result of Ref. [4] (see also [5,6]) is confirmed that the vacuum pion decay constant splits in the medium into a time-like and space-like part, and that is is the time-like one that enters in the in-medium versions of the Gell-Mann–Oakes–Renner and PCAC relations.

Finally, we report that the in-medium pion-pion scattering at leading order is $\mathcal{O}(q^3)$ and therefore belongs to the non-standard counting scenario. The dominate process at low three-momentum and density is the twice-iterated Weinberg-Tomozawa scattering off the nucleon which is of S-wave nature and repulsive.

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Future precision measurements on kaonic hydrogen and kaonic deuterium with SIDDHARTA

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After the most precise measurement on kaonic hydrogen performed up to now by DEAR at the DAΦNE collider of Laboratori Nazionali di Frascati in 2002, result presented at this meeting [1], a new precision measurement of kaonic hydrogen and kaonic deuterium is envisaged in the framework of the new SIDDHARTA project.

The objective of SIDDHARTA (SIlicon Drift Detector for Hadronic Atom Research by Timing Application) is the precision measurement of the K_α line shift and width, due to the strong interaction, in kaonic hydrogen and a similar measurement - the first one - in kaonic deuterium. The aim is a precision determination of the antikaon-nucleon isospin dependent scattering lengths. An accurate determination of the K^-N isospin dependent scattering lengths will place strong constraints on the low-energy K^-N dynamics, which in turn constraints the SU(3) description of chiral symmetry breaking [2]. Crucial information about the nature of chiral symmetry breaking, and to what extent the chiral symmetry must be broken, is provided by the calculation of the meson-nucleon sigma terms [3].

SIDDHARTA represents the natural continuation of DEAR taking advantage, however, of a completely newly designed setup which guarantees a near 4π solid angle coverage, and, as detector, silicon drift detectors (SDD) which exhibit the same performance of CCDs as far as efficiency and energy resolution is concerned, but can be triggered, thus allowing an increasing of the signal/background ratio of orders of magnitude.

The trigger is given by the entrance of the charged kaon in the target volume. The event can be identified and measured with high accuracy and low contamination by the use of a three-scintillator telescope, synchronized with the bunch frequency. First tests of a prototype SDD array, performed at the Beam Test Facility (BTF) of LNF, gave excellent results.

In addition to the precision kaonic hydrogen and deuterium measurements, in SIDDHARTA it is planned a measurement of kaonic helium and a feasibility study of sigmonic hydrogen.

We thank the DAΦNE BTF group for the very good cooperation and team work.

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Lifetime of Kaonium

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The scalar mesons $f_0(980)$ and $a_0(980)$ have been interpreted as two quark-antiquark ($q^2\bar{q}^2$) states by Jaffe and by Achasov, whereas Weinstein and Isgur suggest a quasibound Kaon-Antikaon ($K\bar{K}$) structure. Here we present a prediction for the lifetime of the hadronic atom kaonium based on the mixing with scalar mesons having a ($K\bar{K}$) structure.

The small binding energy of about 20 MeV of the $K\bar{K}$ meson suggests a non-relativistic effective field theory approach[1]. With this in mind we use the standard $SU(3)_V \times SU(3)_A$ Lagrangian to describe the dynamics of the $K\bar{K}$ interaction[2] and decay via the exchange of ρ, ω, ϕ, K^*.... vector mesons, assuming $SU(3)$ symmetry for the coupling constants. Then we replace the OBE potentials by phase–equivalent potentials of the Bargmann type[3] that give rise to the same scattering length and effective range. For these potentials, the associated Jost functions can be constructed explicitly so that both the scattering and bound state properties of the $K\bar{K}$ system are determined without further approximation.

The hadronic atom kaonium so far has found little attention in the literature[5]. We construct the Jost function of kaonium and determine the bound states by the Kudryavtsev–Popov equation[4], Full details can be found in ref.[6]. Below, we present the prediction for the lifetime of kaonium based on the assumption of a $K\bar{K}$ meson structure. The full Jülich meson exchange model contains a hard component in addition to the $K\bar{K}$ meson structure. This reduces the lifetime by a factor 3.

Level	λ	$\Delta E - i\Gamma/2$ (keV)	Lifetime ($\times 10^{-18}$ sec)
3^{rd}	$0.2491 + 0.0005i$	$0.003 - 0.002i$	199
2^{nd}	$0.3318 + 0.0009i$	$0.007 - 0.004i$	84
1^{st}	$0.4965 + 0.0020i$	$0.023 - 0.013i$	25
Ground	$0.9863 + 0.0079i$	$0.180 - 0.103i$	3.2

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Chiral dynamics of the two $\Lambda(1405)$ states

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The $\Lambda(1405)$ has been a long-standing example of a dynamically generated resonance appearing naturally in scattering theory with coupled meson-baryon channels with strangeness $S = -1$. Modern chiral formulations of the meson-baryon interaction within unitary frameworks all lead to the generation of this resonance, which is seen as a near Breit-Wigner form in the mass distribution of $\pi\Sigma$ states with isospin $I = 0$ in hadronic production processes.

As a theoretical consequence, studying the analytical structure of the scattering amplitude in the $S = -1$, $I = 0$ channel obtained by the chiral unitary approach, we find two poles very close to the $\Lambda(1405)$ [1]. Both of them are sitting between the $\pi\Sigma$ and $\bar{K}N$ thresholds, and these two resonances are quite close but different. The important nature of them is that the one at lower energies has a larger width and a stronger coupling to the $\pi\Sigma$ states, while the other at higher energies couples mostly to the $\bar{K}N$ states and has a smaller width. This is the main finding of the present work, thus we conclude that there is not just one single $\Lambda(1405)$ resonance, but *two*, and that what one sees in experiments is a *superposition* of these two states.

The existence of the two pole is strongly related to the flavor symmetry. The underlying $SU(3)$ structure of the chiral Lagrangians implies that, together with the pole around the $\Lambda(1670)$, a singlet and two octets of dynamically generated resonance should appear, but the dynamics of the problem makes the two octets degenerate in the case of exact $SU(3)$ symmetry. In the physical limit, the breaking of the $SU(3)$ symmetry resolves the degeneracy of the octets and two distinct octets appear. The breaking of the degeneracy has as a consequence that one of the $I = 0$ octet poles appears quite close to the singlet pole.

The important theoretical finding here should stimulate new experiments exciting the $\Lambda(1405)$ resonance. We suggest that it is possible to find out the existence of the two resonances by performing different experiments, since in different experiments the weights by which the two resonances are excited are different. In this respect we call the attention to one reaction, $K^- p \to \Lambda(1405)\gamma$, which gives much weight to the resonance which couples strongly to the $\bar{K}N$ states and, hence, leads to a peak structure in the invariant mass distributions which is narrower and appears at higher energies.

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Chiral dynamics of baryons as bound states of constituent quarks

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We developed a manifestly Lorentz invariant chiral quark model for the study of baryons as bound states of constituent quarks in an extention of our previous approach [1,2]. Our investigations are related to the ongoing and planned experiments at ELSA, JLab, MAMI, MIT, NIKHEF on improved measurements of the elastic baryon form factors and their decay characteristics. The approach is based on a non-linear chirally symmetric Lagrangian, which involves effective degrees of freedom - constituent quarks and the chiral (meson) fields. In the first step, this Lagrangian can be used to perform a dressing of the constituent quarks by a cloud of light pseudoscalar mesons and other heavy states using the calculational technique developed by Becher and Leutwyler [3] which is based on the infrared regularization of loop integrals. We calculate the dressed transition operators with a proper chiral expansion which are relevant for the interaction of quarks with external fields in the presence of a virtual meson cloud. Next, these operators are used in the calculation of baryon matrix elements using an effective Lagrangian describing the coupling of a baryon field to the interpolating three-quark current [2]. In Table I we summarized our results for canonical properties of nucleon and Δ: nucleon magnetic moments and charge radii, the helicity amplitudes $A_{1/2}$ and $A_{3/2}$ of the $\Delta \to N\gamma$ transition and the ratio $E2/M1$. For comparison we present the experimental data (central values).

Table I. Static characteristics of nucleon and Δ

	μ_p	μ_n	r_p^E (fm)	$< r^2 >_n^E$ (fm^2)	r_p^M (fm)	r_n^M (fm)	$A_{1/2}$ (GeV$^{-1/2}$)	$A_{3/2}$ (GeV$^{-1/2}$)	$E2/M1$ (in %)
Model	2.79	-1.91	0.85	-0.12	0.84	0.85	- 0.132	- 0.253	- 2.5
Exp	2.79	-1.91	0.86	-0.116	0.86	0.88	- 0.135	- 0.255	- 2.5

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Towards the most precise test of bound state QED

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Collaboration R-98-03.1: PARIS[1] – COIMBRA[2] – FRIBOURG[3] – MPQ MUNICH[4] – TU MUNICH[5] – YALE[6] – PSI[7] – ETHZ[8] – PRINCETON[9] – HSINCHU TAIWAN[10]

An experiment is currently going on at Paul Scherrer Institute to determine the Lamb shift 2S→2P in muonic hydrogen. From this result the rms proton charge radius can be deduced with 10^{-3} accuracy a factor of 30 better than presently known [1].
The principal motivation for this experiment comes from improved determinations of the Lamb shift in hydrogen. At present the interpretation of the 1S-Lamb shift in hydrogen is limited by the uncertainty in the proton charge radius. This limit can be improved an order of magnitude via combining a Lamb shift measurement in μp with that in hydrogen.
A second motivation comes from the variety of available electron scattering data and the still going on discussion of how to derive the rms proton charge radius from them. Since Hofstatters pioniering experiment in 1963 the given value of the proton charge radius changed more and more from 0.805(11)fm [2] to nowadays 0.895(18)fm [3] which is the most recent interpretation of all available experimental data. The muonic hydrogen experiment will help to clarify this undefined situation.

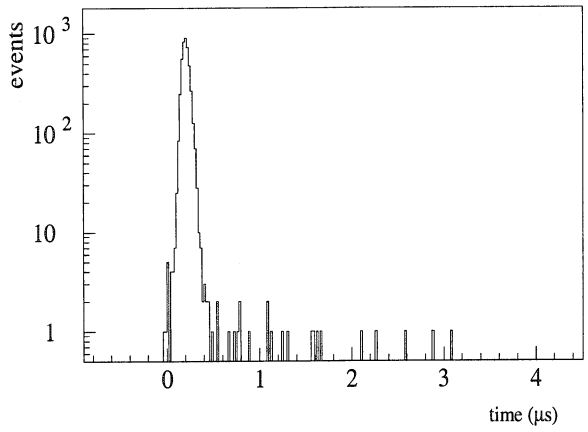

Figure 1: Prompt and delayed x-ray rate in μp after muon capture. Accum. time: 1.5 h.

The experiment is performed as follows: about 60/s low energy (< 20 keV) μ^- are stopped in low pressure (0.5 mbar) hydrogen gas. After capture in n $\approx$ 14 approximately 1 % end up as thermalized muonic hydrogen atoms in the meta-stable 2s-state. There they quench via molecular formation with a decay time exceeding 1 μs. About 1.5 μs after the prompt transitions a 6 μm mid-infrared laser pulse drives the 2s→2p transition. The corresponding 2p→1s decay x-rays are detected relative to the laser wavelength position. The expected signal rate is 2 times the measured background rate (see Figure 1). This makes this experiment very promising.

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Lattice QCD calculations of the I=2 pi-pi scattering length

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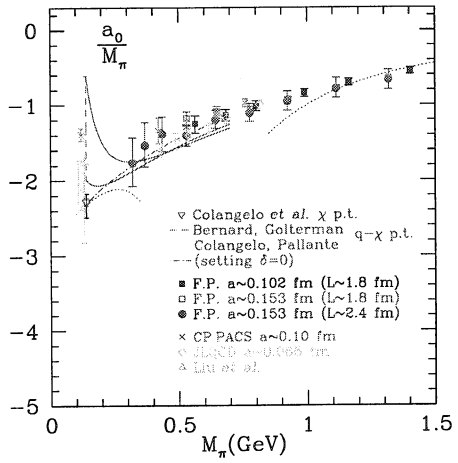
Recent lattice QCD calculations of the I=2 $\pi\pi$ scattering length was presented. In particular, the finite volume method of Lüscher [1] was used to extract the $L = 0$ scattering length with the parametrized fixed point action [2] in the quenched approximation. The highly improved action allowed the calculation to be performed on coarse lattices with nearly chiral fermions. Signals were obtained down to pion masses of roughly 300 MeV[3]. This was the first calculation with chiral fermions. Previous calculations used the Wilson action [4,5,6,7], improved Wilson action [8] and/or staggered fermions. Implications on the chiral [9] and quenched chiral behaviour [10] was discussed as well as the recent progress made in the $N_f = 2$, unquenched calculation [11] with Wilson fermions.



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Towards a lattice determination of QCD low-energy constants

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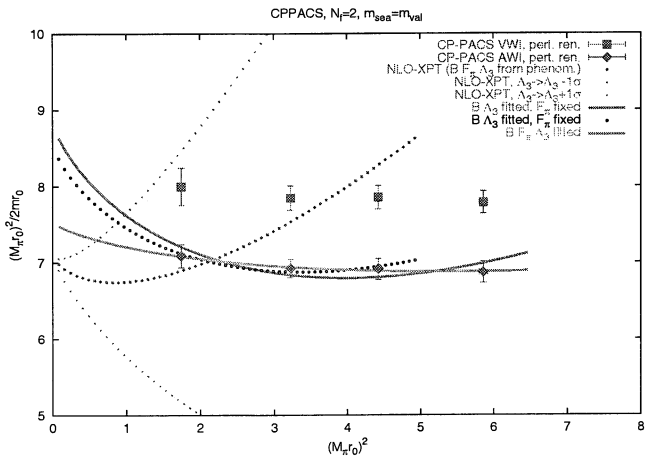
QCD low-energy constants as they appear in Chiral Perturbation Theory [1] fall into two categories: Those which determine how low-energy Green's functions depend on the external momenta and those which specify how they depend on the quark masses. For the latter there is a fair chance that (Euclidean) lattice data will help to pin them down accurately.

In the past, attempts have been limited by the quenched approximation [2], but with the current generation of $N_f=2$ dynamical data, a new attempt seemed worth while. Based on recent data by the CP-PACS [3] collaboration, I have compared the NLO prediction for the degenerate ($m=m_u=m_d$) quark mass dependence of the pseudo-Goldstone boson mass [1]

$$\frac{\tilde{M}_\pi^2}{2\tilde{m}} = \tilde{B}\Big(1+\frac{\tilde{M}_\pi^2}{32\pi\tilde{F}_\pi^2}\log(\frac{\tilde{M}_\pi^2}{\tilde{\Lambda}_3^2})\Big) \qquad (1)$$

to the perturbatively renormalized data (at 1-loop). In (1) all energies are in units of the Sommer scale $r_0^{-1}\simeq 0.4\,\mathrm{GeV}$, i.e. $\tilde{M}_\pi = M_\pi r_0$. In addition, I have taken the liberty to combine the chiral log and the low-energy constant $l_3^{\mathrm{r}}(\mu)$ into something manifestly scale-invariant. The chiral prediction with $l_3^{\mathrm{r}}(\mu\sim 0.77\,\mathrm{GeV}) = (0.8\pm 3.8)10^{-3}$ (equivalent to $\Lambda_3 = 0.6\,^{-0.4}_{+1.4}$ GeV) taken from [1] results in a band which widens rapidly. In comparison, the theoretical uncertainties (the two renormalized quark masses should agree) seem less severe.

The main problem is that a phenomenological analysis suggests that – at best – the most chiral lattice points lie within the permissible range for a NLO chiral fit [4]. If one bluntly ignores this warning and nonetheless attempts a NLO fit to the entire set, the resulting parameters seem reasonable – except F_π which is a bit high [4]. Keeping $F_\pi = 92.4\,\mathrm{MeV}$ fixed, the fit is still acceptable and stable under omitting the heaviest point [4]. These findings look inconsistent with statements in [5], but the main difference is whether r_0 (assumed independent of m_{sea}) or M_ρ (dito) is used to set the scale. Obviously, the conclusion is that it is too early to use the output of current fits in phenomenology, but the time will come when l_3, l_4 will be reliably determined on the lattice.



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Nucleon mass, sigma term and lattice QCD: chiral extrapolations

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Lattice QCD on one side and chiral effective field theory, on the other, are progressively developing as important tools to deal with the non-perturbative nature of low-energy QCD and the structure of hadrons. The merger of both strategies has recently been applied to extract physical properties of hadrons, such as the nucleon, from lattice QCD simulations. Of particular interest in such extrapolations is the detailed quark mass dependence of nucleon properties. Examples are the nucleon mass, its axial vector coupling constant and magnetic moments [1,2]. Accurate computations of the nucleon mass with dynamical fermions and two active flavours are now possible. However, the masses of $u-$ and $d-$quarks used in these evaluations exceed their commonly accepted small physical values by typically an order of magnitude. It is at this point where chiral effective field theory methods are useful - within limitations discussed extensively in the literature - in order to interpolate between lattice results, actual observables and the chiral limit ($m_{u,d} \to 0$). An improved update [3] is given concerning the quark mass dependence of the nucleon mass and the pion-nucleon sigma term σ_N. The framework is relativistic $SU(2)_f$ baryon chiral perturbation theory as described in ref.[4]. The extrapolation to two-flavour lattice QCD results is performed to order p^4. We find $M_0 = 885 \pm 6\,\mathrm{MeV}$ for the nucleon mass in the chiral limit ($m_{u,d} \to 0$) and $\sigma_N = 47 \pm 3\,\mathrm{MeV}$ for the sigma term at the physical value of the pion mass (where the errors indicate statistical uncertainties only).

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