HadAtom02

Workshop on Hadronic Atoms
CERN, CH-1211 Geneva 23, Switzerland
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Abstract

These are the proceedings of the workshop "HadAtom02", held at the CERN, October 14 - 15, 2002. The main topic of the workshop concerned the physics of hadronic atoms and in this contest recent results from experiments and theory were presented. These proceedings contain the list of participants, the scientific program and a short contribution from each speaker.

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1 Introduction

The workshop "HadAtom02" took place at CERN on October 14–15, 2002. It was the 4th in a series of workshops on bound states, in particular hadronic atoms. The previous ones were held in Dubna, Russia (May 1998) [1] and in Bern (October 1999, October 2001) [2,3]. The meeting was attended by about 40 physicists, and contributions were presented by 17 participants.

The workshop programme 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
  - PSI (Pionic Hydrogen Collaboration)
  - NA48
  - Others
- $K_{\ell 4}$ decays

The talks were devoted to recent experimental and theoretical progresses in the investigations of hadronic atoms. Among the highlights of the workshop were the presentation of preliminary results from the DIRAC collaboration on the measurement of the lifetime of pionium, as well as the first measurement of kaonic nitrogen by the DEAR collaboration.

The speakers have provided a two-page summary of the presentations including a list of the most relevant references — these contributions are collected below. These proceedings include also a list of the participants with their e-mail, and the scientific program of the workshop.

Acknowledgment

We would like to thank all participants for their effort to travel to CERN and for making "HadAtom02" an exciting and lively meeting. We furthermore thank our secretary Catherine Moine for her professional contribution to the organization of the meeting. Last but not least, we thank our colleagues from the organizing committee, Juerg Gasser, Leonid Nemenov, Akaki Rusetsky, and Dirk Trautmann for their invaluable contribution in structuring the meeting.

CERN, January 2002

Leonid Afanasyev, Armando Lanaro and Jürg Schacher

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[1] Proceedings of the International Workshop "Hadronic Atoms and Positronium in the Standard Model", Dubna, 26-31 May 1998, ed. M.A. Ivanov, A.B. Arbuzov, E.A. Kuraev, V.E. Lyubovitskij, A.G. Rusetsky.

[2] J. Gasser, A. Rusetsky and J. Schacher, arXiv:hep-ph/9911339.

[3] J. Gasser, A. Rusetsky and J. Schacher, arXiv:hep-ph/0112293.

2 List of participants

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3 Scientific program

Need for new low-energy $\pi\pi$ scattering data

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The importance of low-energy $\pi\pi$ scattering data for probing the mechanism of spontaneous breaking of chiral symmetry (SBChS) in QCD has often been emphasized. Explicit calculations of the $\pi\pi$ scattering amplitude at two-loop level in the framework of chiral perturbation theory (ChPT) allow to relate the scattering parameters to the low-energy constants, describing the features of the vacuum. Present knowledge about these constants, complemented with standard assumptions about the size of the quark condensate (i.e. the validity of the Gell-Mann–Oakes–Renner relation) and available experimental information at medium and high energy, leads to very precise predictions for the S-wave scattering lengths [1]

$$a_0^0 = 0.220 \pm 0.005, \quad a_0^2 = -0.0444 \pm 0.0010. \tag{1}$$

On the other hand, thanks to the solutions of the Roy Equations provided by Ananthanarayan, Colangelo, Gasser and Leutwyler [2], the scattering amplitude is parametrized in terms of only two parameters, the two S-wave scattering lengths, within very small uncertainty in the whole energy range below 800 MeV. Therefore any experimental information below 800 MeV can in principle be translated into a determination of the two S-wave scattering lengths, thus providing a test of the predictions of ChPT. We applied this procedure [3] to the recently published E865 data [4] on charged K_{e4} decays, supplementing them with available data in the $I = 2$ channel below 800 MeV.

The ellipses in the figure (full lines) represent the 1-σ and 2-σ contours of our fit. Our analysis is exclusively based on the new solutions of the Roy Equations [2] and on direct experimental information. In particular no use is made of the correlation between a_0^0 and a_0^2 as inferred from the scalar radius of the pion [5]. If the dispersive determination of the latter, $\langle r^2 \rangle_s = (0.61 \pm 0.04)$ fm^2 is used, this correlation, at the level of two-loop accuracy, is shown by the narrow curved band of the figure. The use of such a strong constraint would result in the filled shaded ellipse, which is perfectly compatible with the two-loop ChPT prediction, represented by the small filled ellipse. The two procedures yield different results at the 1-σ significancy. However the narrow strip constraint depends substantially on the NNLO contributions, which involve unknown $O(p^6)$ low-energy constants: the same correlation without the inclusion of the $O(p^6)$ order would correspond to the narrow straight band in the figure. In order to obtain the $O(p^6)$ narrow strip one has to rely on estimates of the constants appearing at this order, based on the resonance saturation assumption. By reversing the argument, one can use the model-independent result for the scalar scattering lengths

$$a_0^0 = 0.228 \pm 0.012, \quad a_0^2 = -0.0382 \pm 0.0038, \tag{2}$$

to test the narrow strip prediction, i.e. to determine the $O(p^6)$ constants. The latter are found unexpectedly large, which can be interpreted as a manifestation of the exceptional status of the scalar channel, characterized by a strong $\pi\pi$ continuum and OZI rule violation. The situation will hopefully be further clarified by the awaited results of DIRAC and the forthcoming K_{e4} experiment NA48-II. Unfortunately it is unlikely that the measurement of the pionium lifetime

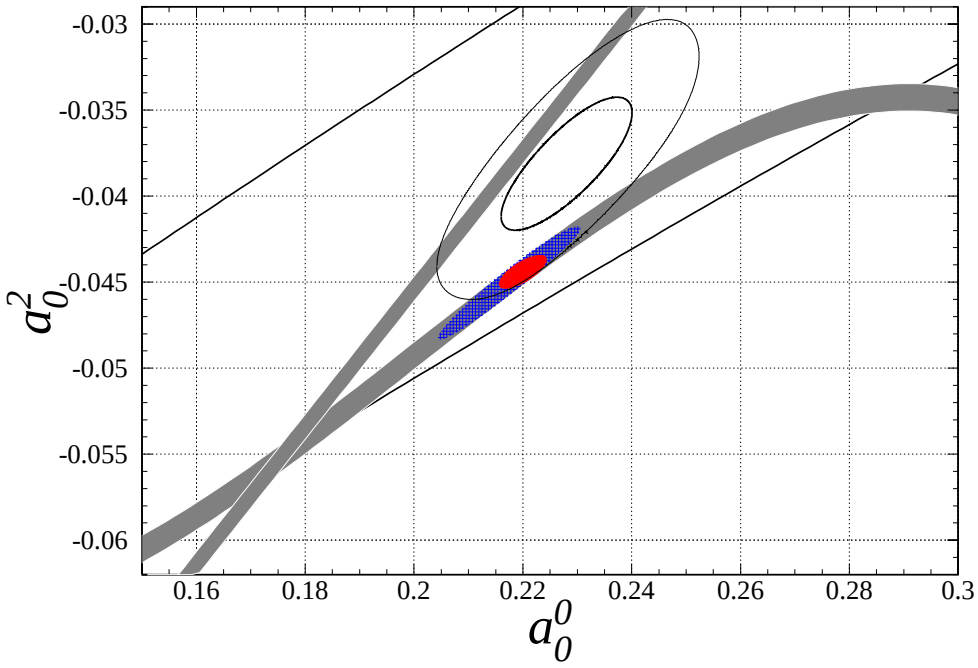

Figure 1: Results of the two-parameter fit to the K_{e4} data and available $I = 2$ data below 800 MeV (see the text). The two straight lines delimit the region where Roy Equations admit solutions.

can distinguish between the two procedures, since all the ellipses shown in the figure correspond to very similar values for the combination $a_0^0 - a_0^2$.

The fit results for a_0^0 and a_0^2 can be used to extract the values of the subthreshold parameters α and β, of the low-energy constants $\bar{l}_3$ and $\bar{l}_4$ as well as of the main two-flavour order parameters: $\langle \bar{u}u \rangle$ and F_π in the limit $m_u = m_d = 0$ taken at the physical value of the strange quark mass. The results for the order parameters read

$$X(2) = \frac{2\hat{m}|\langle \bar{q}q \rangle|}{F_\pi^2 M_\pi^2} = 0.81 \pm 0.09, \quad Z(2) = \frac{F^2}{F_\pi^2} = 0.90 \pm 0.03, \tag{3}$$

signalling that the two-flavour standard ChPT is the appropriate expansion scheme.

[1] G. Colangelo, J. Gasser and H. Leutwyler, Phys. Lett. B **488** (2000) 261 [arXiv:hep-ph/0007112].

[2] B. Ananthanarayan, G. Colangelo, J. Gasser and H. Leutwyler, Phys. Rept. **353** (2001) 207 [hep-ph/0005297].

[3] S. Descotes, N. H. Fuchs, L. Girlanda and J. Stern, Eur. Phys. J. **C24** (2002) 469 [hep-ph/0112088].

[4] S. Pislak *et al.* [BNL-E865 Collaboration], Phys. Rev. Lett. **87** (2001) 221801 [hep-ex/0106071].

[5] G. Colangelo, J. Gasser and H. Leutwyler, Nucl. Phys. **B603** (2001) 125 [hep-ph/0103088]; Phys. Rev. Lett. **86** (2001) 5008 [hep-ph/0103063].

Chiral perturbation theory and massive strange quark pairs

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Low - energy $\pi\pi$ scattering merely involves valence u and d quarks and it probes QCD in the vicinity of the $SU(2) \times SU(2)$ chiral limit in which $m_u = m_d = 0$ and m_s is fixed at its physical value. Nevertheless, the influence of massive virtual $\bar{s}s$ pairs on low-energy $\pi\pi$ scattering, on the two-flavour chiral order parameters $\Sigma(2) = -\lim_{m_u,m_d\to 0}\langle\bar{u}u\rangle|_{m_s=phys} = F^2B$, $F^2 = \lim_{m_u,m_d\to 0} F_\pi^2$, as well as their impact on the estimates of low energy constants $\bar{l}_3$ and $\bar{l}_4$ [1] may be important for the following two reasons: i) First,$m_s \ll \Lambda_H \sim 4\pi F_\pi \sim 1GeV$ suggesting some overall convergence of the $SU(3)\times SU(3)$ chiral expansion . On the other hand, as long as $m_s \sim \Lambda_{QCD}$, the scale at which QCD becomes strong, the vacuum gets populated by abundant virtual $\bar{s}s$ pairs, whereas the creation of heavy quark pairs is suppressed. ii) The second reason is the existence of a strong long range correlation between strange and non-strange $\bar{q}q$ pairs in the $J^P = 0^+$ channel:

$$Z^s = \lim_{m_u,m_d\to 0} i\int dx\langle T\bar{s}s(x)\bar{u}u(0)\rangle_c \tag{4}$$

is subleading in large N_c expansion and it is expected to be suppressed by the OZI - rule. Instead, recent sum rule estimates [2] suggest that Z^s is of a normal size $Z^s \sim \Lambda_{QCD}^2$, reflecting the violation of the OZI-rule and of the $1/N_c$ expansion observed in the scalar channel. This phenomenological information was not available in the past and most of the original χPT considerations and estimates [1], (including the GχPT variant) were based on the OZI-rule and large N_c wisdom. Today, the strong vacuum OZI-rule violating correlation Z^s provides a new element in the discussion and it naturally fits to our microscopic understanding of χSB in Euclidean QCD: The quark condensate represents **the average** and the correlator Z^s **the fluctuations** of the density of smallest modes of the Dirac operator.Notice that $Z^s > 0$.

Vacuum fluctuations of $\bar{s}s$ pairs may lead to important m_s dependence of the two-flavour condensate $\Sigma(2)$. At $m_s = 0$, $\Sigma(2)$ coincides with the three-flavour condensate $\Sigma(3) = -\langle\bar{u}u\rangle|_{m_u=m_d=m_s=0} = F_0^2B_0$ and its derivatives with respect to m_s is precisely the correlator Z^s (related to the low - energy constant L_6). Up to higher order terms one has

$$\Sigma(2) = \Sigma(3) + m_sZ^s + \ldots. \tag{5}$$

$\Sigma(3)$ is the "genuine condensate" of QCD with three massless quarks and no massive quarks left which would be enough light to pollute the vacuum. m_sZ^s represents the positive contribution to the two-flavour condensate $\Sigma(2)$ that is induced from massive $\bar{s}s$ vacuum pairs. The two contributions can be of sensibly comparable size [2], reflecting the suppression of $\Sigma(3)$ relative to $\Sigma(2)$ due to vacuum fluctuations. This can be seen from a non-perturbative analysis of Goldstone-boson mass and decay constant Ward identities [3], provided the quark mass ratio $r = m_s/m$ is not too small ($r > 15$). For small Z^s, which in turn implies a precise fine tuning of $L_6(M_\rho)$ to the critical value $L_6^{crit} = -0.26 \times 10^{-3}$, one would have $\Sigma(2) \approx \Sigma(3)$. For L_6 slightly above L_6^{crit}, the fluctuations grow and the yield of the genuine condensate $\Sigma(3)$ in Eq. (5)decreases. This decrease is, however, compensated by a growing induced contribution

$m_s Z^s$. As a result, the massive $\bar{s}s$ pairs stabilize the two-flavour condensate $\Sigma(2)$ and keep it large independently of vacuum fluctuations and of the suppression of the genuine condensate $\Sigma(3)$,(see the talk by S. Descotes-Genon).

It is instructive to compare the $N_f = 2$ χPT (i.e. expansion in powers of $m_u = m_d = m$ for a fixed m_s) with the $N_f = 3$ χPT expansion (in powers of m **and** m_s) of the same quantity $F_\pi^2 M_\pi^2$. Keeping the LO and the NNLO contributions, one gets

$$F_\pi^2 M_\pi^2 = 2m\Sigma(2) + \frac{m^2 B^2}{8\pi^2}(4\bar{l}_4 - \bar{l}_3) + \dots \tag{6}$$

$$F_\pi^2 M_\pi^2 = 2m\Sigma(3) + 2mm_s Z^s + 4m^2(Z^s + A) + \dots . \tag{7}$$

respectively. The two expansions have to coincide order by order in m. The most important part of the OZI - rule violating contribution to rhs of Eq. (7), $m_s Z^s$, is absorbed into $\Sigma(2)$. The contribution of Z^s to the LEC's $\bar{l}_3, \bar{l}_4$ is not enhanced by the factor m_s and it should be of a comparable size as the "normal" contribution A (related to L_8). Hence, vacuum fluctuations will slightly shift the OZI-rule based estimate [1] $\bar{l}_3 = 2.9 \pm 2.4$ towards a negative values without spoiling the convergence of the $N_f = 2$ χPT. The $N_f = 2$ expansion is dominated by the condensate term $\Sigma(2)$, since the latter is enhanced by the contribution induced by $\bar{s}s$ pairs. On the other hand, the genuine condensate $\Sigma(3)$ need not dominate the $N_f = 3$ expansion of Goldstone boson masses, since the vacuum fluctuation term $m_s Z^s$ now counts as NLO. It is useful to express both condensates in appropriate GOR units

$$X(N_f) = \frac{2m\Sigma(N_f)}{F_\pi^2 M_\pi^2} \qquad N_f = 2, 3 \tag{8}$$

and to compare $X(2) > X(3)$ with one. The $N_f = 2$ low-energy parameters can be extracted from precise $\pi\pi$ scattering experiments . Our analysis [4] including most recent experimental data yields $X(2) = 0.81 \pm 0.07$, $F^2/F_\pi^2 = 0.89 \pm 0.02$ and $\bar{l}_3 = -17 \pm 15$ confirming both the dominance of the two-flavour condensate and the expected shift of $\bar{l}_3$. (See the talk by L. Girlanda for more details.)

Suppression of $X(3)$ does not necessarily mean a bad convergence of the $N_f = 3$ χPT for "good observables" such as (7). However, provided in the latter the LO term $2m\Sigma(3)$ and the NLO term $2mm_s Z^s$ are of a comparable size, we face an instability which prevents us to proceed perturbatively eliminating low-energy parameters in terms of observables. A systematic non-perturbative alternative to this standard procedure does exist and it makes a new $N_f = 3$ analysis of precise $\pi\pi$, πK and η-decay data both meaningful and interesting.

[1] J. Gasser and H. Leutwyler, Annals Phys.**158** (1984) 142, Nucl.Phys. **B250** (1985), 465.

[2] B. Moussallam , Eur. Phys. J. **C14** (2000) 111, [arXiv:hep-ph/9909292], S. Descotes, JHEP **0103** (2001) 002, [arXiv: hep-ph/0012221].

[3] S. Descotes-Genon, L. Girlanda, and J. Stern, [arXiv: hep-ph/0207337] and references therein.

[4] S. Descotes, N.H. Fuchs, L. Girlanda and J. Stern, Eur.Phys.J. **C24** (2002) 469, [arXiv: hep-ph/0112088].

QED Theory of Hydrogen-like Atoms

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About fifty years ago the experimental discovery of the Lamb shift and the anomalous magnetic moment of electron initiated a long competition between QED theory and experiment. Today a list of quantities used to test QED is quite impressive and includes:

- the anomalous magnetic moments of the electron and muon;
- hyperfine splitting of the $1s$ and $2s$ states in hydrogen and deuterium atoms and helium-3 ion;
- gross and fine structure intervals and the Lamb shift in hydrogen, deuterium and helium-4 ion;
- hyperfine splitting and $1s-2s$ transition in muonium and positronium,
- decay rates of para- and orthopositronium including rare modes;
- energy levels of high- (like e.g. bismuth) and medium-Z (like e.g. carbon) ions with few electrons;
- g factors of a bound electron in hydrogen-like atoms;
- energy levels of muonic and exotic atoms;
- energy levels of three-body atoms (helium, antiprotonic helium, muonic helium).

Twenty years ago the experimental accuracy of most QED tests was significantly better than the theoretical one. With time situation changed so that after successful devopments modern QED theory dominates over experiment.

However, there is the third side in this competition. Unfortunately, theory and experiment cannot speak the same language. Experiment leads to results expressed in units of Hertz and Mev, while theory delivers only expressions containing values of fundamental constants (such as the fine structure constant α, electron mass m_e) and particle/nuclear parameters (like e.g. the proton charge radius). In other words, theory is actually not in position to predict any numbers building instead bridges between different experiments. As a bridge, theory is the most accurate part of most QED tests. However, trying to calculate some quantity needed to make a prediction we often discover that the input data of the calculation, i.e. the fundamental and auxiliary constants, are not known accurately enough from their measurements in other experiments.

In the case of hadronic effects for some QED quantities (like e.g. hyperfine interval in the hydrogen atom or anomalous magnetic moment of muon) we even need functions (such as the proton electric form factor) to be somehow determined as the input data.

The lesson we have to learn from precision studies of simple atoms and QED tests is that the situation for free particles ($g-2$ for electron and muon), low Z atoms (hydrogen, muonium), high Z atom (bismuth, lead), muonic and exotic atoms is actually quite similar:

- the QED calculations themselves can be done with high enough accuracy to compete with experiment. Actually, QED theory rather wins the competition.

- However, that is not enough:

  - we need to have access to accurate values of the fundamental constants to transform QED expressions into numbers;

  - we also need to know some functions like form factors to put into the calculation.

- Eventually, comparison of theory and experiment is often not quite a QED test, but rather a determination of some fundamental constants or study of nuclear effects.

The crucial orders of magnitude important for comparison of theory and experiment are summarized in the Table below. In most of the cases the QED tests confirm theory.

Quantity	Order
Hydrogen, deuterium (gross structure)	$\alpha(Z\alpha)^7 m$, $\alpha^2(Z\alpha)^6 m$
Hydrogen (fine structure and Lamb shift)	$\alpha(Z\alpha)^7 m$, $\alpha^2(Z\alpha)^6 m$
$^3He^+$ ion ($1s/2s$ hyperfine structure)	$\alpha(Z\alpha)^7 m^2/M$,$\alpha(Z\alpha)^6 m^3/M^2$, $\alpha^2(Z\alpha)^6 m^2/M$, $(Z\alpha)^7 m^3/M^2$
$^4He^+$ ion (gross structure and Lamb shift)	$\alpha(Z\alpha)^7 m$, $\alpha^2(Z\alpha)^6 m$
Muonium ($1s$ hyperfine structure)	$(Z\alpha)^7 m^3/M^2$, $\alpha(Z\alpha)^6 m^3/M^2$, $\alpha(Z\alpha)^7 m^2/M$
Positronium (gross structure and $1s$ hyperfine structure)	$\alpha^7 m$
Parapositronium (decay rate)	$\alpha^7 m$
Orthopositronium (decay rate)	$\alpha^8 m$
Parapositronium (4γ branching)	$\alpha^8 m$
Orthopositronium (5γ branching)	$\alpha^8 m$

Table 1. Comparison of QED theory and experiment: crucial orders of magnitude

More detail on comparison of theory versus experiment can be found in [1]. A detailed review of theory is presented in [2]. Most of recent results and projects related to QED tests and simple atoms along with reviews were presented at two conferences on *Precision Physics of Simple Atomic Systems* (PSAS) in 2000 (Castiglione della Pescaia) [3] and 2002 (St. Petersburg) [4].

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[1] S. G. Karshenboim, In *Atomic Physics* **17** (AIP conference proceedings 551) Ed. by E. Arimondo et al. (AIP, 2001), p. 238; arXiv:hep-ph/0007278.

[2] M. I. Eides, H. Grotch and V. A Shelyuto, Phys. Rep. **342**, 63 (2001).

[3] S. G. Karshenboim, F. S. Pavone, F. Bassani, M. Inguscio and T. W. Hänsch. *Hydrogen atom: Precision physics of simple atomic systems* (Springer, Berlin, Heidelberg, 2001).

[4] The contributed papers to PSAS 2002 are scheduled for publication in *Canadian Journal of Physics* in November, 2002, while the book of review contributions is in preparation to be published in 2003.

Ground-state energy of pionic hydrogen to one loop

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In my talk I discussed recent work on pionic hydrogen performed in Ref. [1]. In Ref. [2], the relation between the scattering length combination $|a_{0+}^{+} - a_{0+}^{-}|$ and the strong energy-level shift of pionic ground state has been worked out at leading order in the low-energy expansion of the isospin breaking correction. In Ref. [1], we have carried out the calculation at next-to-leading order, where the effect of the photon-neutron intermediate state first shows up in the chiral expansion. This amounts to evaluating the elastic $\pi^- p \to \pi^- p$ amplitude at order p^3, including isospin breaking contributions generated by the quark mass difference $m_u - m_d$ and by virtual photon loops. In order to have a systematic framework, we have extended the infrared regularization method developed by Becher and Leutwyler [3], such that it includes virtual photons as well. Furthermore, we have performed a heat-kernel evaluation of all singular parts in the one-loop calculation, including meson, baryon and photon fields. As far as we are aware, this provides for the first time a consistent set of effective lagrangians at this order in the low-energy expansion. We find that triangle-type graphs generate large corrections, whereas the effect of the low-energy constants at order p^3 is suppressed by the factor $m_\pi/m_{\rm proton}$. On the other hand, the constant f_1, that occurs at leading order, may contribute significantly to the energy shift [1]. Unfortunately, it has not yet been determined with sufficient accuracy. We conclude that the potential-model calculations available in the literature largely underestimate the systematic error, because these models are not properly matched to the underlying theory (QCD+QED). Furthermore, claims made in the literature that a precise measurement of the strong energy-level shift in pionic hydrogen will provide a corresponding precise determination of $|a_{0+}^{+} - a_{0+}^{-}|$ are too optimistic at the present stage of the theoretical knowledge: Experiment is ahead of theory in this case. For further references and details, I refer to [1]. A very recent article is [4] - we plan to comment on this work elsewhere [5].

[1] J. Gasser, M. A. Ivanov, E. Lipartia, M. Mojzis and A. Rusetsky, Eur. Phys. J. C **26** (2002) 13 [arXiv:hep-ph/0206068].

[2] V.E. Lyubovitskij and A. Rusetsky, Phys.Lett. B494 (2000) 9 [arXiv:hep-ph/0009206].

[3] T. Becher and H. Leutwyler, Eur. Phys. J. C9 (1999) 643 [arXiv:hep-ph/9901384].

[4] T.E.O. Ericson, B. Loiseau and S. Wycech, arXiv:hep-ph/0211433.

[5] J. Gasser and A. Rusetsky, in preparation.

The influence of the γn channel on the energy and width of pionic hydrogen

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We reconsider the corrections presented in the paper of Sigg et al. [1] for the extraction of the hadronic $s-$wave πN scattering lengths from measurements of the energy and width of pionic hydrogen. Our starting point is the Deser type formulae given in the multi-channel situation by Rasche and Woolcock [2]. These relate the energy shift to the nuclear scattering length, a^n_{cc}, for the process $\pi^- p \to \pi^- p$ and the width for decay to the $\pi^0 n$ channel to the scattering length, a^n_{c0} for the process $\pi^- p \to \pi^0 n$. These nuclear scattering lengths are in turn related to the hadronic scattering lengths by the expressions

$$a^n_{cc} = a^h_{cc}(1 + \delta_{cc}),$$
$$a^n_{c0} = a^h_{c0}(1 + \delta_{c0}),$$

where δ_{cc} and δ_{c0} are the electromagnetic corrections. Values for these were first considered in [2], later examined in more detail in [1] and more recently recalculated in [3].

In addition to the hadronic channels $\pi^- p$ and $\pi^0 n$, pionic hydrogen also decays to the channel γn, the widths being related by the Panofsky ratio

$$\frac{\Gamma_{\pi^0 n}}{\Gamma_{\gamma n}} = P = 1.546 \pm 0.009.$$

This channel also influences the EM corrections and the first crude estimates of its effect were made in [1] where the effective potential in the $\pi^- p \to \pi^0 n$ channel was empirically increased so that it gave a value a^{eff}_{c0} which reproduced the full width i.e.

$$a^{eff}_{c0} = a^n_{c0}\sqrt{1 + P^{-1}}.$$

This modified potential was then used to calculate new EM corrections and the differences between these values and the values from the unmodified 2-channel calculation, $\Delta\delta_{cc}$ and $\Delta\delta_{c0}$, were assigned to the influence of the γn channel. The final values with errors given in [1] were

$$\begin{aligned} \delta_{cc} &= -(2.1 \pm 0.5)\% \\ \delta_{c0} &= -(1.3 \pm 0.5)\% \end{aligned}$$

where the contributions from the γn channel were

$$\begin{aligned} \Delta\delta_{cc} &= -0.73\% \\ \Delta\delta_{c0} &= +0.15\%. \end{aligned}$$

What the authors of [1] overlooked was that the modification of the effective potential in the $\pi^- p \to \pi^0 n$ channel not only changes a^n_{c0} to a^{eff}_{c0} but also modifies a^n_{cc}, an effect which can also be considered as a type of EM correction. In order to examine this effect we have extended the calculations used in [3] to the case where we have the three channels, $\pi^- p$, $\pi^0 n$ and γn. Such calculations involving mass 0 photons are possibly dangerous due to the fact that the reduced mass of the γn system is 0. As pointed out in [4], this problem does not occur in the case of a relativistic equation of motion. In our case we use the relativised Schrödinger equation where the appropriate term in the non-relativistic equation, $2M^{red}_{\gamma n} V_{c\gamma}$, becomes $2M^{red}_{\gamma n} f_{c\gamma} V_{c\gamma}$ where

$$M^{red}_{\gamma n} f_{c\gamma} = \frac{M_n m_\gamma}{M_n + m_\gamma} \frac{W^2 - M_n^2 - m_\gamma^2}{2 m_\gamma W}$$

which has a finite limit as $m_\gamma \to 0$. In this calculation we also need effective potentials to describe the three channel system. For the $\pi^- p$ and $\pi^0 n$ channels we use hadronic potentials fitted to the low energy phase shifts together with the Coulomb and vacuum polarization potentials corrected for finite size effects. For $\pi^- p \to \gamma n$ and $\pi^0 n \to \gamma n$ we adjust the potentials to fit the E_{0+} photoproduction multipole amplitudes and for $\gamma n \to \gamma n$ we adjust to fit the low energy $\gamma n \to \gamma n$ cross section. We now make the same type of calculations as in the two channel case i.e. we compare the value of the threshold K-matrix calculated in the full three channel case with its purely hadronic value. For the EM corrections, preliminary calculations show only a very small change in δ_{c0} but δ_{cc} increases to a value around zero.

Can we understand this physically? What we are seeing might well be called an extended Ball-Frazer mechanism. The addition of the extra inelastic channel gives an effective attraction which increases the binding energy. This seems to be an effect which comes from the requirements of multichannel unitarity and as such will not be seen in lowest order calculations which ignore these requirements.

Another very important point is that our EM corrections refer to a hypothetical hadronic world which is, by tradition, defined as one in which nucleons have the mass of the proton, pions the mass of the charged pion and where the effective potentials are isopin invariant. This should be remembered when comparing to the results of Gasser et al. [5] who refer to a hadronic situation consistent with chiral perturbation theory. We could, of course, use a similar definition of our hadronic reference point. The hadronic masses would then be taken from chiral perturbation theory and the effective potentials adjusted to reproduce the low energy chiral perturbation theory amplitudes. To do this without assuming isospin invariance requires the low energy amplitudes in all three channels, $\pi^- p \to \pi^- p$, $\pi^- p \to \pi^0 n$ and $\pi^0 n \to \pi^0 n$ and we therefore ask the chiral perturbation theory experts for these values so that we can proceed with this work.

[1] D. Sigg, A. Badertscher, P.F.A. Goudsmit, H.J. Leisi and G.C. Oades, Nucl. Phys. **A 609** (1996) 310.

[2] G. Rasche and W.S. Woolcock, Nucl. Phys. **A 381** (1982) 405.

[3] A. Gashi, E. Matsinos, G. Rasche, G.C. Oades and W.S. Woolcock, arXiv:hep-ph/0009081 and Nucl.Phys **A 686** (2001) 463.

[4] P.B. Siegel and W.R. Gibbs, Phys. Rev. **C 33** (1986) 1407 and W.B. Kaufmann and W.R. Gibbs, Phys. Rev. **C 35** (1987) 838.

[5] J. Gasser, M.A. Ivanov, E. Lipartia, M. Mojzis and A. Rusetsky, arXiv:hep-ph/0206068.

Coupled channel approach to breakup of pionium

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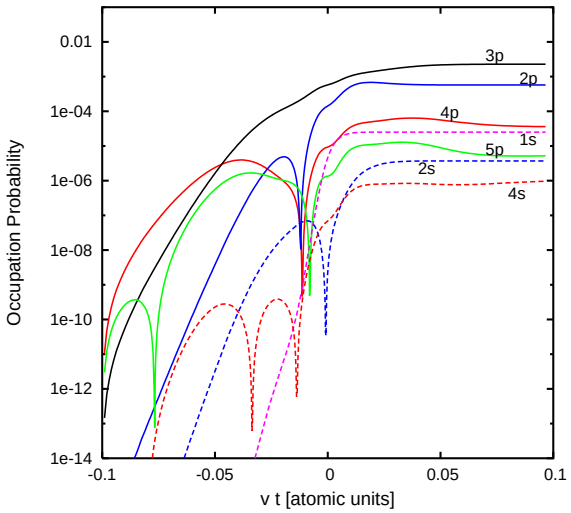
Since the experiment DIRAC does not directly observe the neutral pions from the strong decay channel $\pi^+\pi^- \to 2\pi^0$, but rather looks at the charged pions from electromagnetic breakup in the target, this electromagnetic breakup process must be calculated with very high accuracy (on the order of 1%) as a required input for the analysis of the experiment. In order to extract the pionium lifetime from the observed breakup probability, the passage of pionium through the target matter is studied in a simulation which in turn requires detailed knowledge of the cross sections for bound-bound and bound-free transitions of the pionium [1].

In previous work [2–4] we have shown that the semiclassical approximation provides the appropriate tool for this problem. In first order Born approximation the accurate description of both the pionium and the target system with its atomic structure, as well as their relativistically correct interaction (including magnetic terms), has been implemented successfully (accurate to far better than 1% within this model). However, it has been noted by studying the total cross sections [5], and veryfied by explicitly calculating the bound-bound transitions in the Glauber formalism [6] that higher order contributions can change the first order results by up to several per cent. We have estimated the validity of the Glauber approximation in [6] by studying the influence of finite interaction times within a simple extension of the sudden approximation. We found that the results varied within less than 0.1% which may thus be regarded as the accuracy of the higher order calculation (clearly below the required 1% limit).

In order to provide a further, independent test of the validity of the Glauber approximation, we study the time evolution of the occupation probabilities for a few selected bound states of the pionium in a coupled channel approach. The figure shows this time evolution for various channels as indicated. In this example, the pionium starts out initially in the 3s-state (all other states not occupied; Nickel target). As time evolves, other pionium states acquire non-zero occupation probabilities. Our goal is to verify whether the cross sections obtained in this approach agree with our previous (numerically less demanding) calculations in a few test cases.



[1] L.G. Afanasyev *et al.*, Phys. Lett. B **338** (1994) 478.
[2] Z. Halabuka *et al.*, Nucl. Phys. B **554** (1999) 86.
[3] T.A. Heim, K. Hencken, D. Trautmann and G. Baur, J. Phys. B **33** (2000) 3583.
[4] T.A. Heim, K. Hencken, D. Trautmann and G. Baur, J. Phys. B **34** (2001) 3763.
[5] L. Afanasyev, A. Tarasov and O. Voskresenskaya, J. Phys. G **25** (1999) B7.
[6] M. Schumann *et al.*, J. Phys. B **35** (2002) 2683.

On the influence of low n and high n states cross section in the break-up probability of pionium

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The study of the break-up probability (P_{br}) dependence of pionium as a function of lifetime in a target of definite material and thickness is a master key in the measurement that DIRAC collaboration aims to achieve in its experiment PS-212 at CERN [1].

A detailed explanation of the physical problem can be found in [2] and [3] and can be resumed as to solve the differential equation system that links the population p_{nlm} of the different atomic bound states (defined by the usual quantum numbers of an hydrogen-like system, n, l and m) as a function of the target position of the atom (s):

$$\frac{dp_{nlm}(s)}{ds} = \sum_{n'l'm'} a_{nlm}^{n'l'm'} p_{n'l'm'}(s) \qquad \begin{cases} a_{nlm}^{n'l'm'} = \frac{\sigma_{nlm}^{n'l'm'} \rho N_0}{A} \\ a_{nlm}^{nlm} = \frac{\sigma_{nlm}^{total} \rho N_0}{A} - \begin{cases} \frac{2M_\pi}{Pc\tau_n} & \text{if } l = 0 \\ 0 & \text{if } l \neq 0 \end{cases} \end{cases}$$

where ρ is the density and A the atomic weight of the target, N_0 the Avogadro number, M_π the mass of the pion, τ_n the lifetime of the bound state and P the center of mass momentum of the atom (average around 4.2 GeV/c in DIRAC experimental conditions). However, the main input to the equation is given by the pionium-target atom interaction cross sections, either for the probability of a transition between bound states ($\sigma_{nlm}^{n'l'm'}$) or for the total interaction probability (σ_{nlm}^{total}).

These cross sections have been calculated in the Born approximation using different parameterizations for the atomic form factors [2,4] and with the Glauber [5] approximation that accounts for multi-photon exchange. The three calculations lead to similar results with discrepancies between 1% and 4% if the states involved in the transition are low energy ones ($n \leq 5$) and increase as n does up to differences higher than 10%.

However, the difference in the breakup probability result of pionium is to the level of 1%. As an example, asumming 2.91 femtoseconds for pionium lifetime:

$$P_{br}^{G} = 0.454 \qquad P_{br}^{B1} = 0.460 \qquad P_{br}^{B2} = 0.465$$

where P_{br}^{G} was calculated with the Glauber cross sections of [5], P_{br}^{B1} with the Born cross sections of [2] and P_{br}^{B2} with the Bron cross sections of [4].

This agreement between the three results is explained by four things:

1. The atomic bound states are produced (initial conditions) according to: $p_n^{prod} \propto 1/n^3$ [6] and hence the amount of atoms created with $n \geq 5$ is negligible.

2. The probability of annihilation also behaves as $p_n^{annih} \propto 1/n^3$ [7] and hence there are almost no atoms annihilated from states with $n \geq 5$.

3. The atoms show a clear tendency to be excited or broken rather than to be de-excited, $\sum_{n'<n,l',m'} \sigma_{nlm}^{n'l'm'} \gg \sum_{n' \geq n,l',m'} \sigma_{nlm}^{n'l'm'}$ (see Figure).

4. The total cross section increases very fast as n does. And as a consequence the mean free path of the atom ($\lambda_{nlm} = A/\sigma_{nlm}^{total}\rho N_0$) decreases very fast with n (see Figure).

All this means that the states with $n \geq 5$ are populated by excitations from lower n states since very rarely atoms are directly created in these states. Moreover, de-excitations from these states to lower n states very seldom happen also. This means that the solution of the differential equation system for the low n states (where annihilation probability is not negligible) does not depend on the population of high n states and hence, the discrepancies between the different sets of cross sections will not lead to differences in the solutions of the equation system for these states populations. Meanwhile, an atom which is excited into a high n state has a very small free path (in all the three sets of cross sections) compared to the target dimensions of DIRAC (tenths of micrometers) and will interact with very high probability until it ends up broken. The discrepancies between the different sets of cross sections will be then irrelevant since they all lead to a breakup probability result of practically 100% for a bound state with $n \geq 5$ [4].

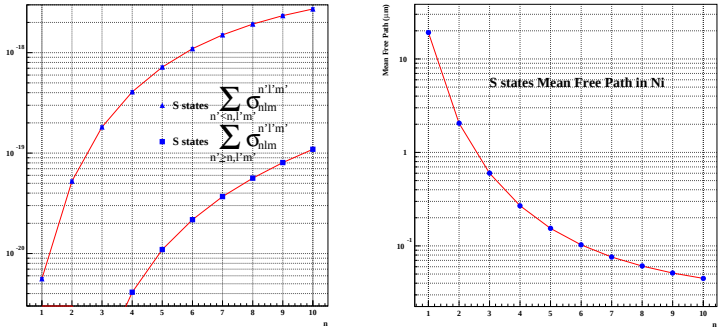

Figure 2: On the left we show up the comparison between the excitation and the de-excitation cross sections of [2] for the S sates of the atoms. On the right we can observe the mean free path value of S states.

We want to thank Prof. Dr. Dirk Trautmann and his group for have kindly provided us their cross sections sets.

[1] B. Adeva *et al.*, *Lifetime measurement of $\pi^+\pi^-$ atoms to test low energy QCD predictions*, CERN/SPSLC 95-1 (1994).
[2] L.G. Afanasyev and A.V. Tarasov, Phys. of At. Nucl. **59** (1996) 2130.
[3] C. Santamarina, Ph. D. Thesis, Universidade de Santiago de Compostela (2001).
[4] T. Heim, K. Hencken, D. Trautmann and G. Baur, J. of Phys. **B 33** (2000) 3583; J. of Phys. **B 34** (2001) 3763.
[5] M. Schumann, T. Heim, K. Hencken, D. Trautmann and G. Baur, J. of Phys. **B 35** (2002) 2683.
[6] L. Nemenov, Sov.J.Nucl.Phys. **41** (1985) 629.
[7] S. Deser, K. Baumann and W. Thirring, Phys. Rev. **96** (1954) 774; S.M. Bilenky, Van Kheu Nguyen, L.L. Nemenov and F.G. Tkebuchava, Sov. J. Nucl. Phys. **10** (1969) 469.

[4] However this would not be the case if the target thickness was much smaller.

Recent results from DEAR at DAΦNE

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In May 2001 the DEAR (DAΦNE Exotic Atom Research) collaboration [1] performed the first measurement of an exotic atom (kaonic nitrogen) at the DAΦNE collider of the Laboratori Nazionali di Frascati dell'INFN. The $7 \rightarrow 6$ at 4.6 keV and $6 \rightarrow 5$ at 7.6 keV transitions were measured with 3 σ and 3.7 σ statistical significance, and the results published in [2]. After this first measurement, a second one was performed in May-June 2002, with an improved setup and better machine conditions (new optics which allowed the increase of luminosity and the decrease of background). The goals of this measurement were: to obtain a clean spectrum, in which only kaonic nitrogen lines are present, to reduce the continuous background with respect to the previous run (May 2001) in the view of the future kaonic hydrogen measurement and to perform a fine-adjustment of the degrader, which takes into account the ϕ production mechanism at a machine as DAΦNE (i.e. the boost). All these goals were successfuly reached.

The target used for this measurement, differently from before, was done in kapton 75μm width, reinforced with carbon fiber. This had as positive consequence the fact that in the X ray spectrum all the eventual electronic transition lines corresponding to "biasing signals", as iron, manganese, copper, were absent or much reduced, and the konic nitrogen signal was much clearer. The measurement was performed with the target filled with nitrogen at about 78 K and 0.98 bar ($\rho \simeq 4.3\rho_{NTP}$). As detector, 16 CCD-55 were used. A pure-background spectrum (so-called "empty-target") was obtained as well, by using an over-dimensioned degrader, stopping the kaons inside, so not allowing the formation of the kaonic nitrogen atoms inside the nitrogen target. This spectrum was used for the shaping of the background and to obtain a background subtracted spectrum.

A preliminary analysis of the data gave as result an overall X ray kaonic nitrogen spectrum which is shown in Figure 1, together with a fit in the region of interest. The empty-target subtracted spectrum is shown in Figure 2. The calcium electronic transition is due to the presence of calcium in the carbon fiber reinforcement of the target, while zirconium was placed, as a thin foil, for calibration purpose.

The analysis (preliminary) of this spectrum gave a number of events in the 7.6 keV peak of 1400 ± 132 (10.6 σ statistical significance) and in the 4.6 keV peak of 700$\pm$142 (about 5 σ). More refined analysis are going to be performed.

The spectrum in Figure 1 shows the nice feature of a continuous backgrouns; no electronic transitions are present in the region of interest (4-10 keV), apart eventually from some iron, which will be shielded in the next run. Moreover, a reduction of background by a factor about 5 was reached with respect to May 2001 run and the optimisation of the degrader was successfuly performed. The kaonic nitrogen transitions were identified with a much better statistical significance as well.

The next stage of the experiment is the measurement of the K-complex in kaonic hydrogen transitions.

[1] S. Bianco *et al.*, Rivista del Nuovo Cimento **22**, No. 11, (1999) 1

[2] G. Beer *et al.*, Phys. Lett. **B535** (2002) 52.

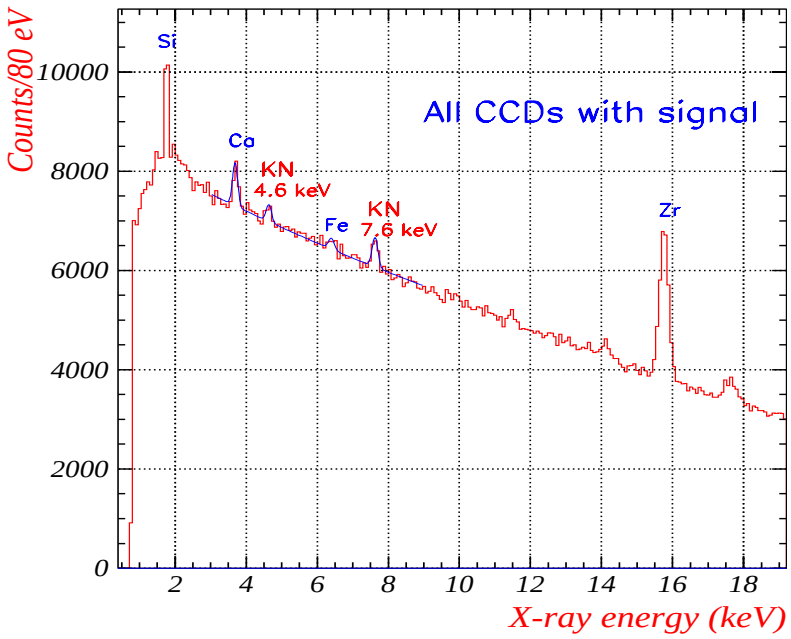

Figure 3: The kaonic nitrogen X ray spectrum with a fit in the region of interest.

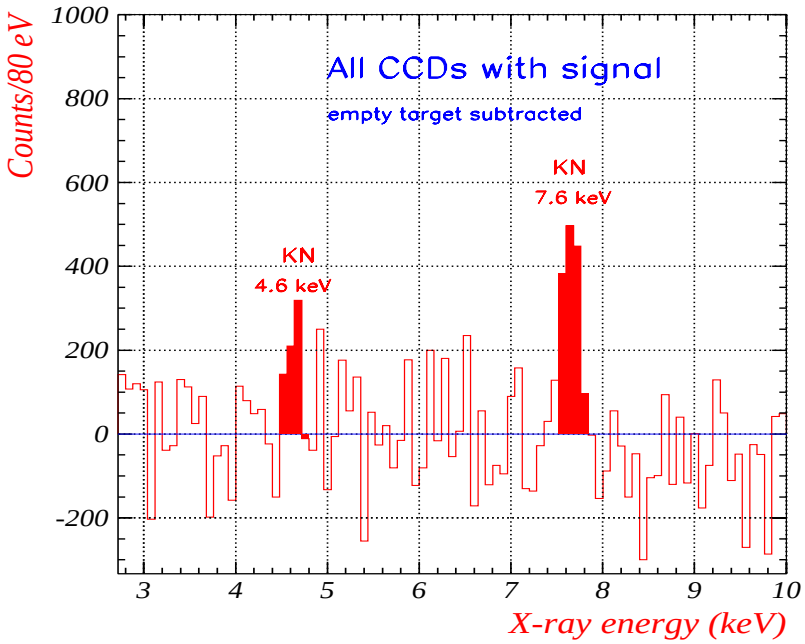

Figure 4: The kaonic nitrogen empty-target subtracted spectrum.

The Pionic-Hydrogen Experiment at PSI

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In pionic hydrogen the hadronic pion–nucleon interaction manifests itself by a change of the energies and of the natural line width of X–ray lines as compared to a purely electromagnetically bound atomic system. Experimentally accessible are the transitions to the 1s ground state emitted in the last de–excitation step of the atomic cascade. Any observed strong–interaction effect can be attributed fully to the 1s state, because 2p–state effects are negligibly small. Hence, the s–level shift and width are exclusively owing to the pion-nucleon s–wave interaction, which is described in the limit of isospin symmetry by the isoscalar and isovector scattering lengths a^+ and a^- [1].

To improve on the accuracy for the hadronic parameters as compared to previous measurements [2], a thorough study of a possible influence of de–excitation processes is essential. A first series of measurements has been completed by the new pionic–hydrogen experiment at the Paul–Scherrer–Institut (PSI), using the new cyclotron trap, a cryogenic target and a Bragg crystal spectrometer equipped with spherically bent silicon and quartz crystals and a large–area CCD array [3]. Data analysis is in progress.

In order to identify radiative de–excitation of the πH system – when bound into complex molecules formed during collisions $\pi^- p + H_2 \rightarrow [(pp\pi^-)p]ee$ [4] – the energy of the $\pi H(3p-1s)$ transition was measured at various target densities. X–ray transitions from molecular states should show up as low–energy satellites with density dependent intensities because of different collision probabilities. In our experiment, covering the pressure range from 3.5 bar to liquid, no density effect could be established [5]. It is concluded that the decay of molecules is dominated by Auger emission. The value derived for the hadronic shift is in agreement with the result of the previous experiment.

At present, the accuracy for the hadronic broadening (7%) is limited by a not precisely known correction to the measured line width originating from the Doppler broadening due to Coulomb de–excitation [2]. For that reason the precisely measured 1s–level shift in pionic deuterium was used together with the shift of hydrogen in the determination of the πN scattering length [6]. This procedure, however, requires a sophisticated treatment of the 3–body system πD. In addition, up to now it cannot be excluded that the radiative decay channel after molecule formation is enhanced in deuterium compared to hydrogen.

To improve the data base on the line broadening due to Coulomb de–excitation, the three $\pi H(2p-1s)$ (2.4 keV), $\pi H(3p-1s)$ (2.9 keV) and $\pi H(4p-1s)$ (3.0 keV) transitions were

studied at a target density equivalent to 10 bar. An increase of the line width was found for the $2p-1s$ line compared to the $3p-1s$ transition, which is attributed to the higher energy release available for the acceleration of the pionic–hydrogen system. This result is corroborated by a reduced line width of the $4p-1s$ line. For the total line width of the $\pi H(3p-1s)$ transition an increase of 5-10% was found compared to the result of Schröder et al. [2], which may be due to the significantly improved background conditions in the new experiment.

The response of the crystal spectrometer was obtained from the $\pi^{12}C(5g-4f)$ line (3.0 keV), which is negligibly narrow compared to the experimental resolution (Fig. 1). The statistics of such a measurement, however, and with that the accuracy for the response function, is limited due to beam time considerations. In addition, the crystal response has been measured with X–rays emitted from helium–like Ar, ionised by means of an electron–cyclotron resonance ion trap (ECRIT) set up at PSI [7]. With that, studies of the Bragg crystals used up to now with good statistics could be performed within a reasonable time scale.

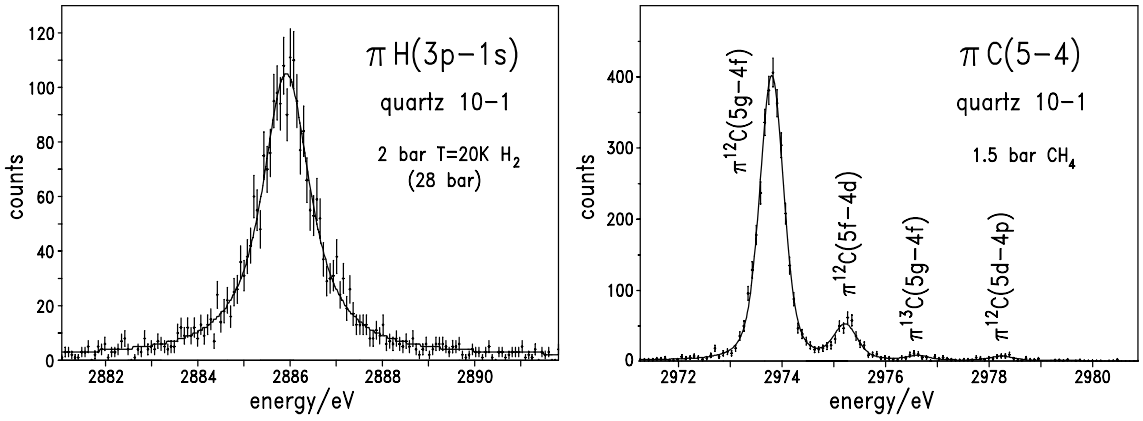

Figure 5: Fig. 1: Ground–state transition $3p-1s$ in pionic hydrogen and the pionic carbon $5-4$ transitions measured with a quartz crystal.

¿From about 2005 on, Coulomb de–excitation will be studied in detail in the absence of strong–interaction effects by measuring K transitions from muonic hydrogen. Together with the detailed knowledge of the response function by using the ECRIT and a newly developed cascade code [8], which includes the velocity dependence of the atomic cascade, a sufficiently accurate correction for the Doppler broadening in pionic hydrogen should be achieved to extract the hadronic broadening at the level of about 1%.

[1] V. E. Lyubovitzkij and A. Rusetski, Phys. Lett. **B 494** (2000) 9.
[2] H.–Ch. Schröder et al., Eur. Phys. J. **C 21** (2001) 433.
[3] PSI experiment R–98.01.
[4] S. Jonsell, J. Wallenius, and P. Froelich, Phys. Rev. **A 59** (1999) 3440.
[5] D. F. Anagnostopoulos et al., proceedings Menu 2001, πN newsletter **16** (2002) 355.
[6] T. E. O. Ericson, B. Loiseau, and A. W. Thomas, Phys. Rev. **C 66** (2002) 014005.
[7] S. Biri, L Simons et al., proc. of ECRIS'02, Jyväskylä, Finland, June, 12-14, 2002, http://www.phys.jyu.fi/ecris02/programme2.htm.
[8] T. Jensen and V. M. Markushin, proceedings Menu 2001, πN newsletter **16** (2002) 358.

Lifetime measurement of $\pi^+\pi^-$ atom at DIRAC

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Introduction

Pionium or $A_{2\pi}$ is a hydrogen-like atom consisting of π^+ and π^- mesons. The lifetime of this atom is inversely proportional to the squared difference between the S-wave $\pi\pi$ scattering lengths for isospin 0 and 2, $|a_0 - a_2|$. This value is predicted by chiral perturbation theory (ChPT) [1], and a measurement of the $\pi^+\pi^-$ atom lifetime provides a possibility to check predictions of ChPT in a model-independent way.

Method of lifetime measurement

The $A_{2\pi}$ are produced by Coulomb interaction in the final state of $\pi^+\pi^-$ pairs generated in proton–target interactions [2,3]. After production $A_{2\pi}$ travel through the target and some of them are broken up due to their interaction with matter: "Atomic pairs" are produced, characterised by small pair c.m. relative momenta $Q < 3$ MeV/c. These pairs are detected in the DIRAC setup. Other atoms annihilate into $\pi^0\pi^0$. The amount of broken up atoms n_A depends on the lifetime which defines the decay rate. Therefore, the breakup probability is a function of the $A_{2\pi}$ lifetime. The dependence of $P_{\rm br}$ on the lifetime τ is determined by the solution of differential transport equations [4].

Also $\pi^+\pi^-$ pairs are generated in free state. Essential fraction of such pairs ("Coulomb pairs") are affected by Coulomb interaction, too.

The aim of DIRAC is to measure the $A_{2\pi}$ breakup probability $P_{\rm br}(\tau)$. $P_{\rm br}(\tau)$ is the ratio between the observed number of "atomic pairs" and the number of produced $\pi^+\pi^-$ atoms which is calculated from the measured number of "Coulomb pairs".

Experimental setup

The purpose of the DIRAC setup [5] is to detect $\pi^+\pi^-$ pairs with small relative momenta. This setup is located at the CERN T8 beam area (East Hall). It became operational at the end of 1998 and uses the 24 GeV proton beam from PS accelerator.

The setup resolution over the relative c.m. momentum Q of $\pi^+\pi^-$ pair is better than 1 MeV/c.

Experimental data

The experimental Q-distribution of $\pi^+\pi^-$ pairs is fit by an approximated distribution of "free pairs" in the region $Q > 3.5$ MeV/c where "atomic pairs" are absent. The number of "atomic pairs" is obtained as excess of experimental Q-distribution above the approximated distribution of "free pairs" only in the region $Q < 3.5$ MeV/c. Differences of experimental and approximated distributions are shown in Fig. 6 for data collected in 1999, 2000, 2001 and in 15 days of 2002. Platinum, nickel and titanium targets havebeen used.

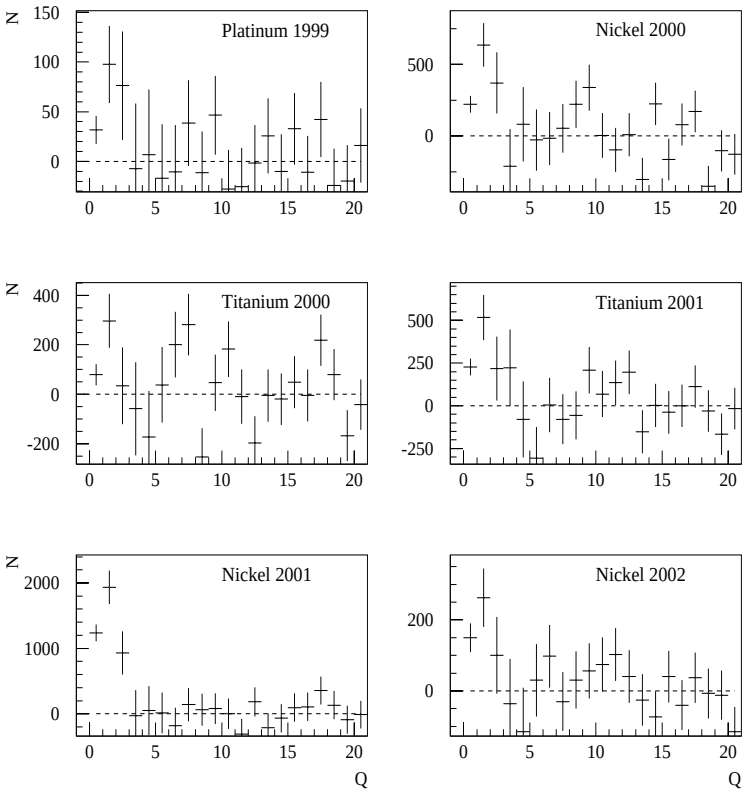

Figure 6: Signals of "atomic pairs" in the region $Q < 3$ MeV/c are obtained with different targets. For 2002 only data collected in 15 days are analysed.

The overall statistics of "atomic pairs" which is collected before the end of 2001 is more than 5000. It provides statistical accuracy for the lifetime measurement at the 20% level.

The data analysis procedure is not completed yet and only very preliminary lifetime estimations are $\tau = 2.8^{+1.1}_{-0.8} \cdot 10^{-15}$s for data collected in 2000 with nickel target and $\tau = 5.4^{+1.5}_{-1.3} \cdot 10^{-15}$s for all titanium target data. Averaged value is $\tau = 3.6^{+0.9}_{-0.7} \cdot 10^{-15}$s.

Conclusions

Preliminary results have been achieved by analysing a sample of 5000 atoms. The statistical accuracy in the lifetime determination reaches 20%. Data collected in 2002 allow us to increase the statistical accuracy up to 15%.

[1] G. Colangelo, J. Gasser and H. Leutwyler, Phys. Lett. B **488**, 261 (2000).
[2] L. Nemenov, Sov. J. Nucl. Phys. **41**, 629 (1985).
[3] L. Afanasyev et al., Phys. Lett. B **308**, 200 (1993).
[4] L. Afanasyev and A. Tarasov, Phys. At. Nucl. **59**, 2130 (1996).
[5] B. Adeva et al., CERN/SPSLC/P 284 (1994).

Prospects for the study of the $K^{\pm}_{e4}$ decays at the NA48/2 experiment

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It is well known that the study of the $K^{\pm} \to \pi^+\pi^- e^{\pm}\nu_e$ decay parameters can provide an important information about the $\pi\pi$ interaction near threshold. Besides the extraction of the decay form-factors which are valuable input for χPT, the measurement of the $\pi\pi$ scattering length a_0^0 is recognized as a crucial cross-check with the current understanding of chiral symmetry breaking of QCD and as an accurate estimate of the size of quark condensate $< 0|u\overline{u}|0 >$ [1]. The two most significant experiments so far were carried out by the Geneva-Saclay [2] and E865 collaborations [3] and are based on 3×10^4 and 4×10^5 collected $K^{\pm} \to \pi^+\pi^- e^{\pm}\nu_e$ events. Since the present experimental uncertainty on a_0^0 is significantly larger than the theoretical one it is of great interest to acquire an additional high statistics and good quality experimental data in this decay mode.

The NA48/2 experiment is approved as an extension of the NA48 experiment at the CERN SPS. Its main goals are the search for direct CP violation in the Dalitz plot asymmetries in the decays of opposite charged kaons, the measurement of the scattering length a_0^0 and the analysis of various rare kaon decays. About 1×10^{11} K^+ and 0.6×10^{11} K^- decays are expected for around 100 days of data taking in 2003. The NA48/2 experiment is based on a slightly modified NA48 set-up. The kaon decays volume is contained in a 114m long vacuum tank which is followed by the NA48 detectors. The charged particles are detected and reconstructed by a high resolution magnetic spectrometer. It consists of four drift chambers and a dipole magnet with horizontal momentum kick of 120MeV/c. The corresponding track momentum resolution is given by $\sigma_P/P[\%] \approx 0.48 \oplus 0.02 \times P[GeV/c]$. The energy, position and time of the showers produced by the charged particles passed through the spectrometer are measured by a quasi-homogeneous liquid krypton electromagnetic calorimeter (LKr). Its transverse structure of ≈1300 readout cells each with size of $2 \times 2\text{cm}^2$ is formed by electrodes extended with an accordion geometry. LKr has a longitudinal size of 127cm (equivalent to $\approx 27X_0$ and $\approx 2\lambda$) and a projective tower geometry pointing to the decay volume. Its energy resolution for e/m showers is $\sigma_E/E = 0.42\% \oplus 3.2\%/\sqrt{E} \oplus 0.09/E$ (E in GeV). A detailed description of the whole NA48 set-up can be found elsewhere [4].

In addition to the present NA48 apparatus, two essential new elements will be introduced to the NA48/2 set-up [5]. The first one is an achromatic beam-line capable to transport and focus simultaneously 60GeV/c±10% K^+ and K^- beams. A kaon beam spectrometer (KABES) will measure the kaon beam sign, momentum and direction in order to improve the reconstruction of the $K^{\pm}_{e4}$ and to recover the $K^{\pm} \to 3\pi$ with one pion escaping detection [5]. KABES consists of three so-called stations - two in the beam-line achromat and one downstream. Each station is formed by two time projection MICROMEGAS chambers [6] with opposite drift directions. The detector prototype has been successfully tested in July 2002 in the environment of an extremely high particle rate of 20-30MHz (comparable to that of the future kaon beam-line) showing excellent time (<1ns) and space (<80μm) resolutions.

Because of the small branching ratio of $K^{\pm} \to \pi^+\pi^- e^{\pm}\nu_e$ an important point in the systematic free measurement of a_0^0 is the reduction of the major background coming from

RMS	Geneva-Saclay	E865	NA48/2 (expected)
$M_{\pi\pi}$ (MeV)	2.5	16	1.6
$M_{e\nu}$ (MeV)	6.3	25	5.1
$\theta_{\pi\pi}$ (mrad)	50	63	37
$\theta_{e\nu}$ (mrad)	40	47	47
ϕ (mrad)	157	172	168

Table 1: Resolution on Cabibbo-Maksymowicz variables.

Mode	Background
$K^{\pm} \to \pi^+\pi^-\pi^{\pm}$ (τ)	$\leq 1\%$
$K^{\pm} \to \pi^+\pi^-\pi^{\pm} \to e^{\pm}\nu$	$< 0.4\%$
$K^{\pm} \to \pi^{\pm}\pi^0 \to e^+e^-\gamma$	$< 0.3\%$
$K^{\pm} \to \pi^{\pm}\pi^0\pi^0 \to e^+e^-\gamma$	$< 0.1\%$
$K^{\pm} \to e^{\pm}\nu\pi^0 \to e^+e^-\gamma$	$< 0.1\%$
$K^{\pm} \to \mu^{\pm}\nu\pi^0 \to e^+e^-\gamma$	$< 0.1\%$
$K^{\pm} \to e^{\pm}\nu\pi^+\pi^- \to \mu\nu$	$< 0.2\%$

Table 2: Background contaminations.

$K^{\pm} \to \pi^+\pi^-\pi^{\pm}$ decays with $\pi^{\pm}$ misidentified as an electron. The situation is even more complicated since the background populates the low $\pi\pi$ invariant mass region which is the most sensitive to a_0^0. To cope with the relatively large expected $K^{\pm} \to \pi^+\pi^-\pi^{\pm}$ background the NA48/2 collaboration has introduced a *Neural Network* (NN) based approach [7] of exploiting the whole available LKr information about the longitudinal and transverse electromagnetic and hadronic showers development. Each electron candidate is described by the charged track measured by the spectrometer and the associated LKr shower parameters and is passed then as an input to a specially designed multilayer NN. The candidate is identified as an electron or rejected as a pion taking into account the probability of electron hypothesis given by NN output. The NN was developed, trained and tested using pure experimental samples of electrons and charged pions. By applying the described above method a pion rejection factor of 3500 at 94% electron detection efficiency is achieved.

In order to estimate the expected acceptance, resolution and background for $K_{e4}^{\pm}$ decays a GEANT based Monte-Carlo simulation of the apparatus has been used. The $K^{\pm} \to \pi^+\pi^-e^{\pm}\nu_e$ decay has been described by three real form-factors ($\overline{g} = g/f_s$, $\overline{g}' = g'/f_s$, $\overline{h} = h/f_s$) and one phase ($\delta = \delta_0^0 - \delta_1^1$). The values for these parameters were taken from [2]. The scattering length a_0^0 has been extracted following the procedure in [2]. The selection of $K^{\pm} \to \pi^+\pi^-e^{\pm}\nu_e$ events has been made by applying a set of standard acceptance and kinematic cuts (including a cut on the transverse momentum of the three charged tracks) as well as the NN electron identification. The expected acceptance of $\approx 30\%$ has been found relatively flat upon the Cabibbo-Maksymowicz variables leading to a conclusion of small systematic effects due to the inexact knowledge of the detector response. Taking into account the expected charged kaon flux in 2003 the expected $K^{\pm} \to \pi^+\pi^-e^{\pm}\nu_e$ decay statistics is $> 1 \times 10^6$ and the corresponding statistical uncertainty on a_0^0 is less than 0.01. The estimated resolution and background contaminations are presented in Table 1 and Table 2, respectively. As one can see the extremely good performance of the charged particles spectrometer reflects in the high resolution on invariant mass variables. On the other hand, the relatively high beam momentum of 60GeV/c leads to moderate resolutions upon the angle variables which are nevertheless comparable to those in the previous low energy experiments. Due to the high e/π separation provided by the NN method the $K^{\pm} \to \pi^+\pi^-\pi^{\pm}$ background is expected to be less than 1%. A detailed analysis of this background has shown that the corresponding systematic effect in the measurement of a_0^0 is less then 0.01.

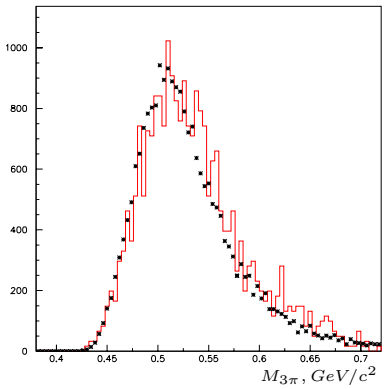

Figure 7: The 3π invariant mass distributions for the data (solid line) and MC (stars).

In the framework of the preparation for the future experiment, in September 2001 the NA48/2 collaboration has performed a 4 hours charged kaons beam test run. The already tuned $K^{\pm}_{e4}$ decays selection and reconstruction has been applied to the collected during this run data. 1477 events passed all the selection criteria including the NN electron identification procedure. The corresponding branching ratio has been evaluated using $K^{\pm} \to \pi^+\pi^-\pi^{\pm}$ decay as a normalization channel. The obtained preliminary result of BR$= (3.75 \pm 0.25) \times 10^{-5}$ is in good agreement with the world average value [8]. A careful study of the differences between the data and Monte-Carlo $M_{3\pi}$ distributions has confirmed that the $K^{\pm} \to 3\pi$ background is less than 1% (Figure 7).

To summarize, the NA48/2 experiment is planning to collect $> 1 \times 10^6$ $K^{\pm} \to \pi^+\pi^-e^{\pm}\nu_e$ decays for one year data taking in 2003 and to measure the $\pi\pi$ scattering length a_0^0 with a statistical precision of <0.01. The excellent e/π separation power combined with the good detector resolution will allow to keep and to control the systematic uncertainty to the level of less than 0.01. Thus the future measurement of a_0^0 by the NA48/2 together with the forthcoming results from the DIRAC experiment [9] are expected to improve significantly the present experimental picture on this important parameter.

[1] G. Colangelo, J. Gasser, H. Leutwyler, Phys.Rev.Lett. **86**, 5008 (2001).
G. Colangelo, J. Gasser and H. Leutwyler, Phys.Lett.B **488**, 261 (2000).
M. Knecht et al., Nucl.Phys. **B471**, 445 (1996).
[2] L. Rosselet et al., Phys.Rev.D **15**, 574 (1977).
[3] S. Pislak et al., Phys.Rev.Lett. **87**, 22 (2001).
[4] A. Lai et al., Eur.Phys.J. **C22**, 231 (2001).
[5] J.R. Batley et al., CERN/SPSC 2000-003 (2000).
V. Kekelidze, SPSC/M671, CERN/SPSC 2001-030 (2001).
V. Kekelidze, SPSC/M691, CERN/SPSC 2002-035 (2002).
[6] I. Giomataris et al., Nucl.Instr.Meth. **A376**, 29 (1996).
[7] L. Fausett. Fundamentals of Neural Networks, Prentice-Hall, NJ, 1994.
[8] K. Hagiwara et al., Phys.Rev.D **66**, 010001 (2002).
[9] B. Adeva et al., CERN/SPSLC 95-1 (1995).

Future experimental investigation of the $\pi^+\pi^-$ atom

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The difference ΔE_n between the energy of atomic ns and np states of $A_{2\pi}$ includes the contributions of the vacuum polarisation ΔE_n^{vac}, and of the strong interaction ΔE_n^s effects, where $\Delta E_n^s \sim 2a_0 + a_2$, and a_0 and a_2 are the s-wave $\pi\pi$ scattering lengths with isotopic-spin quantum numbers 0,2 [1,2]. The value of ΔE_n^{vac} is well known from QED calculations [1,3]. For this reason the measurement of ΔE_n will give, in a model independent way, the value of $2a_0 + a_2$ [4,5].

Some possibilities are discussed for measuring the $np - ns$ energy splitting in $(\pi^+\pi^-)$ atoms in experiments with relativistic particle beams, using the electromagnetic field control of annihilation process [6,7]. Significant resonant enhancement of annihilation probability may be observed in an oscillating field. The resonance provides much more spectacular changes in the decay rate than corresponding decay rate changes in a steady field. The position of resonance on the frequency axis gives an additional and more accurate information on the np-ns transition energy, than the data on the ratio between the field-free and dc-field-induced annihilation rates. Numerical results are presented for the states $n = 2$ and $n = 3$.

[1] A. Gashi et al., Nucl. Phys. A **628** (1999) 101.
[2] G. Efimov et al., Sov. J. Nucl. Phys. **44** (1986) 296.
[3] A. Karimkhodzhaev and R.N. Faustov, Sov. J. Nucl. Phys. **29** (1979) 232.
[4] G. Colangelo, J. Gasser and H. Leutwyler, Phys. Lett. B **488** (2000) 261.
[5] M. Knecht et al., Nucl. Phys. B **457** (1995) 513.
[6] L.L. Nemenov and V.D. Ovsiannikov, Phys. Lett. B **514** (2001) 247.
[7] L.L. Nemenov, V.D. Ovsiannikov, E.V. Tchaplyguine, Nucl. Phys. A **710** (2002) 303–328.

Relevance of $K\pi$ atom measurements

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It is pointed out that measurements of the lifetime and of the $2s-2p$ energy level splitting may provide information about the combinations $(a_0^{1/2}-a_0^{3/2})$ and $(2a_0^{1/2}+a_0^{3/2})/3$ of the strong interaction S-wave scattering lengths, with isospins $1/2$ and $3/2$, respectively. Corrections to the nonrelativistic formulas of these quantities can be estimated with the use of the chiral effective lagrangian in the presence of electromagnetism. The combination $(a_0^{1/2}-a_0^{3/2})$ is not sensitive at leading order to the chiral symmetry breaking mechanism, but may provide information about the low energy constant L_5. The combination $(2a_0^{1/2}+a_0^{3/2})/3$ is sensitive to the quark condensate value and to Zweig rule violating effects through its dependences upon the low energy constants $(2L_6+L_8)$ and L_4. The electromagnetic and isospin breaking corrections are estimated to be of the order of a few percent in the lifetime value. For the $2s-2p$ energy level splitting, the first main correction comes from vacuum polarization with a 25% effect. The next corrections come from the other electromagnetic and isospin breaking effects and are of the order of a few percent.

The Roy equations for the πK system

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In the past, πK scattering attracted the interest of experimentalists as well as theorists. Unfortunately, the theoretical analyses of this process often suffered from the low statistics of the experiments and sometimes from over-simplified theoretical assumptions. On the other hand high statistics experimental data became available in the late seventies and eighties which have never been subject of a stringent theoretical analysis. Recently, there has been a revival in the interest in πK scattering: there are indications for a flavour dependence of the size of the quark condensate [1], and as the πK system is the most simple $SU(3)$–process involving kaons, this process is a suitable place to test this dependence; effects of isospin violation in the above process are studied in the framework of ChPT [2] in order to obtain reliable predictions for the two S–wave scattering lengths from the πK bound state experiment of DIRAC [3]; the πK σ–term has been analyzed [4] which can be regarded as an intermediate step towards ambitious calculations for the KN system; and finally πK scattering data were used to investigate the existence of a κ resonance [5].

However, all these calculations strongly depend on reliable experimental data at very low energies. Unfortunately, the available high statistics data start only at about 800 MeV so that one is left with a gap at low energies. It has been shown for the $\pi\pi$ system that solving the Roy-equations is a suitable tool to close this gap [6]. Here we apply this method to the πK system.

Assuming isospin to be a conserved quantity, πK scattering can be described in terms of the isospin–even and –odd amplitudes $F^+(s,t)$ and $F^-(s,t)$, respectively, the crossed channel, $\pi\pi \to K\bar{K}$ is given by $F^{I_t=0}(s,t)$ and $F^{I_t=1}(s,t)$. By combining fixed–t and hyperbolic dispersion relations with at most two subtractions for each of these amplitudes, one can derive twice–subtracted dispersion relations where the two S–wave scattering lengths a_0^+ and a_0^- play the role of the unknown subtraction constants. Projecting these dispersion relations onto partial waves, together with unitarity, yields a set of coupled integral equations for the s– and t–channel partial waves (Roy–equations) with two a priori free parameters a_0^+ and a_0^- [7], e.g.

$$\begin{aligned} g_1^1(t) &= \frac{2\sqrt{2}m_+a_0^-}{3(m_+^2-m_-^2)} + \frac{t}{\pi}\int_{4m_\pi^2}^{\infty}\frac{d\,t'}{t'}\frac{\mathrm{Im}\,g_1^1(t')}{t'-t} \\ &\quad + \frac{1}{\pi}\int_{m_+^2}^{\infty} d\,s'\left\{G_{10}^-(t,s')\mathrm{Im}\,f_0^-(s') + G_{11}^-(t,s')\mathrm{Im}\,f_1^-(s')\right\} + d_1^1(t), \end{aligned}$$

where the G_{ij}^- are the kernel functions and d_1^1 is a so–called driving term accounting for the contributions of the higher partial waves.
Using the available experimental data for the s– and t–channel above 1 GeV and the driving terms as input, one can show — in analogy to the $\pi\pi$–system, see [6] and references therein — that the system of Roy–equations has a unique solution below 1 GeV.

The equations then can be solved in several steps: using a Schenk–type parametrization for the s–channel waves and due to extended unitarity the t–channel partial waves can be

solved by applying Omnès–Muskhelishvili methods. These solutions for the t–channel waves then are used in s–channel equations and by tuning the parameters of the s–channel waves one tries to find the best input/output agreement for the Roy–equations. This procedure generates approximative solutions of the πK Roy–equations for some ranges of values for a_0^+ and a_0^-. However, most of the solutions are not physical and preliminary results indicate that in πK scattering the Roy–equations do not support a universal band, which is a relation between the two S–wave scattering lengths, but one definite point in the a_0^+–a_0^-–plane. Furthermore, these results indicate a value for $a_0^- \equiv (a_0^{1/2} - a_0^{3/2})/3$ which is somewhat larger than what has been predicted by $SU(3)$–ChPT [8], calling thereby for an independent experimental check of the value of a_0^- by the πK bound state experiment of the DIRAC collaboration [3].

[1] J. Stern, hep-ph/9801282; B. Moussallam, Eur. Phys. J. C14 (2000) 111

[2] B. Kubis and U.–G. Meißner, Nucl. Phys. A699:709 (2002)

[3] B. Adeva et al., CERN/SPSC 2000-032, SPSC/P284 Add. 1

[4] M. Frink, B. Kubis, and U.–G. Meißner, Eur. Phys. J. C25:259 (2002); M. Frink, Diploma thesis, Bonn University, unpublished

[5] S.N. Cherry and M.R. Pennington, Nucl. Phys. A 688, 823 (2001)

[6] B. Ananthanarayan, G. Colangelo, J. Gasser, and H. Leutwyler, Phys. Reports 353/4, 207 (2001)

[7] B. Ananthanarayan and P. Büttiker, Eur. Phys. J. C 19, 517 (2001); B. Ananthanarayan, P. Büttiker, and B. Moussallam, Eur. Phys. J. C 22:133 (2001); P. Büttiker, S. Descotes, and B. Moussallam, work in progress

[8] V. Bernard, N. Kaiser, and U.–G. Meißner, Nucl. Phys. B 357, 129 (1991)

$\pi\pi$ scattering and the chiral structures of QCD vacuum

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At low energies, QCD is dominated by the spontaneous breakdown of chiral symmetry which leads to the appearance of pseudoscalar Goldstone bosons π, K, η. Due to the mass hierarchy $m_{u,d} \ll m_s \ll \Lambda_H$, we can consider two different chiral limits:

$$N_f = 2 : \, m_u, m_d \to 0 \,, \; m_s \text{ physical} \,, \qquad N_f = 3 : \, m_u, m_d, m_s \to 0 \,. \tag{9}$$

In both limits, chiral order parameters can be defined, such as the quark condensate: $\Sigma(N_f) = \lim_{N_f} \langle 0|\bar{u}u|0\rangle$, and the pseudoscalar decay constant: $F(N_f) = \lim_{N_f} F_\pi$.

The patterns of chiral symmetry breaking reflected by these parameters can be quite different in the $N_f = 2$ and $N_f = 3$ limits [1]. For instance, the condensates are related through: $\Sigma(2) = \Sigma(3) + m_s Z_{\text{scalar}}$, where $Z_{\text{scalar}} > 0$ describes the violation of the Zweig rule in the scalar sector 0^{++}. There have been recently hints of a significant decrease from $\Sigma(2)$ to $\Sigma(3)$, which would lead to a different low-energy behaviour of the $N_f = 2$ ($\pi\pi$ scattering) and $N_f = 3$ (πK scattering) sectors.

Because of the possibility of a small three-flavour condensate $\Sigma(3)$, more care is needed when dealing with chiral expansions obtained from $N_f = 3$ chiral perturbation theory, e.g.:

$$F_\pi^2 M_\pi^2 = 2m\Sigma(3) + m_q^2[b^q_{\pi Q} \log(M_Q/\mu) + c^q_\pi(\mu)] + F_\pi^2 M_\pi^2 d_\pi \,, \tag{10}$$

$$F_K^2 M_K^2 = (m + m_s)\Sigma(3) + m_q^2[b^q_{KQ} \log(M_Q/\mu) + c^q_K(\mu)] + F_K^2 M_K^2 d_K \,. \tag{11}$$

Next-to-leading-order (NLO) terms contain chiral logarithms ($Q = \pi, K, \eta$), and two low-energy constants L_8 and L_6 (in c_P). L_6 is related to Z_{scalar} and measures how badly the Zweig rule is violated in the scalar sector. The remainders d_P collect NNLO and higher-order terms.

We want to take into account the possibility of a suppressed three-flavour condensate $\Sigma(3)$. We will assume an overall convergence of the chiral series [NNLO remainders $d_\pi, d_K \sim (30\%)^2 \sim 10\%$], but we do *not* make assumptions about the relative sizes of leading- and next-to-leading-order terms. We simply consider the chiral series (10) and (11) as exact identities.

We can first express the three-flavour quark condensate in terms of $F(3)$, r and L_6 [1]:

$$X(3) = \frac{2m\Sigma(3)}{F_\pi^2 M_\pi^2} = 2\frac{1 - \epsilon(r) - d}{1 + \sqrt{1 + \xi}} \,, \qquad \xi = 64 \frac{M_\pi^2}{F_\pi^2}(r + 2)\frac{1 - \epsilon(r) - d}{Z(3)}(L_6 - L_6^{\text{crit}}) \,, \tag{12}$$

where $r = m_s/m$, $Z(3) = [F(3)/F_\pi]^2$, $\epsilon(r) < 0.2$ for $r > 15$ and L_6^{crit} depends (weakly) on r only ($L_6^{\text{crit}}(M_\rho) = -0.26 \cdot 10^{-3}$ for $r = 25$). The NNLO remainder d is estimated as $d \sim d_\pi \sim 10\%$. The square root arising in eq. (12) indicates the nonperturbative resummation of Zweig-rule violating effects. It is expanded in the standard treatment of χPT, assuming $\xi \ll 1$ – inspired

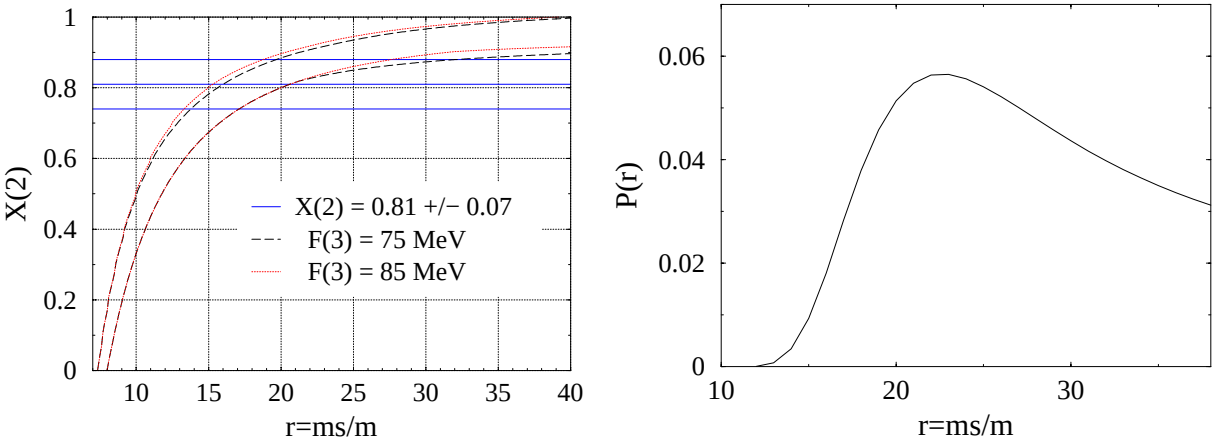
by large-N_c expectations. But a small shift of L_6 from $L_6^{\rm crit}$ of a few 10^{-3} would be magnified by the huge scaling factor $64M_\pi^2(r+2)/F_\pi^2 \sim 4\cdot 10^3$, leading to a damping of $X(3)$.

For the two-flavour quark condensate, the chiral expansions of $F_\pi^2 M_\pi^2$ and $F_K^2 M_K^2$ yield [2]:

$$X(2)[1-\bar{d}_\pi] = X(3) + \frac{r}{r+2}\Big\{[1-X(3)] - \epsilon(r) - d - f[X(3)/Z(3)]^2\Big\}\,, \qquad (13)$$

where $\bar{d}_\pi \sim d_\pi \pm 3\%$ and f is a function of chiral logarithms in the $N_f = 2$ chiral limit ($0.03 \leq f \leq 0.06$). The two-flavour quark condensate $X(2)$ is therefore the sum of two terms: a genuine condensate $X(3)$ and an induced condensate proportional to m_s. For large r ($r > 15$), $X(2)$ remains close to 1 for any size of $X(3)$ due to a compensation from the induced condensate. This phenomenon can be interpreted in terms of the density and fluctuation of small eigenvalues of the Euclidean Dirac operator [2].

$X(2)$ is weakly correlated with the pattern of $N_f = 3$ chiral symmetry breaking, but strongly correlated with the value of the quark mass ratio r [1], as seen from the plot on the left.



Accurate measurements of $\pi\pi$ scattering would pin down $N_f = 2$ chiral order parameters, but would only constrain mildly the pattern of $N_f = 3$ chiral symmetry breaking. The analysis of available $\pi\pi$ data [3] leads to $X(2) = 0.81 \pm 0.07$, implying that $r \geq 15$. The Bayesian approach allows one to express more quantitatively this statement and to combine results concerning different observables [4]. The plot on the right side is a typical outcome, exploiting the $\pi\pi$ results for $X(2)$ and $Z(2)$ to determine the posterior probability of the quark mass ratio r. We see that the current $\pi\pi$ data rule out small values of r (< 15) and favours slightly $r \sim 20$. Including observables from the $N_f = 3$ sector (πK scattering, $\eta \to 3\pi$) within this framework should finally elucidate the $N_f = 2$ and $N_f = 3$ chiral structures of QCD vacuum.

[1] S. Descotes-Genon and J. Stern, Phys. Lett. B **488** (2000) 274 [arXiv:hep-ph/0007082].
S. Descotes-Genon, JHEP **0103** (2001) 002 [arXiv:hep-ph/0012221] and references therein.

[2] J. Stern's talk in these proceedings.
S. Descotes-Genon, L. Girlanda and J. Stern, JHEP **0001** (2000) 041 [arXiv:hep-ph/9910537].
S. Descotes-Genon, L. Girlanda and J. Stern, arXiv:hep-ph/0207337.

[3] L. Girlanda's talk in these proceedings.
S. Descotes-Genon *et al.*, Eur. Phys. J. C **24** (2002) 469 [arXiv:hep-ph/0112088].

[4] S. Descotes-Genon, N. H. Fuchs, L. Girlanda and J. Stern, work in progress.

On the role of multi-photon exchanges in the incoherent interaction of $\pi^+\pi^-$-atom with atoms of matter[5]

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The Glauber theory for interaction of hydrogen-like elementary atoms (EA) with target atoms (TA), developed in the papers [1-3], is essentially based on the assumption that the Coulomb potential, created by TA, does not change during the EA–TA interaction. In other words, in this approximation all possible excitations of TA in intermediate and/or in finale states are completely neglected.

The Glauber theory corrected to account these effects is too cumbersome. Here we list the simplest results of this theory concerning the total cross sections of EA–TA interactions.

$$\sigma^{tot}(i) = \sigma^{tot}_{coh}(i) + \sigma^{tot}_{incoh}(i) \tag{14}$$

$$\sigma^{tot}_{coh,incoh}(i) = \int d^3r |\Psi_i(\vec{r})|^2 d^2b \Gamma(\vec{b},\vec{s})_{coh,incoh} \tag{15}$$

$$\Gamma(\vec{b},\vec{s})_{coh} = 1 - 2\cos\left[\Delta\chi(b,s)\right]\exp\left[-\Phi(b,s)/2\right] + \exp\left[-\Phi(b,s)\right] \tag{16}$$

$$\Gamma(\vec{b},\vec{s})_{incoh} = 1 - \exp\left[-\Phi(b,s)\right] \tag{17}$$

$$\Delta\chi(b,s) = \frac{2Z\alpha}{\beta}\int\frac{d^2q}{q^2}\left(e^{i\vec{q}\vec{b}_+} - e^{i\vec{q}\vec{b}_-}\right)\left[1 - S_1(\vec{q})\right] \tag{18}$$

$$\Phi(b,s) = \frac{4Z\alpha^2}{\beta^2}\int\frac{d^2q_1}{q_1^2}\frac{d^2q_2}{q_2^2}\left(e^{i\vec{q_1}\vec{b}_+} - e^{i\vec{q_1}\vec{b}_-}\right)\left(e^{-i\vec{q_2}\vec{b}_+} - e^{-i\vec{q_2}\vec{b}_-}\right)W(\vec{q_1},\vec{q_2}) \tag{19}$$

$$W(\vec{q_1},\vec{q_2}) = S_1(\vec{q_1}-\vec{q_2}) - S_1(\vec{q_1})S_1(\vec{q_2}) + (Z-1)[S_2(\vec{q_1},\vec{q_2}) - S_1(\vec{q_1})S_1(\vec{q_2})] \tag{20}$$

$$S_1(\vec{q}) = \int d^3r e^{i\vec{q}\vec{r}}\rho_1(\vec{r})\,, \qquad \int d^3r\rho_1(\vec{r}) = 1 \tag{21}$$

$$S_2(\vec{q_1},\vec{q_2}) = \int d^3r_1 d^3r_2 e^{i\vec{q_1}\vec{r_1} - i\vec{q_2}\vec{r_2}}\rho(\vec{q_1},\vec{q_2})\,, \qquad \int d^3r_2\rho_2(\vec{r_1},\vec{r_2}) = \rho_1(\vec{r_1}) \tag{22}$$

$$\vec{b}_\pm = \vec{b} \pm \vec{s}/2\,, \qquad \vec{s} = \vec{r}_\perp \tag{23}$$

$$W(\vec{q},\vec{q}) = S_{incoh}(\vec{q}) \tag{24}$$

Here $\rho_{1,2}$ are one-particle and two-particle electron densities of the target atom, $\sigma^{tot}_{coh,incoh}$ are the total cross sections of EA–TA interactions without or with excitation of the target atom. Φ in the above equations accounts the target atom evitation both in intermediate and in final

[5]The report was not presented because of a visa problem

states. If one put $\Phi = 0$ then Eqs.(1-4) turns to the corresponding relations of papers [1-3]. In particular in this limit $\sigma_{incoh} = 0$. Relative corrections to σ^{tot}_{coh} caused by including intermediate incoherent effects are of order

$$Z^3\alpha^4\frac{\langle r^2\rangle_{EA}}{\langle r^2\rangle_{TA}}\ln\left(\frac{\langle r^2\rangle_{EA}}{\langle r^2\rangle_{TA}}\right) \ll 1 \tag{25}$$

and can be successfully neglected. The same is also true for all partial coherent cross sections. From these estimations it follows that the theory of papers [1-3] provides quite accurate description of the coherent sector of EA–TA interactions.

As for incoherent interactions, it follows from Eq.(4), that they can be described by the Born approximation with the relative accuracy of order

$$Z\alpha^2\frac{\langle r^2\rangle_{EA}}{\langle r^2\rangle_{TA}}\ln\left(\frac{\langle r^2\rangle_{EA}}{\langle r^2\rangle_{TA}}\right). \tag{26}$$

The results of performed analysis can be summarized as follows:

1. for description of the coherent interactions of EA with TA it is enough to use the simplified version of the Glauber theory neglecting effect of intermediate excitation of TA;

2. for description of the in coherent interactions of EA with TA it is enough to use the Born approximation. Just such prescriptions based on an intuitive consideration have been proposed by authors of paper [3].

[1] O.O.Voskresenskaya, S.R.Gevorkyan and A.V.Tarasov: Yad.Fiz. **61**, 1628 (1998); Phys.Atom.Nucl. **61**, 1517 (1998)

[2] L. Afanasyev, A.Tarasov and O.Voskresenskaya, J.Phys. G 25 (1999) B7–B10.

[3] M.Schumann, T.Heim, K.Hencken, D.Trautmann and G.Baur, J. Phys. B: 35 (2002) 2683–2692

Concluding remarks

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In the first part of the talk, I illustrated the relevance of low energy pion physics for our current understanding of the basic interactions, using the example of the Standard Model prediction for the muon magnetic moment. I then discussed the remarkable recent progress achieved in $\pi\pi$ scattering, which now has become a precision science: in combination with the low energy theorems of Chiral Perturbation Theory for the S-wave scattering lengths, the dispersion relations for the partial waves (Roy equations) pin down the scattering amplitude to an amazing degree of accuracy [1-3] – for once in strong interaction physics, theory is ahead of experiment. The recent K_{e_4} data from Brookhaven [4] offer a rough test of one of the hypotheses that underly the theoretical framework, as they show that the quark condensate indeed represents the leading order parameter of the spontaneously broken chiral symmetry. Generalized ChPT has served its purpose and can now be dismissed.

The Roy equations involve two subtraction constants, which may be identified with the two S-wave scattering lengths. K_{e_4} decays are sensitive to one particular combination of these. The forthcoming results from NA48/2 are eagerly awaited as they will narrow down the uncertainty in the experimental information about this combination [5]. The low energy theorem for the scalar radius involves a different combination, but this theorem has not been subject to experimental test. The importance of such a test was thoroughly discussed at this meeting [6-8]. A somewhat more precise determination of the I = 2 $\pi\pi$ phase shift may become possible at the COMPASS detector at CERN [9] and, as pointed out by L. Montanet, there are beautiful data on other processes with two-pion configurations in the final state, such as $D \to 3\pi$, which may also help to narrow down the experimental uncertainties.

The ideal laboratory for exploring the low energy properties of the pions, however, is the atom consisting of a pair of charged pions, also referred to as pionium. The DIRAC collaboration at CERN has demonstrated that it is possible to generate such atoms and to measure their lifetime [10]. Since the physics of the bound state is well understood [11-13], the low energy properties of the scattering amplitude can unambiguously be determined by studying these. It would be most deplorable if this beautiful project were aborted before its physics potential [14] is tapped. In particular, pionium level splittings would offer a clean and direct measurement of the second subtraction constant. Data on πK atoms would also be very valuable, as they would allow us to explore the role played by the strange quarks in the QCD vacuum [15,16].

Experimentally, pionic hydrogen has been explored very successfully [17]. Also, there is significant progress in the physics of the bound state [18-20]. The main problem here is that the ChPT predictions for the scattering lengths have large uncertainties. At this time, accurate results can only be obtained in the unphysical region of πN scattering. Dispersion theory is needed to confront these with data at or above threshold. An analogue of the Roy equations has been formulated [21], but the framework yet needs to be implemented. A comprehensive dispersive analysis of the πN scattering amplitude was carried out by G. Höhler and collaborators 20 years ago [22]. An update of that analysis is under way, but will take some time for completion [23]. Currently, the Standard Model predictions for pionic hydrogen are too uncertain to draw physics conclusions from the available, beautiful data, concerning the size of

the σ-term, for instance. The same applies to the predictions for KN atoms, which are under investigation in the DEAR experiment at Frascati [24].

There is plenty of work to be done in the field of hadronic atoms. Quite a few experimentally accessible quantities can be calculated from first principles. By confronting theory with experiment, we can critically examine our understanding of the laws of nature.

[1] B. Ananthanarayan *et al.*, Phys. Rept. **353** (2001) 207, hep-ph/0005297

[2] G. Colangelo *et al.*, Nucl. Phys. B **603** (2001) 125, hep-ph/0103088

[3] S. Descotes *et al.*, Eur. Phys. J. C **24** (2002) 469, hep-ph/0112088

[4] S. Pislak *et al.* [BNL-E865 Collaboration], Phys. Rev. Lett. **87** (2001) 221801, hep-ex/0106071

[5] C. Cheshkov, *Prospects for the study of $K^+_{e_4}$ decays at the NA48/2 experiment**

[6] L. Girlanda, *Need for new $\pi\pi$ scattering data**

[7] J. Stern, *Massive $\bar{s}s$ pairs and $\pi\pi$ scattering**

[8] S. Descotes-Genon, *$\pi\pi$ scattering and the chiral structure of QCD vacuum**

[9] J. Gasser, talk given at Future Physics @ COMPASS, http://compass-cw2002.web.cern.ch

[10] V. Yazkov, *Lifetime measurement of $\pi^+\pi^-$ atom at DIRAC**

[11] The subject was thoroughly discussed at the preceeding workshop of this series, see the miniproceedings edited by J. Gasser, A. Rusetsky and J. Schacher, hep-ph/0112293

[12] T. Heim, *Coupled channel approach to breakup of pionium**

[13] C. Santamarina, *On the dependence of pionium breakup probability on low and high n bound states cross sections**

[14] L. Nemenow, *Future experimental investigation of the $\pi^+\pi^-$ atom**

[15] H. Sazdjian, *Relevance of the $K\pi$ atom measurements**

[16] P. Büttiker, *The Roy equations for the πK system**

[17] D. Gotta, The pionic hydrogen experiment at PSI*

[18] J. Gasser, *Ground-state energy of pionic hydrogen to one loop**

[19] S. Karshenboim, *QED theory of hydrogen-like atom**

[20] G. Oades, *The influence of the γn channel on the energy and width of pionic hydrogen**

[21] T. Becher and H. Leutwyler, JHEP **0106** (2001) 017, hep-ph/0103263

[22] G. Höhler, in Landolt-Börnstein, **9b2**, ed. H. Schopper (Springer, Berlin, 1983)

[23] M. Sainio, private communication

[24] C. Guaraldo, *Recent results from DEAR at DAFNE**

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* Talk presented at this meeting