To

BV 37 PSI 2006

from the

PIONIC HYDROGEN COLLABORATION

EXPERIMENT R-98.01

1. ADDENDUM: PIONIC DEUTERIUM

2. STATUS PIONIC HYDROGEN

3. BEAM TIME REQUEST 2006

Summary

1. Proposed pionic deuterium measurement

Newest theoretical developments in the treatment of isospin breaking corrections in the πD scattering length should be combined with existing high precision data in πH (from experiment R-98.01) and with the here proposed πD measurement in order to substantially improve the values for the πN isospin scattering lengths a^+ and a^-. In consequence, much improved values for the πN σ-term and the πN coupling constant will be obtained. Therefore a new measurement of the πD system constitutes a **natural completion of experiment R-98.01**.

As a particular case in the field of low-energy hadron physics, the hadronic shift in πD is very sensitive to the isospin-breaking corrections. Secondly, the hadronic width is directly related to NN↔NNπ processes at threshold, which will become calculable at the % level within the framework of Chiral Perturbation Theory (ChiPT) in the near future.

The proposed measurement implies, even more together with the forthcoming improvement on the low-energy constants (LECs) c_1 and f_2, a substantially improved value for the LEC f_1.

2. Status of the pionic hydrogen experiment

Data taking for hydrogen has been finished in 2005 with a high statistics measurement of the πH(2p-1s) transition.

3. Beam time request 2006

For πD in a 4 weeks period of data taking the envisaged accuracy is achievable for the hadronic shift and width. In addition 2 weeks for setting up in the πE5 area are needed.

1. Addendum to proposal R-98.01: PIONIC DEUTERIUM

Status

The most precise experimental values for the strong-interaction shift ε_{1s} and width Γ_{1s} in pionic deuterium (πD) are reported to be (*P. Hauser et al., Phys. Rev. C 58 (1998) R1869*)

$$\varepsilon_{1s} = -2468 \pm 55 \text{ meV } (\pm 2.2\%)$$
$$\Gamma_{1s} = 1193 \pm 129 \text{ meV } (\pm 11\%).$$

The result of a previous experiment is in good agreement but a factor of about two less precise (*D. Chatellard et al., Nucl. Phys. A 625 (1997) 855*).

***It is proposed* to measure the hadronic shift ε_{1s} in pionic deuterium to 0.5%.**

The same data will allow a decrease of the uncertainty of Γ_{1s} by a factor of 3.

Motivation

In the multiple-scattering theory π^-p and π^-n interactions almost cancel each other in pionic deuterium at leading order. This is immediately seen from the fact, that the hadronic shift ε_{1s} in πD is almost a factor of 3 smaller than in pionic hydrogen which amounts to 7.1 eV. Such small leading order contributions (LO) enhance the importance of effects otherwise hidden if the higher order terms are well under control. The hadronic width Γ_{1s} in πD is of the same order of magnitude than in πH (0.8 eV), but of completely different origin because of pion absorption. Real and imaginary part of the πD scattering length, Re $a_{\pi D}$ and Im $a_{\pi D}$, are related to the atomic level shift and width by Deser's formula

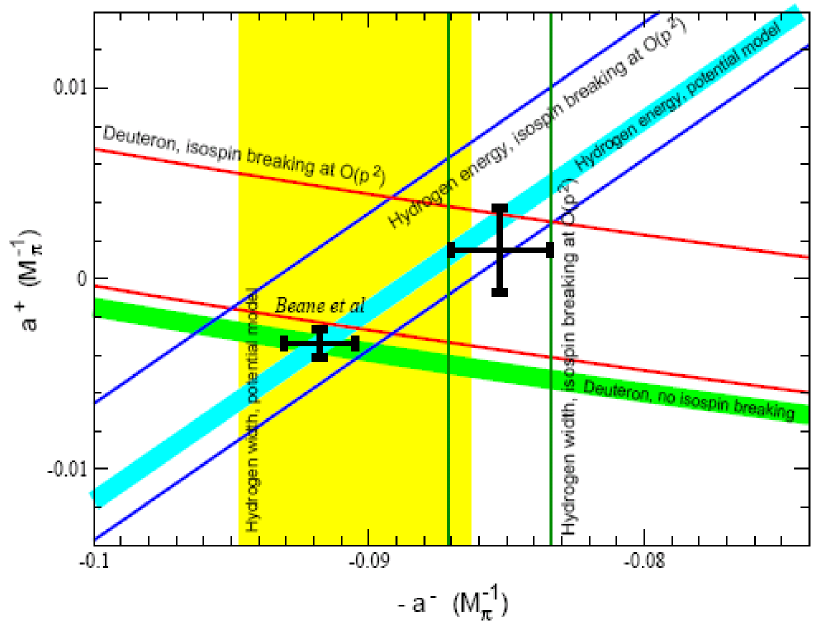
$$\varepsilon_{1s} + i\,\Gamma_{1s}/2 = -2\,\alpha^3\, m_{red}^2 \cdot a_{\pi d}.$$

Re $a_{\pi D}$ can be expressed in terms of the elementary πN amplitudes at threshold, the isoscalar and isovector scattering lengths a^+ and a^-, and includes multi-body and nuclear structure effects (*T. E. O. Ericson, B. Loiseau, A. W. Thomas, Phys. Rev. C 66 (2002) 014005*).

The present situation for the πN scattering lengths a^+ and a^- from analyses within the framework of Chiral Perturbation Theory (ChiPT) is summarised in Fig. 1 (taken from *U.-G. Meißner, U. Raha, and A. Rusetsky, arXiv:nucl-th/0512035, further to be referred as **MRR***). Three constraints are obtained from πH ε_{1s}, πH Γ_{1s}, and πD ε_{1s} for a^+ and a^- and are displayed as shaded bands and boundary lines. The vertical and the diagonal shaded bands correspond to the πH data of the previous experiment (*H.-C. Schröder et al., Eur. Phys. J. C21 (2001) 473*) where the isospin-breaking corrections were calculated in a potential model. The third almost horizontal line displays the correlation between a^+ and a^- using the πD shift without such corrections. The resulting values for the πN scattering lengths a^+ and a^- from a combined πH/πD analysis (*Beane et al., Nucl. Phys. A 720 (2003) 399*) are inconsistent with the smaller value for πH Γ_{1s} obtained from experiment R-98.01 (vertical green boundaries). See also Fig. 5.

Considerable theoretical progress within the ChiPT framework was achieved recently, when isospin breaking corrections are included both for πH and πD. When using the corrections obtained from 3rd order ChiPT calculations for πH ε_{1s} (*J.Gasser et al., Eur. Phys. J. C21 (2002) 13*) and 2nd order calculations for πH Γ_{1s} (*P. Zemp (PhD thesis) and J.Gasser, in* *preparation*), the result of the πD analysis (***MRR***) is now consistent with the values obtained from the πH data of experiment R-98.01. The nearly cancellation of the LO leads to a large correction of 40% from the leading-order isospin-breaking term. Typical higher-order isospin-breaking contributions that are dependent on the deuteron structure turn out to be a few % only. In that order the three low-energy constants (LECs) c_1,f_1 and f_2 appear. It is noteworthy, that the uncertainty of both πH and πD shift are caused by the <u>same</u> combination of the 2 LECs c_1, and f_1, denoted here $F_{LEC}(c_1,f_1)$, where f_1 essentially determines the error.

As the accuracy for Γ_{1s} in πH is expected to increase from the recently collected πH(2p-1s) high-statistics data (see below), the constraint on a^- is further improved by a factor of two. Given such a precise set of data, πH ε_{1s}, πH Γ_{1s} and πD ε_{1s}, a correlated fit to a^+, a^- and the combination of c_1 and f_1 leads to more precise values for both the scattering lengths and F_{LEC}.



<u>Fig. 1:</u> Isoscalar and isovector πN scattering lengths a^+ and a^- as obtained within ChiPT calculations from πH ε_{1s} (blue boundaries bottom left to top right), πH Γ_{1s} (vertical green boundaries) and πD ε_{1s} (red boundaries) (from ***MRR***). Left cross: ChiPT πD analysis (*Beane et al.*) without isospin-breaking corrections for πD; right cross: 2nd order ChiPT calculation including πD isospin-breaking corrections (***MRR***). The shaded areas are due to the analysis of the previous experiment using a potential model (see text) See also Fig. 5.

In other words, **the πD system is an ideal laboratory for a precise test of isospin-breaking corrections**. In view of the sizable 2nd order effects contributions of 3rd order maybe still significant and their calculation is given high priority in the theory community. This in turn requires precise πD data in order to obtain ε_{1s} at the level of 1% or better.

To summarize, a more precise determination of the **shift ε_{1s} in πD** is desirable because

- It provides a consistency check of the calculations for πH and πD within the framework of ChiPT: the 3 bands πH shift and width and πD shift **must cross!**
- The nearly cancellation of the LO terms in πD leads to a large sensitivity on isospin-breaking effects (about 40%) allowing a decisive test of the method. Usually isospin-breaking effects in any $\pi^{\pm}$N interaction amount to a few percent only and, hence, can hardly be extracted (an exception is in the pn$\rightarrow\pi^0$d backward/forward asymmetry – see below).

- The same combination of the LECs of c_1, and f_1 enters both in piH and piD shift, which allows for a correlated fit (***MRR***, *eq. 7-9*). Assuming small experimental errors of πH and πD it yields (i) more precise values for a^+ and a^-, and, (ii) it leads to a better determination of f_1. An extension to calculations in 3rd order requires better experimental accuracy for a sensitive test.
- More precise values for the scattering lengths a^+ and a^- will allow for an improved determination of the πN σ-term (from a^+) and πN coupling constant (from a^-).
- The accuracy of c_1 is expected to improve substantially from the results of a forthcoming πN phase shift analysis (*M. Sainio, priv. comm.*). In addition, the accuracy of f_2 is expected to improve from 40% to 20% from $pn\rightarrow\pi^0 d$ backward/forward asymmetry (*C. Hanhart, priv. comm.*). Due to the sensitivity to f_2, this reaction is in a perfect way complementary to πD measurements. This will lead to another significant improvement on the accuracy of f_1.
- Within the framework of ChiPT, a better knowledge of the LEC f_2 leads to a better constraint on the proton-neutron mass difference, where f_1 enters in the expression of the total hadronic masses (*N. Fettes, U.-G. Meißner, Nucl. Phys. A 693 (2001) 693*).

The imaginary part of the πD scattering lengths, Im $a_{\pi D}$, is obtained from the **1s level broadening Γ_{1s}** by Deser's formula and accounts for the two absorption channels $d\pi^- \rightarrow nn$ and $d\pi^- \rightarrow nn\gamma$. The quantity Im $a_{\pi D}$ is directly related to pion production, which is at present a field of significant theoretical effort within the framework of ChiPT (*V. Lensky et al., arXiv:nucl-th/0511054*). The production reaction $pp \rightarrow d\pi^+$ is connected to absorption $d\pi^+ \rightarrow pp$ by detailed balance, which in the case of charge symmetry is equal to $d\pi^- \rightarrow nn$. Extrapolating the scattering data to threshold and correcting the πD hadronic width for radiative capture $d\pi^- \rightarrow nn\gamma$, the same value for Im $a_{\pi D}$ should be obtained both from scattering and atom data. At present, Im $a_{\pi D}$ is calculated by ChiPT to 30% accuracy, but an improvement to better than 10% is expected soon. For Γ_{1s}, from the same data set an improvement by a factor of about 3 can be expected.

Design of the experiment

In pionic deuterium, the radiative de-excitation from molecular states is predicted to be enhanced significantly compared to hydrogen (*S. Kilic et al., Phys. Rev. A 70 (2004) 042506*). Therefore, at present a significant shift of the observed transition energy of the πD(np-1s) transitions due to molecular X-rays cannot be excluded, and must be investigated. As in the case of πH, the formation probability depends on the collision rate and, hence, on the target density. Consequently, we aim at the measurement of the density dependence of the energy of the πD(3p-1s) transition. Three different (equivalent) target pressures are foreseen: 3.5 bar, 28 bar, and LD_2. Extrapolating the measured value of the transition energy to density zero yields the pure hadronic contribution to the level shift.

Line yields are expected to be equal for πH and πD. Based on the experience of the πH runs, we expect 5000 events in πD(3p-1s) transition for 28 bar equivalent density in a little bit less than one week (Fig. 2 – left and Tab. 1). At lower and higher densities, about 1½ weeks per density point are necessary. Hence, in total **4 weeks of data taking** are sufficient to explore the density dependence and to determine the line position to the envisaged accuracy.

The final accuracy depends on the possible appearance of satellites owing to radiative de-excitation from molecular states. If no energy shift is observed, one can conclude the absence of near-lying unresolved satellites and the full statistics can be used for the determination of the hadronic shift. In this case an accuracy of 0.5% is achievable (Fig. 3). If the hadronic shift has to be derived from the extrapolation to zero density, the final accuracy will be about 1%.

The πD(3p-1s) transition is the most promising case, because as energy calibration the precisely measured Ga Kα fluorescence radiation is available (*R. D. Deslattes et al., Rev. Mod. Phys. 75 (2003) 35*). The X-rays will be excited by means of an X-ray tube at a Ga target positioned at the location of the gas cell containing D_2. High statistics is obtainable in short time (Fig. 2 - right).

Tab. 1: Transition energies and Bragg angles for a silicon 111 crystal. πD and Ga Kα X-rays will be measured in 1st and 3rd order, respectively. The crystal response has been measured to 400 meV (FWHM) with the 3104 eV M1 transition in helium-like Ar (ECRIT run 2004).

	energy / eV	reflection	Θ_{Bragg}	density / bar	counts / 500 Cb
πD(3p-1s)	3075.160 ± 0.055	Si 111	40.01°	3.5	5000
				28	2000
				LD_2	2000
Ga $K\alpha_2$	9224.840 ± 0.027	Si 333	40.01°		
Ga $K\alpha_1$	9257.670 ± 0.066	Si 333	39.84°		

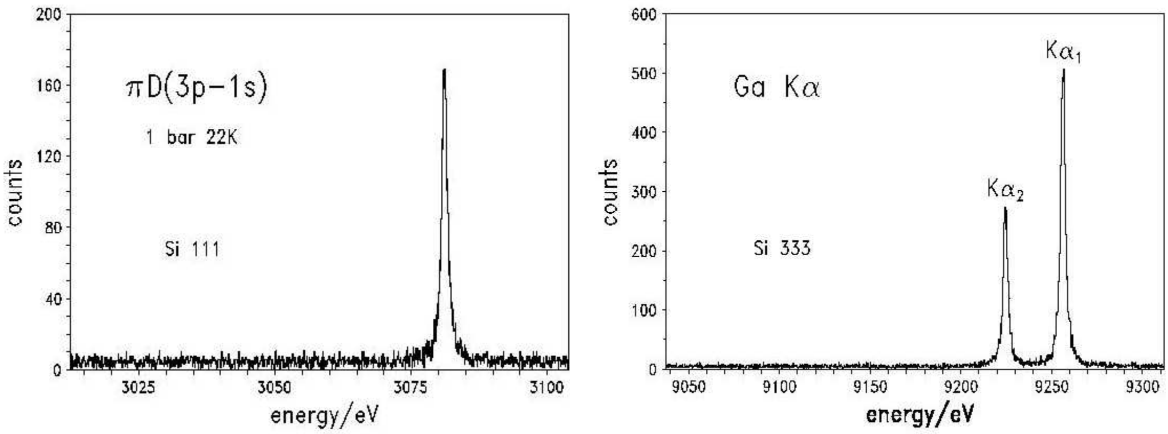


Fig. 2: Left – Monte-Carlo simulation of the πD(3p-1s) transition for 500 Cb integrated accelerator current at intermediate densities, which corresponds to about 4 days data taking at full beam. The πD reflection is positioned at the high-energy edge of the detector to allow the observation of possible satellite due to molecular formation. **Right** – Monte-Carlo generated spectrum of the Ga Kα doublet to be excited by means of an X-ray tube.

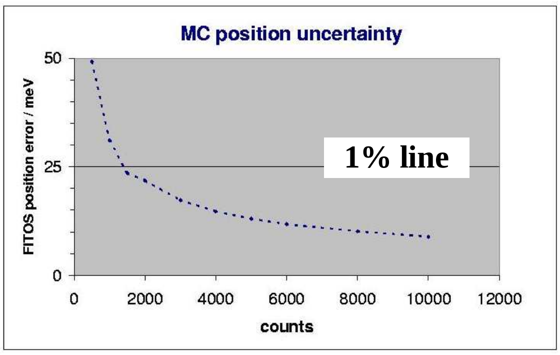


Fig. 3: Relative uncertainty of the energy of the πD(3p-1s) transition as a function of the count rate (Monte-Carlo simulation).

2. Status of experiment R-98.01 (December 2005)

Experimental activities 2005:

- ECRIT: The tests of the crystal response with the Electron-Cyclotron-Resonance Ion Trap (ECRIT) have been completed middle of 2005 using X-rays from helium-like argon. Together with the ECRIT data from 2004, a precise knowledge of the resolution function of all Bragg crystals used in the πH experiment is now available.
- The measuring period in September and October 2005 in the πE5 area has been used to collect a high statistics spectrum of a πH line. The optimum conditions were found for the πH(2p-1s) transitions. In total, almost 40000 events have been accumulated during 5 weeks continuous running (Fig. 4 - left).

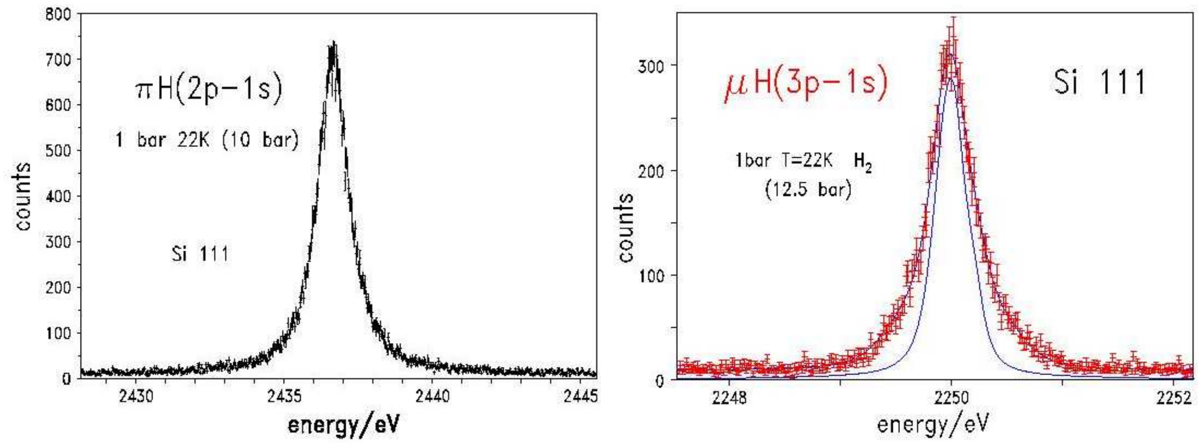


Fig. 4: **Left** - High statistics spectrum of the πH(2p-1s) transition accumulated in a 5 week measuring period (3300 Cb integrated accelerator current) in 2005 using a silicon 111 Bragg crystal. **Right** - Spectrum of the μH(3p-1s) transition. The solid line shows the crystal response as determined from the measurement using X-rays from the ECRIT.

Status of analysis

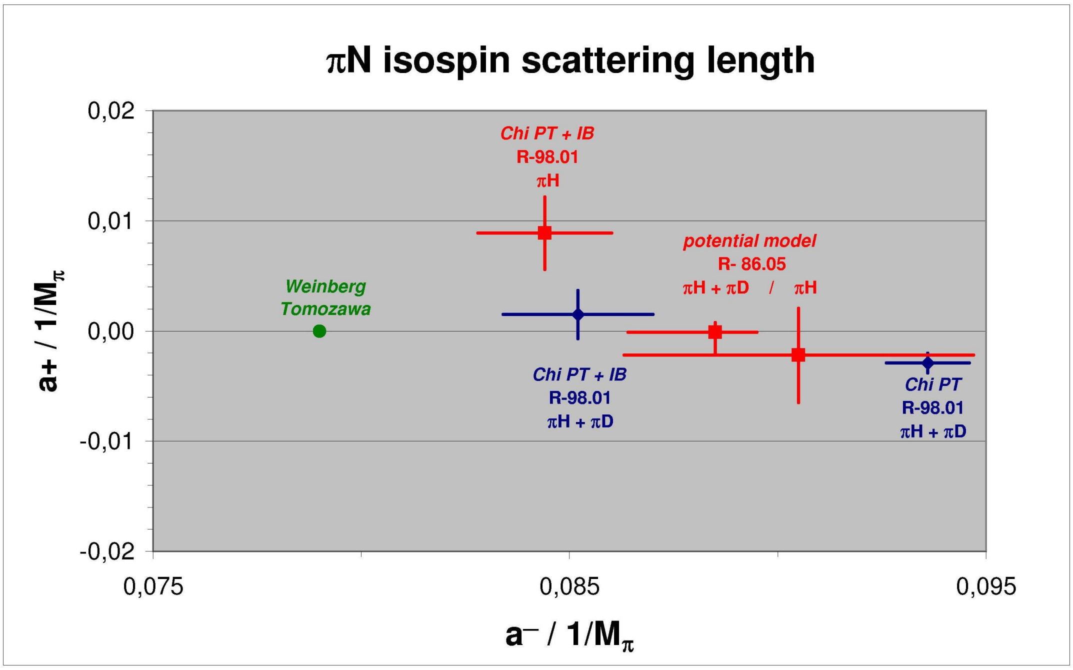
- The analysis of the ECRIT data showed, that the geometrical properties of the spherically bent Bragg crystals are well understood. A re-measurement of the curvature radii at the Carl Zeiss company, Oberkochen, is in good agreement with the data obtained from focal scans using the X-rays of the ECRIT.
- The analysis of the pion mass experiment (R-97.01) has been finished and led to a finished thesis at the University Pierre et Marie Curie (LKB), Paris. The final error achieved is 1.8ppm. A publication is in preparation.
- The μH(3p-1s) transition measured in December 2004 has been pre-analysed (Fig. 4 – right). The deviation of the data points from the response function results from acceleration effects owing to Coulomb de-excitation to be determined. It can be concluded even now, that the statistics is sufficient to extract the necessary information on the Coulomb de-excitation. Within the statistical accuracy collected no satellite lines from molecular formation could be identified.
  An important side result is that the spin triplet-to-singlet ratio is consistent with a statistical population of 3:1 for the μH 1s hyperfine level. The (preliminary) value from a fit to the μH(3p-1s) spectrum shown above is 3.0±0.2.
- The analysis of the πH data from the measurements in 2001 and 2002 is almost finished. The value for the strong shift ε_{1s} slightly changes because of a new and more precise

calculation of the pure electromagnetic transition energies (*P. Indelicato et al., priv. comm.*). The theoretical error is now reported to be ± 1 meV! The value for the width is calculated as the weighted average of 5 measurements (πH(2p-1s), πH(3p-1s), πH(4p-1s) at 10 bar equivalent density and πH(3p-1s) in addition at 28 bar and for LH_2).

$$\varepsilon_{1s} = 7116 \pm 8\,(\text{stat.}) \pm 7\,(\text{sys.})\ \text{meV}$$
$$\Gamma_{1s} = 785 \pm 27\ \text{meV}\ (\pm 3.5\%).$$

The value for the Γ_{1s} is significantly smaller than the one reported by the previous experiment: ε_{1s} = 7108±36 meV, Γ_{1s} = 868± 55 meV (R-86.05 - ETHZ-PSI: *D. Sigg et al., Nucl. Phys. A 609 (1996) 269, H.-C. Schröder et al., Eur. Phys. J. C 21 (2001) 473*).

- The analysis of the new πH(2p-1s) data is going on. We expect an improvement of about two in the accuracy of the hadronic broadening, which represents the experimental limit achievable nowadays.
- The values obtained for the scattering lengths a^+ and a^- from the analysis of the πH 2001 and 2002 data are compared to the final results from the previous experiment R-86.05 (*H.-C. Schröder et al.*). The data from experiment R-86.05 were theoretically interpreted in a potential approach (*D. Sigg et al., Nucl. Phys. A 609 (1996) 310*). The new data from R-98.01 are based on ChiPT calculations. Obviously, in the case of πD a huge shift must be attributed to the first order isospin-breaking correction (***ChiPT* πH+πD** ⟶ ***ChiPT* + *IB* πH+πD**), which demonstrates the need for higher order calculations (Fig. 5).



<u>**Fig. 5:**</u> Isoscalar and isovector πN scattering lengths a^+ and a^- as obtained from the previous (R86.05 πH/πH+πD) and the new pionic hydrogen experiment (R-98.01 πH). The data point ***ChiPT* πH+πD** is due to the extraction of a^+ and a^- within the framework of 2nd order ChiPT (*Beane et al.*). Including leading order isospin-breaking corrections such an analysis leads to results (***ChiPT* + *IB* πH+πD**, ***MRR***) much closer to the R-98.01 result (***ChiPT* + *IB* πH**). These two ChiPT analyses use the R-98.01 πH and the *Hauser et al.* πD data. For comparison the current algebra result (*Weinberg, Tomozawa, 1966*) representing the LO of CHiPT is shown.

3. Beam-time request

Tentative schedule for 2006

From January on — Preparation of the πD measurement. The experiment will be ready for installation from April 2006 on.

From about October on, an improved CCD detector will be available. Therefore, beam time as late as possible in 2006 is preferred. Data taking is possible earlier, but with reduced performance of the X-ray detector.

Beam request 2006

- ***Preferred date: as late as possible in 2006***
- ***Allocation to πE5 area***
- ***Maximum beam intensity***
- ***2 weeks set-up in the area***
- ***4 weeks for the measurement of pionic deuterium at 3 different target densities (includes cleaning of area)***

Outlook

The (additional) measurement of the πD strong interaction effects completes the data taking within the project PIONIC HYDROGEN. Final results and publication of the results is envisaged until end of 2008.

For the PIONIC HYDROGEN collaboration

Detlev Gotta

cc: C. Hofmann, BV chairperson
C. Petitjean, beam coordinator