**Experimental checks of precise QCD predictions
by studying the π+K−, K+π− and π+π− atoms**

ABSTRACT: The lifetime of the short-lived *πK* atoms (,  ), *τth* = 3.5 × 10−15 *s* in the ground state, is given [1] within 1% [2] by the *S*-wave *πK* scattering length combination  (1/2 and 3/2 are the isospin values). For the short-lived *π+π−* atom ( ) in the ground state, the lifetime of *τth* = 2.9 × 10−15 *s* is related [3] with a precision of about 0.6% [4] to the S-wave *ππ* scattering length combination  (0 and 2 are the isospin values). Furthermore, the study of long-lived  states (*s* ) allows to measure the Lamb shift [5,6,7] depending on another *ππ* scattering length combination () [8,9]. Therefore, the investigation of dimesonic atoms is the tool to measure model-independently *πK* and *ππ* scattering lengths, which have been calculated precisely in the framework of LQCD (Lattice QCD) and ChPT (Chiral Perturbation Theory). Up to now, dimesonic atoms have been investigated only in the experiment DIRAC, using the CERN PS 24 *GeV/c* proton beam. At present time, the DIRAC collaboration continues to processing collected data.

The measurements of *S*-wave *ππ* scattering lengths confirm our understanding of chiral  symmetry breaking in QCD, but these measurements - independently from their accuracy - cannot check the understanding of chiral  symmetry breaking. The check can be done by investigating the
*S*-wave *πK* scattering lengths, where also the *s* quark is involved. This is the principal difference between *ππ* and *πK* scattering.

ChPT [10,11] in 2-loop approximation gives = 0.267 with a precision of about 10% [12] in agreement with LQCD calculations [13,14,15]. The best  value has been obtained with a precision of 5% [15]. Further, the same scattering length difference has been calculated in the dispersive analysis using Roy-Steiner equations [16]:  = 0.269 ± 6%. Therefore, a *πK* scattering length measurement is an effective way to check the precise LQCD and ChPT predictions. Until now, one finds only two direct measurements of *πK* scattering lengths (DIRAC experiment): (i) the scattering length combination  = 0.32 has been evaluated from the *πK* atom lifetime measurement [17] with an average precision of 60% and (ii)  = 0.215 with an average precision of about 35% [18]. It is obvious that for the time being LQCD and ChPT predictions, based on chiral  symmetry breaking, could not be checked by any experiment.

For *ππ* interaction, the corresponding scattering lengths  and  and their difference have been calculated precisely [19] in ChPT [20,21]:  ,  , . The essential contribution to the *ππ* scattering length precision is given by the uncertainty of the symmetry breaking coupling constants  and . At present time, these constants were evaluated using Lattice calculations in many works with significantly better precision. Therefore, the ChPT predictions of *ππ* scattering lengths can be improved. In some recent works [13,14,15,22,23], *ππ* scattering lengths were calculated using LQCD:  about 5% and  less than 1.5% precise. Currently, only  has been measured with a precision of about 4% in each approach [24,25,26] confirming with this accuracy the theoretical predictions. The scattering length  has been determined with a precision of 22% [24,25].

A recent study [12] has shown that the dimesonic atom production in p-nucleus interaction can be increased by more than an order of magnitude if the incident proton momentum is raised from 24 to 450 *GeV/c*. Taking into account the dimesonic atom yields at 450 *GeV/c* () and the SPS operating conditions, the number of per time unit generated ,  and  will be 122, 5311 and 245 times higher than in the previous DIRAC experiment. This significant increase in  and  production makes it possible to measure with DIRAC in a comparable running time  at the 5% precision level [27] and so to check for the first time our thinking about chiral  symmetry breaking in QCD. The setup upgrading and geometry modification will enable a significant precision improvement.

A sample of  long-lived with lifetimes *s* has also been observed [28]. At SPS, the 450 *GeV/c* proton beam and experimental adaptions [29] open new possibilities for long-lived *ππ* atom studies: the number of per time unit generated ,  and  will be increased by factors of
609, 26553 and 12024 [12] and the background decreased by about two orders of magnitude [29] compared to the previous DIRAC experiment. The increased statistics and the significantly suppressed background open a possibility to apply a resonance method [7] for measuring only one parameter, the Lamb shift, and evaluating from this parameter the *ππ* scattering length combination (). This method uses only Lorentz transformation and quantum mechanics.

Up to now, the *K*+*K*− atom has not been observed. The possibility to detect *K*+*K*− atoms is under study.

For all investigations of dimesonic atoms, the DIRAC experiment uses very thin targets without disturbing the proton beam and, hence, can be installed upstream of other experiments in the same beam.

CERN, 26 June 2016
Leonid Nemenov, on behalf of the DIRAC collaboration

*References*

[1] S.M.Bilenky et al., Yad. Phys. **10** (1969) 812; Sov. J. Nucl. Phys. **10** (1969) 469.
[2] J.Schweizer, Phys. Lett.  **B587** (2004) 33;
 J.Schweizer, Eur. Phys. J. **C 36** (2004) 483, hep-ph/0405034.
[3] J.Uretsky and J.Palfrey, Phys. Rev. **121** (1961) 1798.
[4] J.Gasser et al., Phys. Rev. **D 64** (2001), 016008.
[5] L.Nemenov, Yad. Fiz.  **41** (1985) 980; Sov. J. Nucl. Phys. **41** (1985) 629.
[6] L.Nemenov and V.D.Ovsiannikov, Phys. Lett.  **B514** (2001) 247.
[7] L.Nemenov, V.D.Ovsyannikov, E.V.Chaplygin, Nucl. Phys.  **A710** (2002) 303.
[8] G.V.Efimov at al., Yad. Fiz. 44 (1986) 460; Sov. J. Nucl. Phys. **44** (1986) 296.
[9] A.Karimhodjaev and R.N.Faustov, Yad. Fiz. **29** (1979) 463; Sov. J. Nucl. Phys. **29** (1979) 232.
[10] V.Bernard et al., Nucl. Phys.  **B357** (1991) 129;
 V.Bernard et al., Phys. Rev.  **D43** (1991) 2757.
[11] J.Bijnens et al., J. High Energy Phys.  **05** (2004) 036, hep-ph/0404150.
[12] O.E.Gorchakov and L.L.Nemenov, J. Phys. G: Nucl. Part. Phys. 43 (2016) 095004.
[13] Z.Fu, Phys. Rev.  **D 87** (2013) 074501.
[14] K.Sasaki et al., Phys. Rev. **D 89** (2014) 054502.
[15] S.R.Beane et al., Phys. Rev. **D 74** (2006) 114503.
[16] P.Buettiker, S.Descotes-Genon, B.Moussallam, Eur. Phys. J. **C 33** (2004) 409;
[17] A.Adeva et al., Phys. Lett. **B735** (2014) 288.
[18] V.Yazkov and M.Zhabitsky, private communication.
[19] G.Colangelo, J.Gasser and H.Leutwyler, Nucl. Phys. **B603** (2001) 125.
[20] S.Weinberg, Physica **A96** (1979) 327.
[21] J.Gasser and H.Leutwyiler, Nucl. Phys. **B250** (1985) 465.
[22] X.Feng, K.Jansen and D.Renner, Phys. Lett. **B684** (2010) 268.
[23] T.Yagi at al., arXiv: 1108.2970.
[24] J.R.Bateley at al., Eur. Phys. J. **C 64** (2009) 589.
[25] J.R.Bateley at al., Eur. Phys. J. **C 70** (2010) 635.
[26] B.Adeva et al., Phys. Lett. **B704** (2011) 24.
[27] V.Yazkov, DIRAC note, to be published.
[28] A.Adeva et al., Phys. Lett. **B751** (2015) 12, arXiv:1508.04712.
[29] O.Gorchakov and L.Nemenov, DIRAC note **2015-05**.

􏰝􏰣􏰪􏰪􏰛􏰡􏰎􏰣 􏰦􏰎􏰛􏰍􏰳􏰥􏰙􏰚 􏰏􏰗􏰠􏰩􏰘􏰥􏰙􏰚 􏰏􏰗􏰙􏰝􏰡􏰍􏰙x vx

xx