TEST OF CHIRAL PERTURBATION THEORY WITH DIRAC AT CERN*

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on behalf of the DIRAC Collaboration
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(Received June 26, 2000)

The DIRAC experiment at CERN aims to form $\pi^+\pi^-$ atomic states and to measure their lifetime with 10% accuracy. This will give a precision of 5% in the determination of $\pi\pi$ S-wave scattering lengths, of the same level of Chiral Perturbation Theory calculations. In this way a crucial test on the theory validity would be performed.

PACS numbers: 24.85.+p

* Presented at the Meson 2000, Sixth International Workshop on Production, Properties and Interaction of Mesons, Cracow, Poland, May 19–23, 2000.

1. Introduction

Chiral Perturbation Theory (ChPT) is the theory of strong interaction at the energy scale of the hadron masses. Here QCD symmetries are used to create an effective field theory which uses the physical pion fields instead of quark and gluon degrees of freedom. The three lightest hadrons ($\pi^{\pm}\pi^{0}$) are pseudo-scalar particles and can be identified as the Goldstone bosons in the frame of chiral symmetry breaking ($m_u \neq m_d \neq 0$). Therefore, the Goldstone nature of the pseudo-scalar mesons implies strong constraints on their mutual interactions that can be precisely evaluated by the theory itself. ChPT is widely used today to describe strong interaction processes, *e.g.* semi-leptonic and non-leptonic weak decays. In particular $\pi\pi$ S-wave scattering lengths, a_0 for $I = 0$ and a_2 for $I = 2$, are calculated as an expansion in powers of the pion mass:

$$\varDelta = |a_0 - a_2| = \varDelta_0(1 + m_\pi^2\varDelta_2 + m_\pi^4\varDelta_4 + \ldots)\,, \tag{1}$$

where

$$m_\pi^2 = B(m_u + m_d) + O(m_q^2)\ ;$$

$$B = -\frac{<0|\bar{q}q|0>}{f_\pi^2};$$

$$f_\pi = \text{pion decay constant} \simeq\ 93\ \text{MeV}.$$

The most recent theoretical evaluation of $\varDelta$ [1], including up to 2-loop corrections, gives:

$$|a_0 - a_2| = 0.258 \pm 3\%\,. \tag{2}$$

Here and further the units $\hbar = c = m_\pi = 1$ are used.

On the experimental side the situation is not so good. No precise and unambiguous measurements of $\pi\pi$ S-wave scattering lengths are available. One set of data comes from the partial wave analysis of the reaction $\pi N \to \pi\pi N$ near threshold. This technique has been used to determine a_0 by many experiments (for a recent review see [2]), but precision here is clearly limited by the compatibility with QCD of the analysis methods. Another approach to determine a_0 is the study of the 4-body decay $K^+ \to \pi^+\pi^- e^+\nu_e$ [3]. This method is model independent, but requires very large statistics of a rare decay channel.

The aim of DIRAC is to determine $|a_0 - a_2|$ through the measurement of the $\pi^+\pi^-$ atom (*pionium*) lifetime. In fact, the pionium lifetime is related through a known expression [4–6] to $|a_0 - a_2|$. From Ref. [6] with a one-loop calculation, one finds

$$1/\tau = \varGamma_{2\pi^0} = 2/9\alpha^3 p^*(a_0 - a_2 + \varepsilon)^2(1 + K)\,, \tag{3}$$

where $p* = (M^2_{\pi^+} - M^2_{\pi^0} - 1/4M^2_{\pi^+}\alpha^2)^{1/2}$; $K = 1.07 \times 10^{-2}$ takes into account Coulomb corrections, $\varepsilon = (0.58 \pm 0.16) \times 10^{-2}$ isospin breaking effects. A measurement of τ at 10% accuracy will give a precision of 5% on $|a_0 - a_2|$, of the same order of ChPT predictions. In this way, the DIRAC experiment could perform an important test on the validity of the standard ChPT, and therefore it will provide decisive information on the nature of the chiral symmetry breaking and on the QCD vacuum [7]. The problem is that pionium decays through strong interaction essentially into $\pi^0\pi^0$ with a lifetime $\tau = 3.25 \times 10^{-15}$ s [6], too small to be directly measured. However, an indirect way to measure this quantity has been thought up and applied [8]. This technique will be illustrated in the next section.

2. Pionium production and lifetime measurement

Pionium ($A_{2\pi}$) can be produced from interactions of high intensity proton beams ($I_p \sim 1 \times 10^{11} p$/spill) on nuclear targets. $A_{2\pi}$ are formed via Coulomb interactions in the final state, when the distance between two pions of opposite charge is of order of some fm. The main characteristics of such an atom are: binding energy ~ 1.9 keV; $J^{\rm PC} = 0^{++}$; Bohr radius 387 fm. Since the binding energy is so small, $A_{2\pi}$ atoms can be easily ionized by interacting with the electric field of the target nuclei. In this way a pair of pions of opposite charge, and same quadri-momentum, is produced (*atomic pair*). The ionization probability increases with Z^2, thus it is more convenient, to enhance the phenomenon, to use target materials with high Z. This break-up probability ($P_{\rm br}$) is a function not only of Z, but also of $A_{2\pi}$ momentum and, above all, of $A_{2\pi}$ lifetime τ. Therefore, once $P_{\rm br}$ has been experimentally measured as the ratio between the number of detected atomic pairs n_A and the number of produced atoms N_A, the value of τ is deduced by comparing the experimental value of $P_{\rm br}$ with its calculated dependency on the lifetime. The break-up probability is a pure electromagnetic process and has been calculated theoretically with high precision. The Glauber approximation has been used to describe the Coulomb interaction of an hydrogen-like atom with other atoms [9]. This model takes into account single and multi-photon exchange giving an accuracy on $P_{\rm br}$ of 1%. Fig. 1 shows the results of these calculations for different target materials. Other theoretical calculations [10] using different approaches are also available. They give essentially the same results and precisions.

The idea of obtaining $|a_0 - a_2|$ with this technique was proposed by Nemenov in 1985 [8], and the experimental feasibility of the method was tested at the Serpukhov proton synchrotron. Here 279 ± 49 $\pi^+\pi^-$ atomic pairs were detected [11], and from this signal a lower limit on the $A_{2\pi}$ lifetime could be given: $\tau > 0.6 \times 10^{-15}$ at 90% C.L. [12].

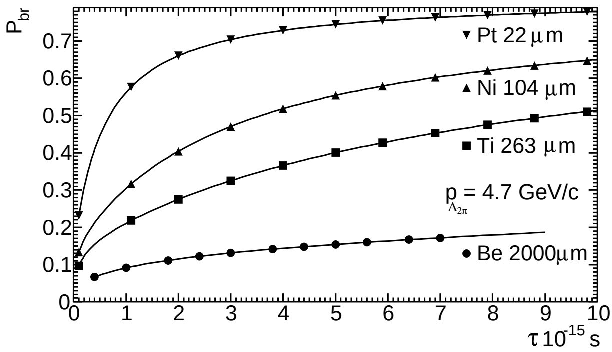

Fig. 1. Probability for an $A_{2\pi}$ atom of 4.7 GeV/c of being ionized ($P_{\rm br}$) for different target materials.

3. The DIRAC experimental apparatus

The DIRAC experiment [13] has to detect $\pi^+\pi^-$ pairs with very small opening angles and has to measure their relative momentum with high precision ~ 1 MeV/c. To accomplish these tasks a double arm magnetic spectrometer was commissioned during October–November 1998 at the T8 experimental area of the CERN PS. A top view of the DIRAC experimental setup is shown in Fig. 2.

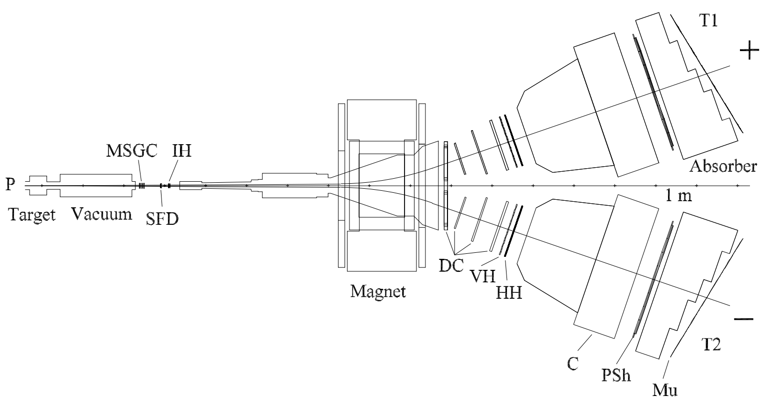

Fig. 2. Schematic top view of the DIRAC spectrometer. Moving from the target station toward the magnet there are: a Microstrip Gas Chamber detector (MSGC), a Scintillating Fiber Detector (SFD) and a Ionization Hodoscope (IH). Downstream the dipole magnet, on each arm of the spectrometer, are located: 4 planes of Drift Chambers (DC), a Vertical and a Horizontal Hodoscope (VH,HH), a Cherenkov counter (C), a Preshower detector (PSh) and, after an iron absorber, a Muon counter (Mu).

The magnetic spectrometer is arranged on a secondary particle channel, inclined 5.7^o with respect to the incoming proton beam, and the channel aperture is 1.2 msr. The 24 GeV/c PS proton beam entering the DIRAC experimental setup encounters the nuclear target system where $A_{2\pi}$ atoms are produced. This system consists of several material (Ni, Pt, ...) that can be put alternatively in the beam line.

To track the produced pion pairs, a first set of detectors is placed upstream the magnet:

— 4 planes of Microstrip Gas Chambers (MSGC) with Gas Electron Multiplier (GEM) to provide a measurement of the pion tracks with a resolution of $40\mu m$;

— a Scintillating Fiber Detector (SFD) made of 2 layers of 0.5 mm diameter scintillating fibers running perpendicularly. This detector contributes to the particle tracking and is essential to implement the second level trigger which select $\pi^+\pi^-$ having a maximum separation of 9 mm;

— a Ionization Hodoscope (IH) made of 16 vertical slabs of scintillator material. This detector discriminates at the second level trigger the double ionization signals expected from pairs hitting scintillator elements.

The $\pi^+\pi^-$ pairs are then bent in the "horizontal" plane by a conventional dipole magnet (1.6 T). After the magnet two identical detector arms have been constructed both housing the following detectors:

— 4 planes of Drift Chambers (DC1-DC4) providing charged particle tracking. The first chamber DC1, which covers both arms, includes also inclined wire planes in order to reject false combinations. The DCs single hit resolution is better than 100 μ m. The signals of the hit wires are used to implement the fourth level topological trigger which selects $\pi^+\pi^-$ pairs with small relative momentum;

— a Vertical and a Horizontal Hodoscope (VH, HH). These are scintillator hodoscopes with vertical and horizontal slabs respectively; they provide the first level trigger which requires the coincidence between the time-averaged VH signals in both arms, and a planarity cut in the horizontal plane by combining each slab of HH1 with a subset (± 2) of slabs in HH2. They also allow proton identification by time-of-flight, and produce the third level trigger. This trigger combines hodoscopes signals with that of forward detectors, in order to cut on the longitudinal component of the relative CM momentum of the 2 tracks ($q_{\rm L} < 30$ MeV/c);

— a threshold gas Cherenkov Counter (C) used at first level trigger for suppressing e^+e^- background pairs. The detector efficiency is $> 99.9\%$ and the pion contamination is less than $< 1\%$. The radiator is N_2 at atmospheric pressure;

— a Preshower Counter (PSh) made of Pb plates of several radiation lengths, followed by scintillator counters. It enforces electron rejection power and improves the trigger system;

— a Muon identification system (Mu) located after a thick iron absorber. The counter is made of scintillator slabs viewed by photomultipliers.

4. Preliminary results

During 1999 the experiment had 2 run periods. These have been devoted to trigger studies, and to carry out detector calibrations necessary to achieve the design momentum resolution. The collected luminosity consists of 150×10^6 events taken with a Ni target and 80×10^6 events taken with a Pt target. Reported in this section are some preliminary results that illustrate the spectrometer performance and show the first steps in the direction of $A_{2\pi}$ lifetime evaluation.

Figure 3 (left) shows the measured time difference between the π^+ and the π^- impacts on the vertical hodoscopes, recorded within a 40 ns gate. This width has been chosen in order to detect not only true coincidences, but

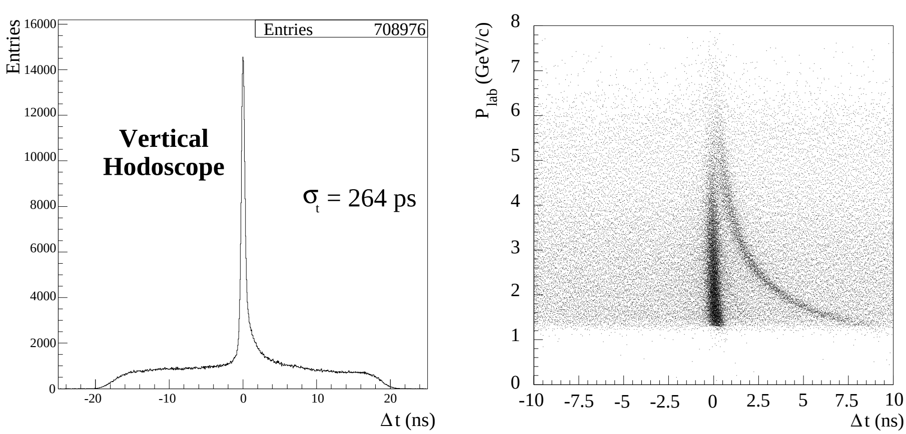

Fig. 3. Left: distribution of the time difference (Δt) between particle hits measured in the Vertical Hodoscopes. The time window width used to record this spectrum is 40 ns, in order to detect either true coincidences (peak) or accidental ones (flat background) (see text for details). Right: correlation between positive particle momentum and Δt. The distribution of points on the right side of the real coincidence band is due to events with protons.

also accidental pairs. In fact, the distribution of accidental pairs is crucial for our analysis method. Making a fit of the accidental distribution for q values > 3 MeV/c, where no atomic pairs are expected, we determine the distribution of *"free pairs"*. Once this shape is known, we can extrapolate it down to the region where atomic pairs are present, and we determine the number of atomic pairs n_A as the difference between the total number of detected pairs and the number of the free ones. Therefore, the signature for the atomic pairs production is the presence of an excess of $\pi^+\pi^-$ pairs at low relative CM momentum q.

The correlation between hit time difference and momentum of the positive track can be seen in the same figure (right). This distribution shows a clear band due to protons, on the right side of real coincidences.

The relative momentum in the center-of-mass frame projected into the direction of flight of the pair, $q_{\rm L}$, is shown in Fig. 4. Here, a cut on the transverse component $q_{\rm T} < 4$ MeV/c has been applied. The distribution, containing both real and accidental pairs, shows an enhancement due to the Coulomb Final State Interactions (FSI) for small $q_{\rm L}$ values. By checking the displacement from zero of this Coulomb peak we are able to evaluate the misalignment of the drift chambers in each arm (asymmetrical errors). A gaussian fit to this distribution gives the result $\langle q_{\rm L}\rangle = 0.095$ MeV/c, which indicates that the alignment is good.

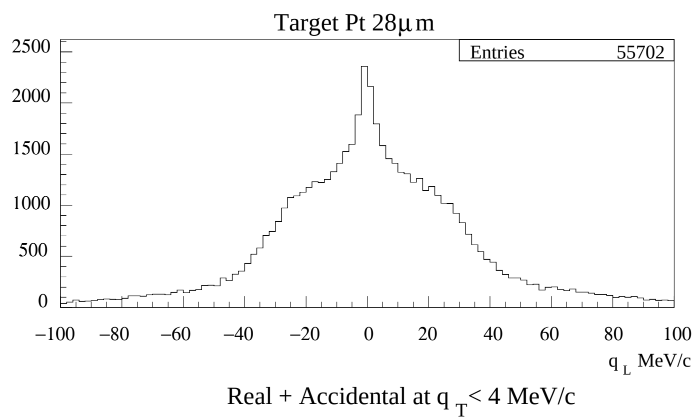

Fig. 4. $q_{\rm L}$ measured in the $\pi^+\pi^-$ center-of-mass frame with a cut $q_{\rm T} < 4$ MeV/c. A clear peak due to Coulomb FSI is observed for small $q_{\rm L}$ values.

Figure 5 shows three spectra of relative momentum q for real coincidences (top), accidental coincidences (middle) and the ratio between the two former (bottom). An enhancement for q less than 10 MeV/c due to Coulomb FSI is clearly observable.

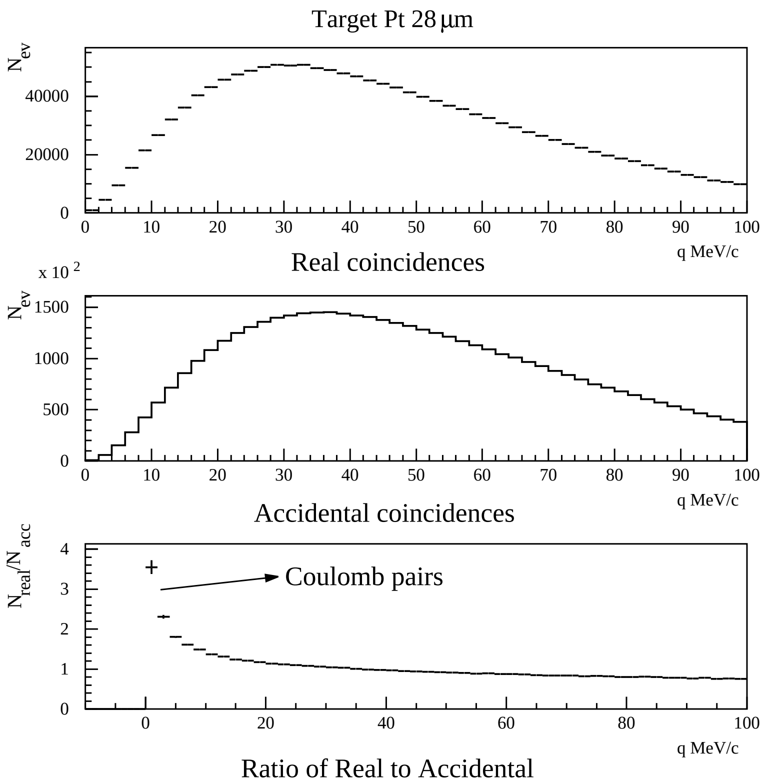

Fig. 5. Spectrum of the relative momentum q for real (top), accidental (middle) pairs separately and the ratio real/acc. (bottom). An enhancement for small q values due to Coulomb correlated $\pi^+\pi^-$ is observable in the last plot.

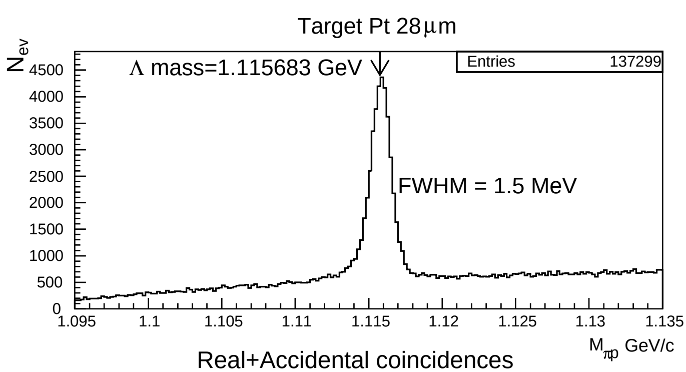

Fig. 6. Invariant mass distribution of $p\pi^-$ events for the complete (real+accidental) data sample.

An important check of the detector momentum resolution has been done by selecting $p\pi^-$ events. By plotting $p\pi^-$ effective mass, the Λ particle signal can be clearly observed (see Fig. 6). A gaussian fit to this signal gives for the Λ a FWHM of 1.5 MeV/c^2, indicating a very good momentum resolution of the spectrometer, $\Delta p/p < 0.6\%$. Such a resolution is needed to explore deeply into the Coulomb region to extract the signal of atomic pairs.

5. Summary and conclusions

The DIRAC experiment has begun its data analysis mainly this year. A preliminary investigation of the detector performance demonstrates its capability in exploiting the foreseen experimental program. Data taking in the year 2000 aims to firstly measure the $\pi^+\pi^-$ atom lifetime with an accuracy of 20% on at least 2 different heavy target materials. The final measurement, with accuracy 10%, is foreseen for years 2001–2002. This experimental result will certainly give new constraints to our knowledge of hadronic physics in the low energy domain.

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