Dimeson lifetime measurement with DIRAC at CERN.

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on behalf of the DIRAC Collaboration

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Contents

The DIRAC experiment at CERN aims to form $\pi^+\pi^-$ atomic states ($A_{2\pi}$ atom) and to measure their lifetime with 10% accuracy. This leads to a precision of 5% in the determination of $\pi\pi$ S-wave scattering lengths. We present the first preliminary results on $A_{2\pi}$ atom lifetime from data collected in the years 2000 and 2001 with two different targets made of Ni and Ti. These results are consistent with the predictions of the Chiral Perturbation Theory.

I. INTRODUCTION

The pion-pion scattering at low energies is analysed in terms of scattering lengths. At present pion-pion scattering is still an unresolved problem in the framework of QCD. However the approach based on an effective langrangian and Chiral Perturbation Theory (CHPT) allows to predict S-wave pion-pion scattering lengths within 2% [1].

On the experimental side the first approach comes from the partial wave analysis of the reaction $\pi N \to \pi\pi N$. This technique has been used to determine a_0, the S-wave pion scattering length with I=0, by many experiments (see reference [2] for a recent review), but precision here is clearly limited by the compatibility with QCD of the analysis methods. Another experimental approach to determine a_0 comes from the study of the 4-body decay $K^+ \to \pi^+\pi^- e^+\nu_e$. This method is model independent and reference [3] claims the measurement of a_0 with a precision of about 5%.

The aim of the DIRAC experiment [4] is to determine the difference $\Delta \doteq (a_0 - a_2)$ of the S-wave pion scattering lengths with I=0,2. This is possible through the measurement of the $\pi^+\pi^-$ atom ($A_{2\pi}$) lifetime in the ground state. The $A_{2\pi}$ atom decay is mainly determined by the charge exchange process (branching ratio $\sim$ 99.6%) shown in Fig. 1.

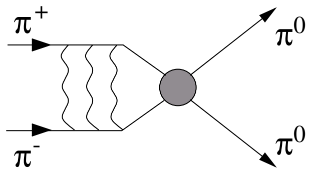

FIG. 1. The main decay of $A_{2\pi}$ atom.

In the framework of QCD (including photons), the decay width $\Gamma_{2\pi^0}$ of the $A_{2\pi}$ atom in the ground state can be written as [5] :

$$\Gamma_{2\pi^0} = \frac{1}{\tau} = \frac{2}{9}\alpha^3 p^* A^2 (1+K) \tag{1}$$

with

$$p^* = \left(M_{\pi^+}^2 - M_{\pi^0}^2 - \frac{1}{4} M_{\pi^+}^2 \alpha^2 \right)^{1/2} \tag{2}$$

$$A = (a_0 - a_2) + \epsilon \tag{3}$$

$$K = \frac{k}{9}(a_0 + 2a_2)^2 - \frac{2\alpha}{3}(ln\alpha - 1)(2a_0 + a_2) + o(\delta) \tag{4}$$

where τ is the lifetime of the atom, α is the fine structure constant, M_{π^+} and M_{π^0} the mass of π^+ and π^0 respectively, and $k = (M_{\pi^+}^2/M_{\pi^0}^2) - 1$. The correction parameter ϵ takes into account isospin breaking effects [5]. The recent predictions for the pion scattering lengths [1] allows the estimation of the $A_{2\pi}$ atom lifetime to be $\tau = (2.9 \pm 0.1) \times 10^{-15} sec$ [5].

By measuring the lifetime τ of the $A_{2\pi}$ atom, one is able to obtain the physical quantity Δ in a model independent way. An accuracy of 10% in the measurement of the lifetime corresponds to an accuracy of 5% in Δ. DIRAC with this measurement can perform an important test on the validity of the standard Chiral Perturbation Theory and contribute to the better understanding of the nonperturbative region of QCD.

II. EXPERIMENTAL METHOD

The $A_{2\pi}$ atoms can be formed via Coulomb interactions in the final state, when the distance between two opposite charged pions is of the order of few fm. The $A_{2\pi}$ atoms can be produced from interactions of high intensity proton beams on nuclear targets. The main characteristics of the $A_{2\pi}$ atom are

- Bohr radius 387 fm.
- Binding energy ~ 1.9 KeV.
- $J^{PC} = 0^{++}$.

The $A_{2\pi}$ atoms can be easily ionized while they move inside the target by interacting electromagneticaly with the target nuclei. The result of this interaction is the break-up of the atom into two oppositely charged pions which we call "atomic" pair. The detection of these "atomic" pairs is the signature of the existence of $A_{2\pi}$ atoms. The main characteristics of the "atomic" pair are:

- Very small $Q < 3$ MeV/c in the center of mass system.
- Almost equal momentum per pion $\mathbf{p}_+ \approx \mathbf{p}_-$
- Very small opening angle $\Theta_{lab} < 2.5\ mrad$.

The break-up probability (P_{br}) is defined as the ratio of the number of detected "atomic" pairs (n_A) over the number of produced atoms (N_A). It is a function of Z of the target matterial, of the momentum and mainly of the lifetime τ of the $A_{2\pi}$ atom. The break-up probability is a pure electromagnetic process and has been calculated theoreticaly with high precision [6] using the first Born approximation (single photon exchange) and the Coulomb-modified Glauber approximation (multiphoton exchange). Figure 2 shows the break-up probability as a function of the $A_{2\pi}$ atom lifetime for various targets. For the Pt target we plot the results for the first Born approximation (dashed line) and the Coulomb-modified Glauber approximation (solid line). For the rest of the targets the two approximations give exactly the same results.

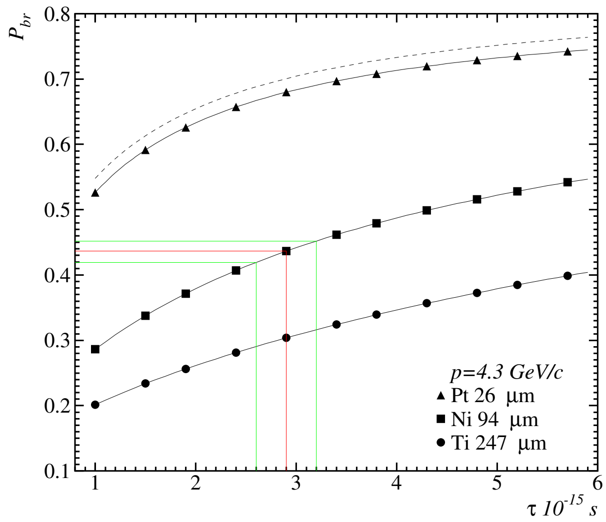

FIG. 2. The break-up probability versus the $A_{2\pi}$ atom lifetime for various targets.

From the above picture it is evident that a measurement of the break-up probability leads to the measurement of the lifetime τ of the $A_{2\pi}$ atom. The idea of obtaining the physical parameter Δ with this technique was proposed by L. Nemenov in 1985 [7] while the experimental feasibility of the method was tested at the Serpukhov proton synchrotron [8], [9].

III. THE DIRAC APPARATUS

The DIRAC experimental apparatus has been designed to detect atomic pairs with very small opening angles and low relative momentum with a resolution better than 1 MeV/c. To accomplish these tasks a double arm magnetic spectometer (Fig. 3) was constructed at the T8 experimental area of the CERN PS.

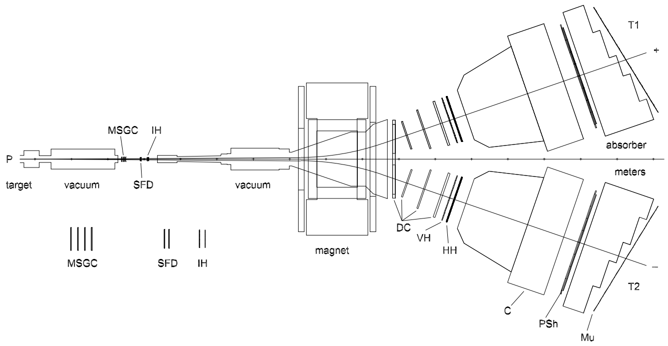

FIG. 3. The DIRAC experimental setup.

The primary PS proton beam with 24 GeV/c momentum hits the nuclear target system where $A_{2\pi}$ atoms are produced. The target system contains several targets made of various materials (Ni, Ti, Pt etc.) that can be positioned alternatively in the beam line. The magnetic spectrometer is arranged on a secondary particle channel covering 1.2 msr solid angle and being inclined by 5.7° with respect to the incoming proton beam.

The detectors we meet after the target station and upstream the magnet are the following:

- Four planes of Microstrip Gas Chambers (MSGC) with GEM (Gas Electron Multiplier) with a spatial resolution of 50 μm. These detectors give the first signals of charged particles coming from the target.
- The Scintillating Fiber Detector (SFD) consisting of 2 layers, the first positioned vertically and the second horizontally in respect to the plane of the spectrometer. The diameter of each fiber is 0.5 mm. Five fibers one behind the other construct one column and each plane has 240 such columns. This detector detects charged particles coming from the target and is used also in the trigger of the experiment.
- The Ionization Hodoscope (IH) consisting of 2 layers, the first two positioned vertically while the third and the fourth horizontally in respect to the plane of the spectometer. Each layer has 16 slabs of sciltillating material with dimensions of 100 $mm \times 7$ $mm \times 1$ mm. This detector measures double ionization signals expected from pion pairs and is used also in the trigger of the experiment.

The magnet of the experiment is a conventional dipole magnet (1.65 T) and is used to bend the $\pi^+\pi^-$ pairs in the horizontal plane. After the magnet we meet two identical arms each one having the following detectors:

- Four planes of Drift Chambers (DC1 to DC4). The first chamber covers both arms and includes also inclined wire planes to avoid ambiguities. These detectors compose the downstream tracking devices of the experiment. The DCs single hit resolution is better than 100 μm. These detectors are also used in the higher trigger level of the experiment.
- The Vertical and the Horizontal Hodoscope (VH and HH) detectors. The VH consists of 18 scintillator hodoscopes positioned vertically with dimensions 400 mm × 72.3 mm × 20 mm. The HH consists of 16 scintillator hodoscopes positioned horizontally with dimensions 1300 mm × 25 mm × 25 mm. VH provide time-of-flight measurements for charged particles crossing them. Both VH and HH are used in the trigger of the experiment.
- The threshold gas Cherenkov Counter (C) used for suppressing on line e^+e^- pairs. The radiator is N_2 at atmospheric pressure and the detector efficiency is better than 99.9%.
- The Preshower Counter (PSh) is made of 8 scintillator slabs. In front of each slab there is one Pb plate of several radiation lengths. It is used to improve the electron rejection.
- The Muon Detector (Mu) used to identify muons. It consists of 28 scintillator slabs positioned vertically and is located after a thick iron absorber.

A multi-level trigger was designed to select pion pairs with low relative momentum in the center of mass of the pair system (small opening angle and equal energies in the lab system) and by recording a sufficiently large number of accidental pairs for the offline analysis. The various levels of the trigger are the following:

- The first level trigger (T1) uses the information of VH and HH from both arms in coincidence to define a candidate pair. It applies a planarity cut in the horizontal plane by combining each slab of HH1 with a subset (±2) of slabs in HH2. It also uses the information from the Cherenkov Counter to suppress e^+e^- pairs.
- The Neural Network Trigger (DNA+RNA) which uses the information of SFD, IH and VH detectors to select events with $Q_\ell < 30$MeV/c and $Q_T < 10$MeV/c.
- The High Level Trigger (T4) that involves the DC hit information and selects events with $Q < 30$MeV/c.

IV. RESULTS

In this section we present the preliminary analysis of data, which were collected with a Ti target during the years 2000-2001 and with a Ni target during the year 2000. We also present the preliminary analysis of a data set collected with a Pt target during the very initial stage of the experiment (November 1999). The last data set was collected as a first attempt to observe "atomic" pairs and no measurement of the life time of $A_{2\pi}$ can be extracted.

As mentioned in section II, "atomic" pairs have low relative momentum Q in the center of mass system ($Q < 3$ MeV/c). The distributions of "atomic" pair relative momentum and of its projections are defined by the initial Q distribution of the pairs after breakup, the setup momentum resolution (affects mainly Q_ℓ), the resolution of the pair opening angle measurement and by multiple scattering in target, membranes and detectors (affects mainly Q_T). As a result of the analysis the Q_ℓ "atomic" pair distribution is found to show a Gaussian-like shape with $\sigma_{Q_\ell} = 0.65$ MeV/c. For Q_x and Q_y the distributions exhibit a value of around 1 MeV/c for both σ_{Q_x} and σ_{Q_y}. Therefore, a new variable F instead of Q is introduced in order to provide a better signal-to-background ratio:

$$F = \sqrt{\left(\frac{Q_\ell}{0.65\ \mathrm{MeV/c}}\right)^2 + \left(\frac{Q_x}{1\ \mathrm{MeV/c}}\right)^2 + \left(\frac{Q_y}{1\ \mathrm{MeV/c}}\right)^2} \tag{5}$$

For the analysis, events have been preselected applying the following criteria:

- Absence of a signal in the Cherenkov Counter and in the Muon Detector.
- Select events with the sum of particle momentum in laboratory system inside the expected region: 3 GeV/c < $(P_+ + P_-) < 9$ GeV/c and $P_+ < 4.5$ GeV/c to reject fast protons.
- Select events that have $Q_\ell < 22$ MeV/c, $Q_x < 4$ MeV/c and $Q_y < 4$ MeV/c.

Then using the time difference, measured by the Vertical Hodoscopes and shown in Fig. 4, we define the "accidental" pairs (regions N1 and N4) and the "correlated" pairs (regions N2 and N3).

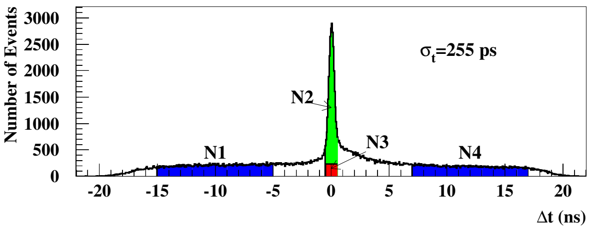

FIG. 4. Time difference between hits in VH placed on the two arms.

"Accidental" pairs are events where the two pions are coming from two different proton interactions as shown in Fig. 5. The two pions are uncorrelated in time and they have the following distribution:

$$\frac{dN_{\rm acc}}{dF} \propto \Phi(F) \tag{6}$$

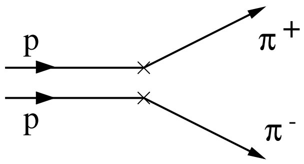

FIG. 5. "Accidental" pion pairs.

The distribution of "correlated" pairs consists of the sum of three distributions:

- The "atomic" pair distribution, where the two pions are coming from the breakup of an atom $A_{2\pi}$ (Fig. 6), and is observed in the region $F < 4$.

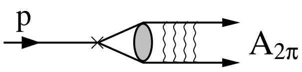

FIG. 6. "Atomic" pion pairs.

- The non-Coulomb pair distribution, where one of the two pions comes from decays of long-lived sources (Fig. 7), and has the form:

$$\frac{dN^{\rm long}_{\rm acc}}{dF} \propto \Phi(F) \tag{7}$$

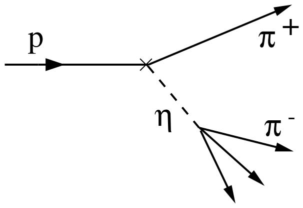

FIG. 7. Non-Coulomb pion pairs.

- The Coulomb pair distribution, where decays of short-lived sources are involved and Coulomb interaction between the two pions take place (Fig. 8). This distribution has the form:

$$\frac{dN^{\rm short}_{\rm corr}}{dF} \propto \Phi(F)(1+kF)A_{\rm C}(F) \tag{8}$$

where the term $(1+kF)$ takes into account strong interaction effects in the final state and $A_{\rm C}(F)$ being the Coulomb factor.

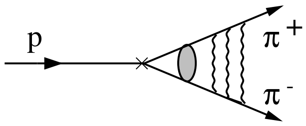

FIG. 8. Coulomb pion pairs.

From the above the "correlated" pairs distribution in the region where $F > 4$ can be written as:

$$\frac{dN_{\rm corr}}{dF} = \frac{dN^{\rm long}_{\rm acc}}{dF} + \frac{dN^{\rm short}_{\rm corr}}{dF} = N\Phi(F)\left[(1+kF)A_{\rm C}(F) + f\right] \tag{9}$$

with N, k and f as free parameters which can be extracted from the experimental data.

Figure 9 shows , for the Ni target data, the event distributions for "accidental" pairs (top) and "correlated" pairs (midle) after subtracting the "accidental" pairs that corresponds to region N3. The last can be found by multiplying the "accidental" pairs distribution (top) by $\Delta t_3/(\Delta t_1 + \Delta t_4)$ where Δt_1, Δt_3 and Δt_4 the time intervals for the regions N1, N3 and N4 respectively. By fitting the "correlated" pairs distribution in the region where $F > 4$ with the approximation function

$$A(F) = N\Phi(F)\left[(1+kF)A_{\rm C}(F) + f\right] \tag{10}$$

we can evaluate the free parameters N, k and f. Then using these parameters we obtain the fitted function in the region where $F < 4$. The difference between the "correlated" pairs experimental distribution and the approximation function $A(F)$ describes the contribution of "atomic" pairs. Figure 9 (bottom) shows the "atomic" pair distribution as function of F for data collected in the year 2000 with Ni target. The "atomic" pairs existence can be seen clearly at the low values of F where we expect them.

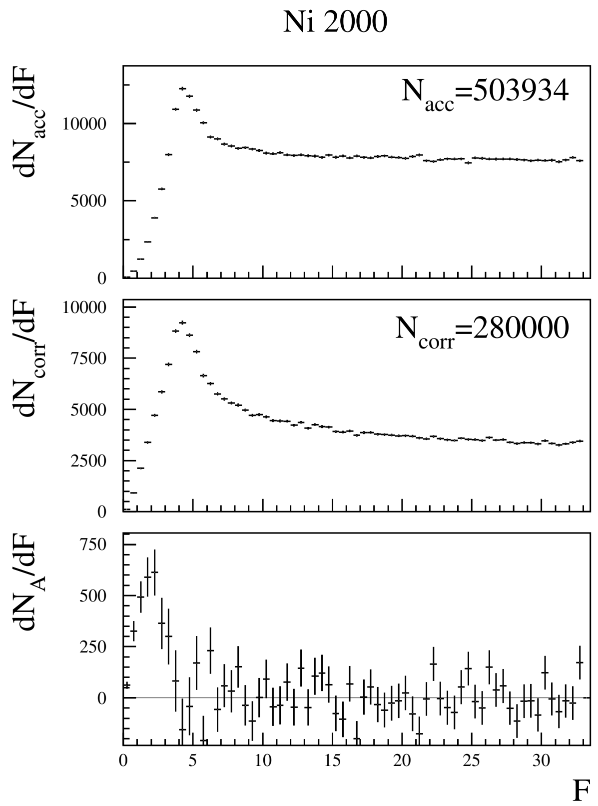

FIG. 9. The event distributions for "accidental" pairs (top), "correlated" pairs (middle) and the "atomic" pair distribution (bottom) as function of F for data collected in the year 2000 with Ni target. We note that N_A in the above figure and in the following ones corresponds to n_A in the text.

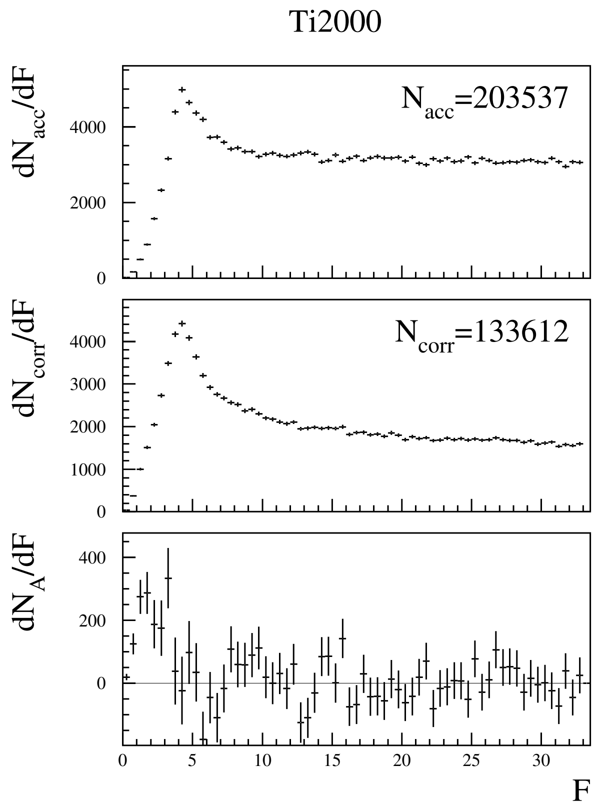

FIG. 10. The event distributions for "accidental" pairs (top), "correlated" pairs (middle) and the "atomic" pair distribution (bottom) as function of F for data collected in the year 2000 with Ti target.

Figure 10 shows, the event distributions for "accidental" pairs (top), "correlated" pairs (middle) and the "atomic" pair distribution (bottom) as function of F for data collected in the year 2000 with Ti target. Figure 11 shows the "atomic" pair distribution as function of F for all data with Ti (years 2000-2001). The last figure shows clearly the existence of "atomic" pairs at the low values of F also with this target.

Finaly the existence of "atomic" pairs can be seen also clearly in Fig. 12 where we plot the results of the analysis with the Pt target data.

From the distributions of figures 9 to 11 and for $F < 2$ the total number of "atomic" pairs (n_A) and Coulomb pairs (N_C) can be extracted and are shown below, for the Ni and Ti targets:

- Pt (year 1999): $n_A = (150 \pm 35)$, $N_C = (250 \pm 30)$.
- Ni (year 2000): $n_A = (1470 \pm 140)$, $N_C = (4730 \pm 130)$.
- Ti (year 2000): $n_A = (710 \pm 100)$, $N_C = (2010 \pm 85)$.
- Ti (year 2001): $n_A = (1120 \pm 130)$, $N_C = (3820 \pm 120)$.

We also include for completeness the results from the Pt target data which have been collected in the early stage of the experiment.

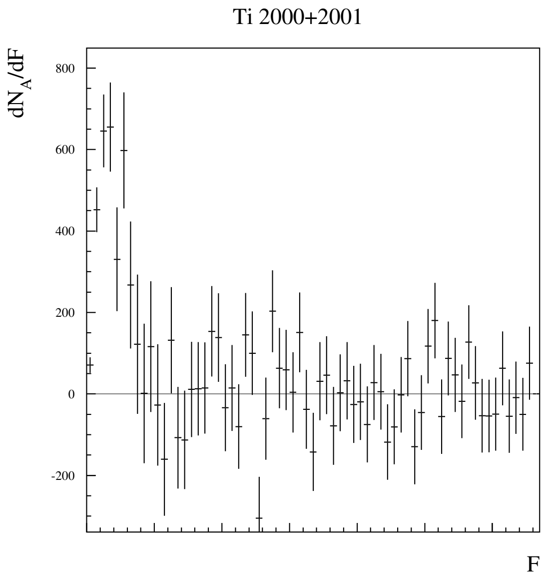

FIG. 11. The "atomic" pair distribution as function of F for data collected in the year 2000-2001 with Ti target.

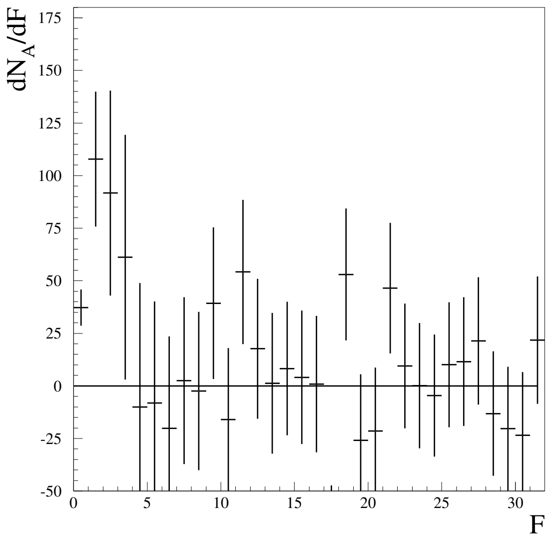

FIG. 12. The "atomic" pair distribution as function of F for data collected in the year 1999 with Pt target.

To evaluate the breakup probability $P_{br} = n_A/N_A$ the total number N_A of $A_{2\pi}$ atoms generated inside the target is needed. The total number N_A of $A_{2\pi}$ atoms can be calculated from the number N_C of the Coulomb pairs. The cross section of $A_{2\pi}$ atoms production is:

$$\frac{d\sigma_n^A}{d\mathbf{p_A}} = (2\pi)^3 \frac{E_A}{M_A} |\psi_n(0)|^2 \frac{d\sigma^0}{d\mathbf{p_1}d\mathbf{p_2}}|_{\mathbf{p_1}=\mathbf{p_2}=\mathbf{p_A}/2} \tag{11}$$

with $\mathbf{p_A}$, E_A and M_A the momentum, the energy and the mass of $A_{2\pi}$ atoms in the labsystem and $\frac{d\sigma^0}{d\mathbf{p_1}d\mathbf{p_2}}$ the double production cross section for $\pi^+\pi^-$ pairs from short lived sources.

After numerical integration of the above in the interval $F < 2$ and taking into account the multiple scattering in the target and the resolution of the detector we obtain the total number N_A of $A_{2\pi}$ atoms from the number N_C of the Coulomb pairs. Below we present the ratio n_A/N_C and the breakup probability $P_{br} = n_A/N_A$ for the various targets and periods of data taking.

- Pt (year 1999): $n_A/N_C = (0.58 \pm 0.16)$, $P_{br} = (0.81 \pm 0.24)$.
- Ni (year 2000): $n_A/N_C = (0.31 \pm 0.04)$, $P_{br} = (0.43 \pm 0.05)$.
- Ti (year 2000): $n_A/N_C = (0.35 \pm 0.06)$, $P_{br} = (0.49 \pm 0.09)$.
- Ti (year 2001): $n_A/N_C = (0.29 \pm 0.04)$, $P_{br} = (0.36 \pm 0.05)$.

Using the above value of the breakup probability for Ni we find the lifetime (Fig. 13) of the $A_{2\pi}$ atoms to be:

$$\tau_{(\mathrm{Ni\ year\ 2000})} = \left(2.8^{+1.1}_{-0.8}\right) \times 10^{-15} sec \tag{12}$$

For the target Ti we find

$$\tau_{(\mathrm{Ti\ year\ 2000-2001})} = \left(5.4^{+1.5}_{-1.3}\right) \times 10^{-15} sec \tag{13}$$

We note here that our results are preliminary and errors are only statistical.

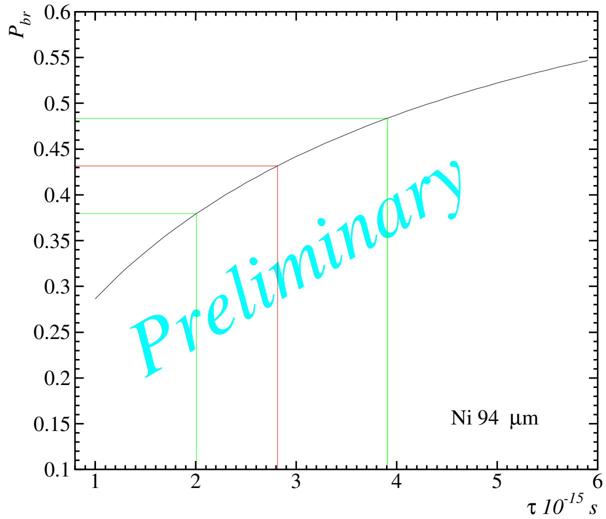

FIG. 13. Preliminary result of the $A_{2\pi}$ atom lifetime using the the data collected in the year 2000 with Ni target

V. CONCLUSIONS

The DIRAC experiment has a very clear signal of about 3500 $\pi^+\pi^-$ "atomic" pairs so far (figures 9 to 12). Our preliminary results (equations 12 and 13) on the $A_{2\pi}$ atom lifetime are consistent with the predictions of the Chiral Perturbation Theory. The DIRAC experiment with the data of the years 2001-2002 will achieve the accuracy of 10% in the $A_{2\pi}$ atom lifetime and will be able to determine the physical quantity Δ with a precision of 5%.

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