PROCEEDINGS OF SCIENCE

Experimental investigation of $\pi^+\pi^-$ and K^+K^- atoms

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The adapted DIRAC experiment at the CERN PS accelerator observed for the first time long-lived hydrogen-like $\pi^+\pi^-$ atoms, produced by protons hitting a beryllium target. A part of these atoms crossed the gap of 96 mm and got broken up in the 2.1 µm thick platinum foil. Analysing the observed number of atomic pairs, $n_A^L = 436^{+157}_{-61}\big|_{\text{tot}}$, the lifetime of the $2p$ state is found to be $\tau_{2p} = (0.45^{+1.08}_{-0.30}\big|_{\text{tot}}) \cdot 10^{-11}$s, not contradicting the corresponding QED $2p$ state lifetime $\tau_{2p}^{\text{QED}} = 1.17 \cdot 10^{-11}$s. This lifetime value is three orders of magnitude larger than our previously measured value of the $\pi^+\pi^-$ atom ground state lifetime $\tau = (3.15^{+0.28}_{-0.26}\big|_{\text{tot}}) \cdot 10^{-15}$s. Further studies of long-lived $\pi^+\pi^-$ atoms will allow to measure energy differences between p and s atomic states and so to determine $\pi\pi$ scattering lengths with the aim to check QCD predictions.

At the same setup, there were identified more than 7000 K^+K^- pairs with effective mass less than $2M_K + 5$ MeV. In the distributions of K^+K^- pairs there is a strong signature of the Coulomb enhancement: the number of pairs increases with decreasing of the relative momentum in the pair c.m.s. The observed number of K^+K^- pairs with small relative momentum will allow us to evaluate for the first time the number of the produced K^+K^- atoms.

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1. Long-lived hydrogen-like $\pi^+\pi^-$ atoms

The DIRAC collaboration aims to check low-energy QCD predictions using double-exotic $\pi^+\pi^-$ and $\pi^\pm K^\mp$ atoms, which have been observed and studied [1]. After investigation of $\pi\pi$ and πK atoms with "short" lifetimes of the order of 10^{-15}s, DIRAC continues its scientific program by exploring $\pi\pi$ atomic states ($A^L_{2\pi}$) of "long" lifetimes of the order of 10^{-11}s. The $A^L_{2\pi}$ atoms were observed in [2]. The method of long-lived $A^L_{2\pi}$ investigation is shown in Figure 1. $A_{2\pi}$ atoms are produced by the primary 24 GeV/c CERN PS beam in a 103 µm thick Be target. Moving inside the target, relativistic $A_{2\pi}$ interact with the electric field of the target atoms, resulting in a possible change of the $A_{2\pi}$ orbital momentum l by one or more units. Some of them leave the target with $l > 0$. For such states all decays are suppressed. The only decay mechanism is the radiative deexcitation to an ns state, annihilating subsequently with the "short" lifetime $\tau \cdot n^3$ into two π^0. For the average momentum of detected $A_{2\pi}$ $\langle p_A \rangle$=4.44 GeV/c ($\gamma \simeq 15.9$), the decay lengths are 5.6 cm (2p), 18.4 cm (3p), 43 cm (4p), 83 cm (5p) and 143 cm (6p). On their way to the 2.1 µm thick Pt foil placed at a distance of 96 mm behind the Be target, a part of the produced long-lived atoms $A^L_{2\pi}$, depending on their lifetimes, decays, whereas the other part enters the Pt foil. By interacting with Pt atoms, the atoms $A^L_{2\pi}$ break up (get ionized) and generate atomic $\pi^+\pi^-$ pairs with relative momenta $Q < 3$ MeV/c in the centre-of-mass (c.m.) system of a pair. The foil is introduced at 7.5 mm above the primary proton beam to avoid interaction of the beam halo with Pt. Between the target and the breakup foil, there was installed a permanent retractable magnet with a pole distance of 60 mm and a maximum horizontal field strength of 0.25 T (bending power 0.02 Tm). The magnet enlarges the value of the vertical component Q_Y of $\pi^+\pi^-$ pairs, generated in Be by $Q_Y = 13.15$ MeV/c (see Figure 1). For all pairs generated in Pt foil, the fringing magnetic field modifies the vertical component Q_Y only by 2.3 MeV/c. This large difference in the Q_Y shift for pairs from Be and Pt allows to suppress the background by a factor of about 6 in detecting atomic pairs from long-lived $A^L_{2\pi}$.

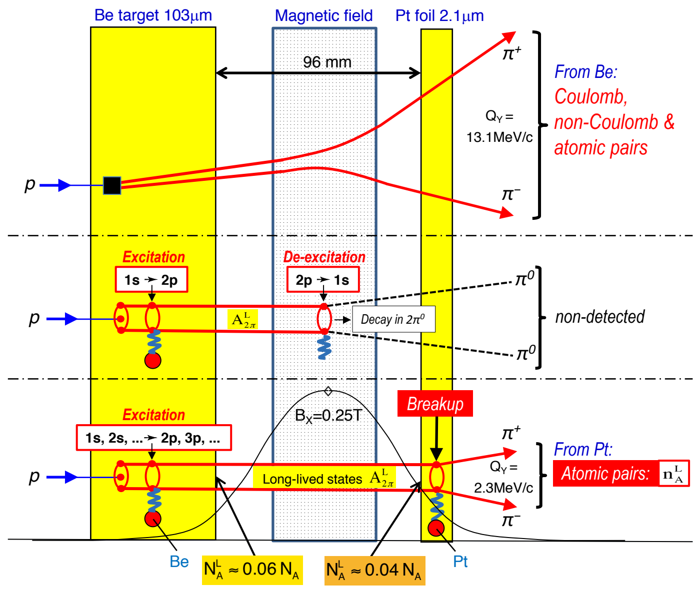

Figure 1: Method to investigate long-lived $A^L_{2\pi}$ by means of a breakup foil (side view). N_A is the total number of the produced $A_{2\pi}$ and N^L_A the number of excited $A^L_{2\pi}$ with $l > 0$.

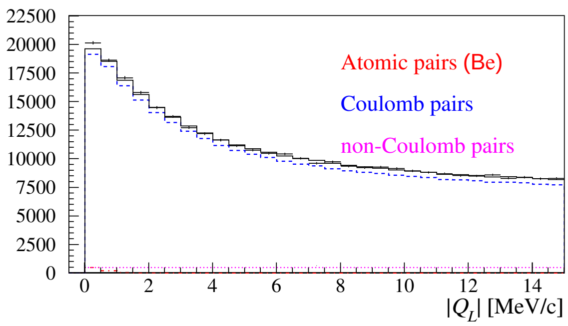

Figure 2: Experimental distribution of $\pi^+\pi^-$ pairs over longitudinal component Q_L (points with error bar) for the Be target fitted by the sum of simulated distributions of "atomic", "Coulomb" and "non-Coulomb" pairs. The summed distribution of free pairs is shown as black line.

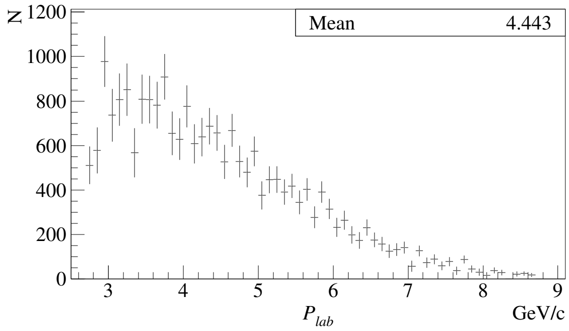

Figure 3: Lab momentum spectrum of $A_{2\pi}$ produced in Be.

Figure 2 shows an observation of $\pi^+\pi^-$ pairs produced in Be target used to evaluate the number of produced $A^L_{2\pi}$ and Figure 3 the momentum spectrum of $A^L_{2\pi}$. Figure 4 shows an observation of atomic pairs from long-lived $A^L_{2\pi}$ broken in Pt. Comparison of the number of produced and broken $A^L_{2\pi}$ allows to evaluate their lifetime. As all atomic states have different lifetime predicted in QED τ_i^{QED} their variation have been done with one common factor $\alpha = \tau_i/\tau_i^{\mathrm{QED}}$. The measured $A^L_{2\pi}$ number corresponds to $\alpha = 0.383^{+0.926}_{-0.254}$. As $\alpha = 1$ is included in the error band, one concludes that the measured lifetime does not contradict the QED calculations. The lifetime of the $2p$ state, which is the shortest of all long-lived states, is found to be $\tau_{2p} = \left(0.45^{+1.08}_{-0.30}\big|_{\mathrm{tot}}\right)\cdot 10^{-11}$ s. This value is in agreement with the QED calculation, $\tau_{2p}^{\mathrm{QED}} = 1.17\cdot 10^{-11}$ s, which is three orders of magnitude larger than the $A_{2\pi}$ ground state lifetime [3].

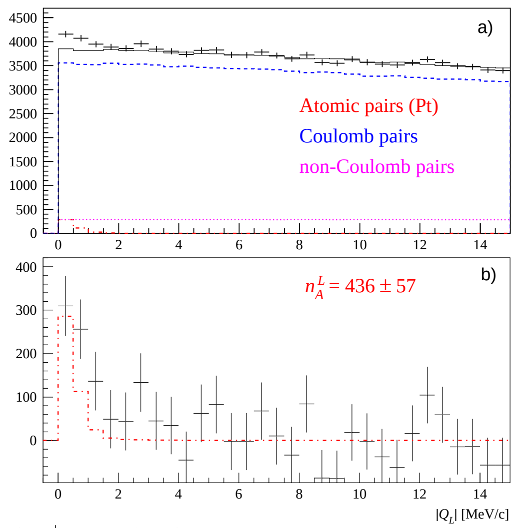

Figure 4: $|Q_L|$ distribution of $\pi^+\pi^-$ pairs for $Q_T < 2.0$ MeV/c: a) the experimental distribution (with statistical error bar) and simulated background (solid line); b) the experimental distribution after background subtraction (+ with statistical error bar) and simulated distribution of atomic pairs from $A^L_{2\pi}$ broken up in Pt (dotted-dashed line).

2. Observation of Coulomb K^+K^- pairs

Initially, studying of K^+K^- pairs was not included in the DIRAC program. Nevertheless, in our data there were identified more than 7000 K^+K^- pairs using time-of-light technique. Figure 5 shows $|Q_L|$ distribution of K^+K^- pairs for different intervals of Q_T. The peaks at small $|Q_L|$ are due to the Coulomb interaction in the final state. This is the first observation of such effect for K^+K^- pairs with high statistics. For the different data sets, figure 6 shows Q distribution of the ratio between the experimental data and simulated ones generated under assumption of a point-like production region of the K^+K^- pairs. The lack of a peak at the origin validates that K^+K^- atom can not be observed at current condition as its expected lifetime is of the order of 10^{-18} s. A small deep at $Q < 10$ MeV/c is due to a non-point size of K^+K^- pair origination. Further study of such dependence will provide information about the spacial distribution of K^+K^- pairs.

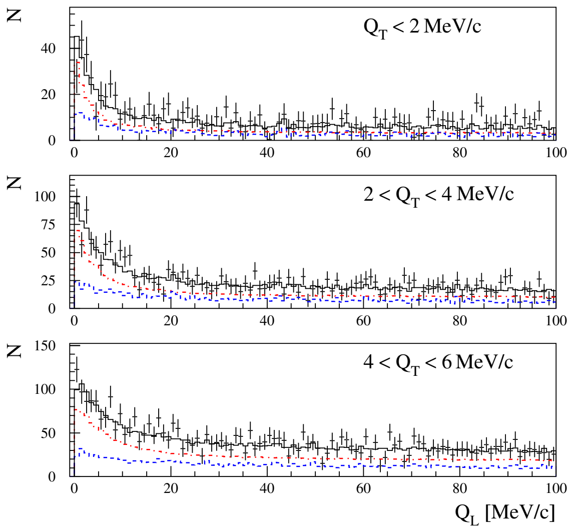

Figure 5: $|Q_L|$ distribution of K^+K^- pairs for different intervals of Q_T. The peaks at small $|Q_L|$ are due to the Coulomb interaction in the final state.

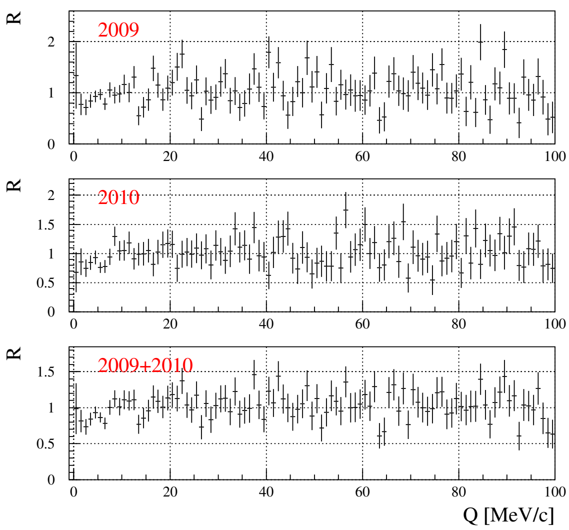

Figure 6: Ratio between the experimental K^+K^- data and simulated ones generated under assumption of a point-like production region of K^+K^- pairs, for data sets collected in 2009 and 2010.

References

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[2] B. Adeva et al., Phys. Lett. **B751** (2015) 12.

[3] B. Adeva et al., CERN-EP-2018-281, cds.cern.ch/record/2642499.