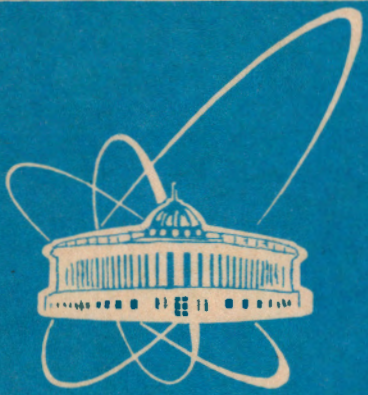

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EXPERIMENTAL ESTIMATION OF THE LIFETIME OF ATOMS FORMED BY π^+ AND π^- MESONS

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Экспериментальная оценка времени жизни атома, состоящего из π^+- и π^--мезонов

На основании наблюдения 272 ± 49 атомов, образованных π^+- и π^--мезонами, получена оценка времени жизни основного состояния $\pi^+\pi^-$-атома: $\tau = (2.9^{+\infty}_{-2.1}) \cdot 10^{-15}$ с или с вероятностью 90% $\tau > 0.6 \cdot 10^{-15}$ с. Атомы наблюдались в инклюзивной реакции p Ta при энергии протонов 70 ГэВ.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

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Experimental Estimation of the Lifetime of Atoms Formed by π^+ and π^- Mesons

Based on observation of 272 ± 49 atoms formed by π^+ and π^- mesons an estimation of the atom lifetime in the ground state is obtained: $\tau = (2.9^{+\infty}_{-2.1}) \cdot 10^{-15}$ s or $\tau > 0.6 \cdot 10^{-15}$ s at 90% confidence level. Atoms were produced in inclusive p Ta interactions at 70 GeV.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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1 Introduction

In the experiment [1] 272 ± 49 atoms formed by π^+ and π^- ($A_{2\pi}$) were observed in the inclusive process p Ta $\to A_{2\pi} X$ at the proton energy 70 GeV. The atoms are produced in S-states with principal quantum numbers n with the cross section [2]:

$$\frac{d\sigma_n^A}{d\vec{p}_A} = (2\pi)^3 \frac{E_A}{M_A} |\Psi_n(0)|^2 \frac{d\sigma_0}{d\vec{p}_1 d\vec{p}_2}, \qquad (1)$$

where $\vec{p}_A$, E_A and M_A are the momentum, energy and mass of the $A_{2\pi}$ in the lab system, respectively, $d\sigma_0/d\vec{p}_1 d\vec{p}_2$ is the double inclusive production cross section for $\pi^+\pi^-$ pairs from short-lived sources (quark processes, decays of $\rho, \omega, K^* \ldots$) without taking into account $\pi^+\pi^-$ Coulomb interaction in the final state, $\vec{p}_1$ and $\vec{p}_2$ are the π^+ and π^- momenta in the lab system. The momenta of π^+ and π^- mesons obey the relation: $\vec{p}_1 = \vec{p}_2 = \vec{p}_A/2$. $\Psi_n(0)$ is the atomic wave function of nS-states at the origin. As shown in [3, 4] the difference of $\Psi_n(0)$ from pure Coulomb atomic wave function is less than 10^{-3}. $|\Psi_n(0)|^2$ depend on n as n^{-3}.

The lifetime τ_n of $A_{2\pi}$ in nS states is determined by the charge-exchange process $\pi^+\pi^- \to \pi^0\pi^0$ (branching $\sim$ 99.6%) and may be written through the S-wave $\pi\pi$-scattering lengths a_0 and a_2 with isospin values 0 and 2 [5]:

$$\frac{1}{\tau_n} = \frac{8\pi}{9} \left(\frac{2\Delta m}{\mu} \right)^{1/2} (a_0 - a_2)^2 |\Psi_n(0)|^2, \qquad (2)$$

where $\Delta m = M_A - 2m_{\pi^0}$, m_{π^0} is π^0 meson mass and μ is the $A_{2\pi}$ reduced mass. The lifetime dependence on n is determined by $|\Psi_n(0)|^2$ and given by expression the $\tau_n = \tau_1 \cdot n^3$.

It follows from (2) that the measurement of τ_1 with 10% precision would allow to determine $|a_0 - a_2|$ in a model independent way with 5% accuracy. Therefore, it would allow to test the prediction of the chiral perturbation theory [6, 7] which gives a_0 and a_2 within 5% [7] : $a_0 = (0.20 \pm 0.01) m_\pi^{-1}$, $a_2 = (-0.042 \pm 0.002) m_\pi^{-1}$. Inserting these values in (2) τ_1 may be calculated: $\tau_1 = (3.7 \pm 0.3) \cdot 10^{-15}$ s. As pointed out in [8] the measurement of τ_1 would be a crucial test of the chiral perturbation theory.

In the present paper the first experimental estimation of the $A_{2\pi}$ lifetime based on the measurement of the number of broken up (ionized) atoms [2] is given.

2 Detection of $A_{2\pi}$

The experiment [1] was carried out at the 70 GeV proton synchrotron at Serpukhov. Pionic atoms and $\pi^+\pi^-$ pairs ("free" pairs) were produced in a 8μm thick tantalum target inserted into the internal proton beam. The atoms can either annihilate into $\pi^0\pi^0$ pairs or break up into $\pi^+\pi^-$ pairs ("atomic" pairs) inside the same target. The "free" and "atomic" pairs get into the 40 m long vacuum channel (the acceptance is $3.8 \cdot 10^{-5}$ sr) at 8.4° to the proton beam. The channel is connected to the accelerator vacuum pipe without any partition and is shielded against the accelerator and the Earth magnetic fields. Pairs of $\pi^+\pi^-$ were detected in the $0.8 \div 2.4$ GeV/c pion momentum interval by drift chambers and scintillation counters. Cherenkov gas counters

and μ-identificators were used for rejection of electrons and muons, respectively. The experimental setup has a resolution on the relative momentum in c.m.s. of a pair of about 1 MeV/c.

Pions in "atomic" pairs have small relative momenta $Q < 3$ MeV/c. This signature allows to identify "atomic" pairs in the range of relative momenta $Q < 2$ MeV/c over the background of "free" pairs [1, 2].

The distribution of pionic pairs was fitted for $Q \gtrsim 3$ MeV/c (where "atomic" pairs are absent) by an approximating distribution based on the accidental $\pi^+\pi^-$ pair distribution. The number of "atomic" pairs was then determined as the difference between the total number of $\pi^+\pi^-$ pairs in the interval $Q \lesssim 2$ MeV/c and the corresponding number of "free" pairs, obtained for the same interval by an extrapolation of the curve fitted to the data in the region $Q \gtrsim 3$ MeV/c [1].

The following number of pairs in excess interpreted as "atomic" pairs was obtained: $n_A = 272 \pm 49$. This value is 71% [1] of the whole number of broken atoms. The number of "free" $\pi^+\pi^-$ pairs from short-lived sources for $Q < 2$ MeV/c was obtained from fitting also: $N_C = 983 \pm 54$.

Equation (1) allows to calculate the total number N_A of produced $A_{2\pi}$ from N_C. After a numerical integration of (1) and of the pion pair distribution in the interval $Q < 2$ MeV/c, taking into account multiple scattering in the target and the resolution of the detector, we have $N_A = 0.97 N_C$. The spectrum of $A_{2\pi}$ was obtained using (1). Thus the probability of $A_{2\pi}$ breakup in the tantalum target of the 8 μm thickness was found to be

$$P_{br} = 0.40 \pm 0.09 . \qquad (3)$$

The measured value of P_{br} depends on the $A_{2\pi}$ lifetime and on the interaction with target atoms leading to the $A_{2\pi}$ breakup. These processes can be calculated with enough accuracy to obtain P_{br} as a function of the lifetime and therefore to estimate τ_1 using the measured value of P_{br}.

3 Interaction cross section of $A_{2\pi}$ with target atoms.

After production in hadron-nucleus interaction $A_{2\pi}$ is moving in material of the target and interacts dominantly, via electromagnetic field with target atoms (Coulomb interaction). Cross sections of these processes depend on charge as Z^2 so that the interaction of $A_{2\pi}$ with atom electrons is Z times smaller than with the nucleus. For tantalum the interaction with atom electrons (so called incoherent scattering) increases the cross section by about 1.5% only [10]. As shown in [11, 12] one has also to take into account the interaction of $A_{2\pi}$ with magnetic fields that arise due to Lorentz transformation. For example, for the interaction of relativistic $A_{2\pi}$ with Pb the total cross section of the magnetic interaction is 0.4% of the electric one.

For the description of the Coulomb interaction of $A_{2\pi}$ with atoms we used the first Born approximation (see for example [13]) which considers only single photon exchange. Another method, the so called Coulomb-modified Glauber approximation, allows to take into account all multiphoton exchanges [14]. The accuracy of this method is estimated to go as $(Z^{1/3}\alpha)^2$ and for Ta it is better than 0.2%. It has been shown [14] that all the estimated cross sections at this approach are smaller than the ones

corresponding to the Born approximation. For the total cross section of $A_{2\pi}$ in 1S state with Ta this difference does not exceed 7%.

In the first Born approximation the transition and total cross sections of atom-atom interactions are expressed via atom form factors:

$$\sigma_i^f = 4\pi \frac{(Z\alpha)^2}{\beta^2} \int_0^\infty \left(1 - \frac{F_t(q)}{Z}\right)^2 |F_i^f(q/2)|^2 \frac{dq^2}{q^4} \qquad (4)$$

$$\sigma_i^{tot} = 8\pi \frac{(Z\alpha)^2}{\beta^2} \int_0^\infty \left(1 - \frac{F_t(q)}{Z}\right)^2 \left(1 - F_i^i(q)\right) \frac{dq^2}{q^4} . \qquad (5)$$

Here β is the velocity of $A_{2\pi}$ ($\hbar = c = 1$), i and f denote the initial and final discrete states of $A_{2\pi}$, $F_i^f(q)$ is the transition form factor of $A_{2\pi}$, $F_t(q)$ is the atomic form factor of the target atom, q is transfer momentum.

For $A_{2\pi}$ form factors $F_i^f(q)$ we employed exact analytic expressions (see [15]). For target atom form factors $F_t(q)$ we used the Moliére parametrization of the Thomas--Fermi potential [16] (T.F.M.). A more accurate representation of $F_t(q)$ can be achieved with the use of the self-consistent field method of Hartree-Fock [17, 18]. Calculations performed for interaction of $A_{2\pi}$ with various materials using these two methods [10] show that the uncertainty on the cross sections calculated with the T.F.M. parametrization is about 1% for the $A_{2\pi}$ ground state and slightly more for exited states.

Thus we calculated the transition and total cross sections for $A_{2\pi}$ interaction with target atoms to an uncertainty not greater than 7%. Using the more accurate methods mentioned above may allow to calculate cross sections within accuracy better than 0.5%.

Table 1: Total cross sections ($\sigma_{n\mathrm{S}}^{tot}$) of $A_{2\pi}$ nS state interaction with Ta are shown for different principal quantum number n. The ratio $\sum_{n_2 \le 10} \sigma_{n\mathrm{S}}^f / \sigma_{n\mathrm{S}}^{tot}$ gives a probability of transfer from nS state to any another discrete state f with the principal quantum number $n_2 \le 10$. The ratio $\sum_{n \le n_2 \le 10} \sigma_{n\mathrm{S}}^f / \sigma_{n\mathrm{S}}^{tot}$ gives a probability of transfer to any discrete state f with the principal quantum number n_2 obeying $n \le n_2 \le 10$ that is the probability of excitation.

n	$\sigma_{n\mathrm{S}}^{tot}$, cm^2	$\sum_{n_2 \le 10} \sigma_{n\mathrm{S}}^f / \sigma_{n\mathrm{S}}^{tot}$	$\sum_{n \le n_2 \le 10} \sigma_{n\mathrm{S}}^f / \sigma_{n\mathrm{S}}^{tot}$
1	$3.468 \cdot 10^{-20}$	0.619	0.619
2	$3.128 \cdot 10^{-19}$	0.887	0.887
3	$1.038 \cdot 10^{-18}$	0.940	0.935
4	$2.240 \cdot 10^{-18}$	0.957	0.946
5	$3.812 \cdot 10^{-18}$	0.960	0.944
6	$5.597 \cdot 10^{-18}$	0.958	0.937
7	$7.448 \cdot 10^{-18}$	0.952	0.926

In the Table 1 some illustrative values of the interaction cross sections with Ta are given for nS states. Total cross sections increase with increasing n and hence size of

the excited atoms. By interactions the exited $A_{2\pi}$ mainly transfer to some other exited states and predominantly to states with greater quantum numbers. The probability of excitation also increases with increasing n. So to obtain the probability of $A_{2\pi}$ breakup in the target we need to take into account an evolution of the atom state population during $A_{2\pi}$ passing through the target.

4 Description of $A_{2\pi}$ passing through a target.

Let us consider a scheme of calculation of the probability of $\pi^+\pi^-$ pair yield from the $A_{2\pi}$ breakup inside a target (in the following it will be called: probability of $A_{2\pi}$ breakup). Using the calculated transition (excitation and deexcitation) and the total cross sections we can describe the evolution of the atom state populations when passing through the target, taking also into account the $A_{2\pi}$ annihilation. For the calculation of the transition cross sections (4) we use form factors $F_i^J(q)$ of $A_{2\pi}$ obtained in the frame with quantization axis along the atom momentum. This axis is conserved for all subsequent collisions as the atom momentum is much greater than the transfered one. This allows us to describe the evolution of the atom state population in a simple way.

For this goal we used a set of differential kinetic equations:

$$\frac{dp_i(s)}{ds} = \sum_{j=1}^{\infty} a_{ij} p_j(s) . \tag{6}$$

Here $p_i(s)$ is the probability of $A_{2\pi}$ to be in the state i after travelling a distance s in the matter, a_{ij} is the matrix of inverse lengths of the transition from the state j to the state i. For $i \neq j$ a_{ij} is written

$$a_{ij} = \frac{\sigma_j^i \rho N_0}{A} . \tag{7}$$

Here ρ and A are the density and atomic weight of the target, respectively, N_0 is the Avogadro number. For $i = j$ the a_{ii} describes the total decrease of the population of the state i:

$$a_{ii} = -\frac{\sigma_i^{tot} \rho N_0}{A} - \begin{cases} M_A / p_A c \tau_n & \text{for } n\text{S states} \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

Here the first term is related to the population decrease due to interactions with the target and the second one is related to annihilation. (Elastic scattering is forbidden in the first Born approximation.) We neglect the decrease of population of any other states due to annihilation and we neglect the decrease of population of all states due to radiation transition as they have much greater lifetime for these processes than the time of flight through the target [2].

The initial condition for the set of equations (6) is given by the probability of $A_{2\pi}$ production with different quantum numbers (1). The lifetime and momentum of $A_{2\pi}$ are parameters of equation (6).

We have solved equation (6) for all states with $n \leq n_{max} = 7$. The uncertainty in solution of equation (6) caused by this limit has an influence only for states with n close to n_{max}, as atoms transfer occur mainly to states with the nearest quantum number.

Thus we know populations of all states with $n \leq n_{max}$ as a function of the path s in the target. This function takes into account excitation and deexcitation by interactions

with target atoms and $A_{2\pi}$ annihilation. $A_{2\pi}$ production is distributed uniformly over the target thickness. So we have to use the average values over this distribution for all discussed probabilities.

From calculations one can conclude that the sum of population of discrete atomic states P_{dsc} with $n \leq 7$ is known with precision much better than 1% and the summed population P_n of atomic states with fixed n has an asymptotical behavior $an^{-3} + bn^{-5} + \ldots$ at high n. We calculated the constants a and b and thus estimated the sum of populations of all other atomic states P_{tail} that were not included in the equation set ("tail" with $n > 7$). An uncertainty in this estimation (about 20%) has little influence on the final results because of the smallness of the "tail" (see (10)). Atoms annihilate mainly from 1S state (2). The population of the first few states is known with high accuracy so we evaluate the probability of $A_{2\pi}$ annihilation P_{anh} with the same accuracy.

Thus we have calculated the probability of $A_{2\pi}$ stays in a discrete state or annihilates while passing through the target. The remainder is the probability of the $A_{2\pi}$ breakup P_{br}:

$$P_{br} = 1 - P_{dsc} - P_{tail} - P_{anh} . \tag{9}$$

The following values of probabilities were obtained with $\tau_1 = 3.7 \cdot 10^{-15}$ s, the average momentum of $A_{2\pi}$ in the experiment $\langle p \rangle = 1.43$ GeV/c and the target thickness of 8 μm Ta.

$$P_{dsc} = 0.421, \quad P_{tail} = 0.006, \quad P_{anh} = 0.159 \quad \text{and} \quad P_{br} = 0.414 \tag{10}$$

To illustrate the validity of n_{max} limit used in these calculations, the value of P_{br} obtained with $n_{max} = 5$ differs from the above one obtained with $n_{max} = 7$ by 0.36%. From an analysis of the "tail" one can conclude that the accuracy the P_{br} calculation procedure is estimated not worse than 0.5%. This is much better than that of the precision on the cross sections. Thus the accuracy of P_{br} is limited by the precision of the cross section calculations and is found to be about 7%.

The approach discussed in this section neglects two effects. The first one is the formation time of atom states. This time is small in comparison with the time between subsequent collisions. We therefore neglect this formation time. This assumption is valid for levels with principal quantum numbers $n \leq 7$. Secondly we neglect possible interference effects between atom states with equal n and m and with orbital quantum numbers l that differ by $\Delta l = 2$. This interference is due to Coulomb degeneration of atom states. Its influence can not be significant because the interference is permitted only for states with $n \geq 3$ which have small populations. These two effects could be taken into account if one describes the evolution of atom by quantum mechanics equations in terms of density matrix elements.

In the Fig. 1 the $A_{2\pi}$ breakup probability averaged over the spectrum of atoms is shown as a function of the lifetime. Using this function and the measured value of P_{br} (3) we obtain an estimation of the $A_{2\pi}$ lifetime in the ground state

$$\tau_1 = (2.9^{+\infty}_{-2.1}) \cdot 10^{-15} \text{s} \tag{11}$$

or the limitation for the lifetime at 90% confidence level

$$\tau_1 > 0.6 \cdot 10^{-15} \text{s} . \tag{12}$$

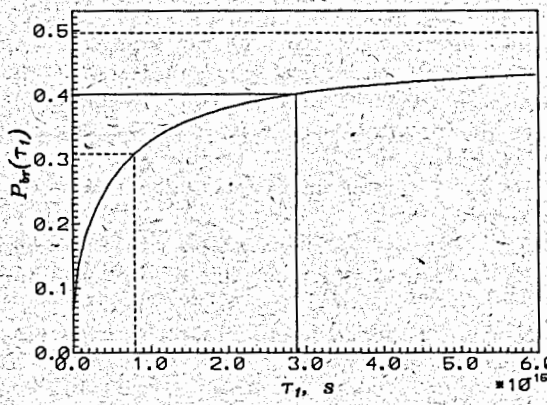

Figure 1: Probability of the $A_{2\pi}$ breakup in the target as a function of atom lifetime.

This result agrees with the theoretical value of $\tau_1 = (3.7 \pm 0.3) \cdot 10^{-15}$ s mentioned above.

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