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SEARCHES FOR d' RESONANCE IN DOUBLE CHARGE EXCHANGE REACTIONS OF π^+-MESONS ON NUCLEI IN NUCLEAR PHOTOEMULSION

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In the middle of the 80-ies both theoreticians and experimenters were very interested in studying the properties of dibaryonic states [1]. Their interest was due to the existence in QCD of an additional degree of freedom, colour, which allowed assuming the presence in the spectrum of six-quark states of unusual states with hidden colour [2].

In ref.[3], L.A.Kondratyuk, B.V.Martem'yanov and M.G.Schepkin considered in detail the features of the non-strange dibaryons spectrum within the framework of the model of "elongated rotating (stringlike) bag with colour quark clusters at their ends", and, which is especially important, the model took into account the spin-orbital interaction of quarks.

The most significant prediction of this model turned out to consist in the possible existence of the narrow d'-resonance ($T = 0$, $J^P = 2^-$) near the πNN energy threshold of mass in the range of 2.05 GeV, that is produced by interaction of incident particles with the two nucleons less separated in space.

The first experimental indication of the existence of such a resonance was obtained in ref.[4] in a measurement of the forward differential cross sections of the double charge exchange (DCX) of π^+-mesons on the ^{14}C nucleus – $^{14}C(\pi^+,\pi^-)^{14}O$ [DIAS] – in the 20÷100 MeV incident pion energy range. Contrary to the results of calculations within the framework of the Standard Model [5] (which assumed "sequential charge exchange" of the π^+-meson on two neutrons of the target nucleus: $\pi^+ \to \pi^0 \to \pi^-$), a maximum was observed at the pion kinetic energy $T_{\pi^+} = 50$ MeV.

A successful attempt at explanation of the unusual energy behaviour of the differential cross section DCX of π^+-mesons was undertaken by B.V.Martem'yanov and M.G.Schepkin [6], who assumed the existence in the process considered of a d'-resonance, exhibiting a sole decay mode into protons and a π^--meson.

Further confirmation of the existence of an isoscalar 0^- dibaryonic resonance, introduced into the nuclear environment, was provided by experiments carried out during the period of 1989-1998 at LAMPF, TRIUMF and PSI for measuring the energy dependence of $d\sigma/d\Omega(\theta = 5^0)$ DCX reactions of π^+-mesons on ^{12,14}C, ^{18}O, ^{42,44,48}Ca, ^{58}Fe nuclei [7,8].

From analysis of the obtained experimental data it follows that the peak observed in the vicinity of $T_{\pi^+} \approx 50$ MeV can be described for all the channels studied of the π^+-meson DCX reaction by the d'-resonance in the $pp\pi^-$ subsystem possessing $J^P = 0^-$, $T = 0$, a mass of 2065 MeV and $\Gamma = 0.50$ MeV (for the d'-resonance in vacuum) [7,8].

Taking into account the d'-dibaryon resonance with its measured parameters also significantly improves the agreement of experimental data with theoretical calculations in the description of the energy dependence of the total cross sections of π^+-meson DCX on the ^{4}He nucleus [9].

However, among the numerous experimental and theoretical confirmations of the existence of the d'-resonance there is also an alternative description of the maximum at $T_\pi \cong 50$ MeV in the energy behaviours of the cross section of π^+-meson DCX on nuclei. Thus, in ref.[10] it is shown that this peak arises naturally owing to the propagator in the ordinary sequential charge exchange $(\pi^+ \to \pi^0 \to \pi^-)$ and quite agrees with the experimental data. In this case, theoretical calculations of the pion DCX are based on the traditional impulse approximation of distorted waves, and the amplitude of this process is estimated in the second order not only for the distorted incoming (π^+) and outgoing (π^-) pion waves, but also for the distorted Green function of the π^0-mesons that described the pion propagator between the two nucleons.

Consequently, in order to clarify the above situation it is necessary to carry out direct experimental tests of the existence of the d'-resonance by measuring its invariant mass.

If the d'-resonance exists not only in a nuclear environment, but in vacuum also, then it can decay via the following channels:

$$d' \to np\pi^0 \qquad d' \to nn\pi^+ \qquad d' \to pp\pi^-$$

and in this case the most attractive reaction for revealing it experimentally is the channel

(1) $$pp \to \pi^+ d' \hookrightarrow pp\pi^-,$$

since all the particles in the final state will be charged.

Such an experiment was carried out at the ITEP accelerator in a proton beam of kinetic energy 920 MeV. Measurement of reaction (1) was performed by the difference method on two targets: CH_2 and C [11]. Analysis of the experimental data yielded the following parameters of the d'-resonance: $M_{d'} = (2057 \pm 2)$ MeV, $\Gamma = 10.8 \pm 2.1$ MeV, the d' production cross section in reaction (1) turned out to be ≤ 1 μb.

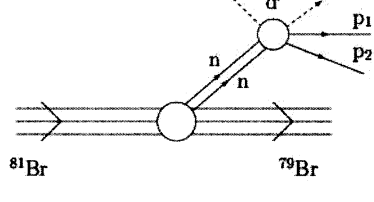
Subsequently, reaction (1) was studied at the storage ring of the CELSIUS accelerator by irradiation of the hydrogen clots a jet target with 750 MeV protons [12]. The spectrum of invariant masses $M_{pp\pi^-}$ obtained in this experiment (although the reliability of this measurement was not very high) reveals a peak in the vicinity of 2.063 GeV corresponding to the d'-resonance within three standard deviations from the distribution calculated by the Monte Carlo method for ordinary non-resonance production process of two π-mesons in pp-collisions, that accounts for a 7% contribution to the reaction.

In refs. [13-17] $\pi^\pm$-meson DCX was observed on the nuclei of photoemulsion, and some characteristics of these processes were studied in the 40÷140 MeV interval of pion kinetic energies.

The following was found:

1. The DCX cross sections of both positive and negative pions increase with the atomic number of the target nucleus; consequently, in photoemulsion this process will proceed mainly on heavy (Ar, Br) nuclei.
2. The π^+-meson DCX cross section is higher than the DCX cross section of π^--mesons throughout the entire energy interval. This fact can be explained by the excess of neutrons in the surface layer of heavy nuclei, which transform into two protons in the case of π^+-meson DCX and which leave the nucleus with a high probability. We note, also, that the reaction $(\pi^+ \rightarrow \pi^-)$ is energetically more advantageous owing to the difference between the neutron and proton masses.
3. The prong multiplicity distribution of π^+-pion DCX events in the photoemulsion revealed the average charged particle multiplicity (not counting the secondary pion and electrons) per single "star" to be 2.07±0.09 in the 40±140 MeV energy interval. This fact confirms the conclusion that, most likely, two secondary protons leave the nucleus with a high probability.
4. Analysis of all possible reaction channels of π^+-meson DCX on the nuclei present in photoemulsion revealed it to be impossible for "stars" with prong multiplicities inferior to two to be produced in the light nuclei (C, N, O), indicating that they resulted from pion interactions with Ag and Br nuclei. The same conclusion can be made concerning two-prong events without any fast electron leaving the center of the "star". From calculations by the cascade model it follows that approximately 80% of all the events of π^+-meson DCX in photoemulsion are due to interaction with the heavy nuclei [17].

Now consider the kinematical picture of the π^+-meson DCX process on the outer neutron shell of a heavy nucleus involving production in the intermediate state of a $d' \rightarrow p + p + \pi^-$. The corresponding diagram of this process, for example, on the ^{81}Br nucleus can be represented as follows:



(2) $\pi^+ + {}^{81}Br[2n + {}^{79}Br] \rightarrow d' + {}^{79}Br; \quad (d' \rightarrow \pi^- + p_1 + p_2)$.

The mass of the d'-resonance amounts to ~2.9% of the mass of the ^{79}Br nucleus ($M_{^{79}Br}$ = 73490 MeV), while the maximum energy of the incident π^+-meson is 140 MeV. Thus, the purely non-relativistic case is realized, in which the center-of-mass reference system of the reaction studied coincides with the laboratory system.

In kinematical calculations of the energy-momentum balance for reaction (2), within the experimental measurement accuracy, one may neglect the kinetic energy and momentum of the recoil nucleus owing to the large difference between the masses of the d'-resonance and of the ^{79}Br nucleus. Moreover, one should take into account that the mass of the target nucleus coincides within 2.5% with the mass of the residual nucleus. Taking into account these assumptions, we obtain that the momentum of the d'-resonance equals the momentum of the incident π^+-meson, while its effective mass can, then, be calculated by formula **[I]**.

[I] $$M_{d'}^{eff} = [(E_{p1} + E_{p2} + E_{\pi^-})^2 - (P_{\pi^+})^2]^{1/2},$$

where E_{p1}, E_{p2}, E_{π^-} are the respective total energies of the secondary nucleons and pion.

The full description of the experimental procedure for studying π^+-meson DCX reactions on nuclei in photoemulsion is presented in ref. [15]. Scanning of two photoemulsion chambers revealed 612 events of the reaction studied within the 72÷140 MeV incident pion energy interval. The number of events proceeding via the channel

(3) $$\pi^+ + \textit{"Nuclei in photoemulsion"} \rightarrow \pi^- + 2 \text{ charged particles}$$

was 210. To discard in reaction (3) the possible background, due to the interaction of pions with the light nuclei (C, N, O) in the photoemulsion, those events were selected that had no fast electron leaving the center of the "star". There turned out to be 146 such events.

For each of the selected events calculation was performed by formula **[I]** of the effective invariant mass of the secondary π^--meson and two protons. The resulting mass distribution is presented in Fig. 1. The curve shown in the figure was obtained by Monte Carlo phase space calculations of process (2) carried out by V.I.Kochkin (staff member of the JINR Laboratory of informational technologies) taking into account the energy distributions of the secondary π^--meson and of the protons, as well as the excitation function for the π^+-pion DCX process within the 72÷140 MeV incident pion energy interval.

From Fig. 1 it is seen that the calculated curve correctly reflects the shape of the experimental spectrum, with the exception of the (2060÷2072) MeV interval of effective masses, where a noticeable peak is observed that exceeds the theoretical curve by four standard deviations.

The average effective invariant mass of this peak is M_{eff} = (2065.5±3.6) MeV, which is in good agreement with all previous experimental and theoretical estimates of the d'-resonance mass.

The results of Monte Carlo theoretical calculations performed by the cascade model, and taking into account our experimentally obtained d'-resonance are presented in Fig. 1 (the solid curve). One can see that the calculated curve is in quite good agreement with the experimental data (the degree of agreement between the curve and the experimental distribution is characterized by $\frac{\chi^2}{\tilde{\chi}^2} = 1.3$).

The estimate of the d'-resonance production cross section via reaction (2) determined from the excess of the number of events above the phase space curve (Fig. 1) in the 2060÷2072 MeV interval of the effective mass spectrum amounts to $\sigma_{d'} \sim 0.15\,\text{mb}$.

Thus, the presented analysis of π^+-meson DCX events on heavy nuclei (Ag, Br) in photoemulsion allows to draw the following two important conclusions:

1. For the first time, on the basis of measurements of the effective invariant masses of secondary particles produced in the reaction $\pi^+ + {}^{81}Br({}^{109}Ag) \rightarrow \pi^- + p + p + {}^{79}Br({}^{107}Ag)$, experimental confirmation has been obtained of production of the d'-resonance of mass (2065.5±3.6) MeV in positive pion DCX processes on heavy nuclei in photoemulsion with a production cross section
$$\sigma_{d'} \sim 0.15\,\text{mb}.$$
2. With a high probability the process studied proceeds on the outer neutron shell that is weakly coupled to the heavy nucleus. Observation of the d'-resonance, considering the conditions of its production, permits making the conclusion that in the surface layer of a heavy nucleus there may exist compact pairs of neutrons (something like dineutron states).

The authors are grateful to V.I.Kochkin for carrying out Monte Carlo calculations.

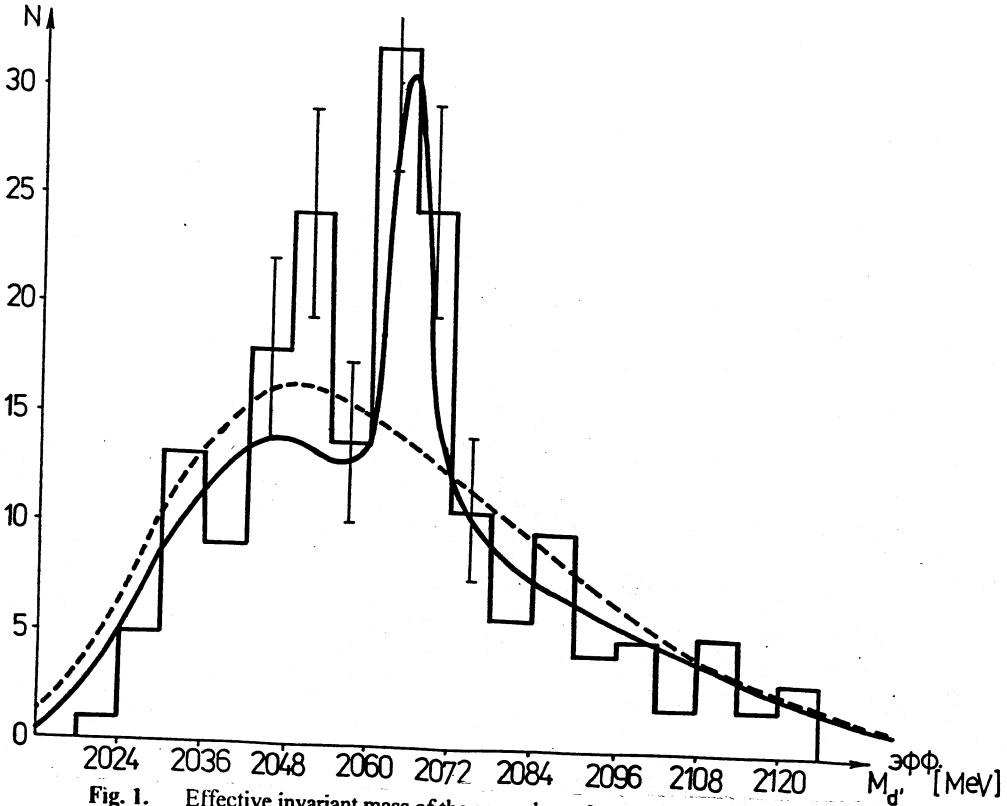


Fig. 1. Effective invariant mass of the secondary π^--meson and two protons. The dashed line (the invariant mass distribution) was obtained by Monte Carlo phase space calculations of process (2); The solid curve represents calculations performed by the cascade model taking into account our experimentally obtained d'-resonance.

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Батусов Ю. А. и др. E1-2002-227
Поиски d'-резонанса в реакциях двойной перезарядки π^+-мезонов на ядрах в фотоэмульсии

Проанализировано 797 событий реакций двойной перезарядки π^+-мезонов, зарегистрированных в фотоэмульсионных камерах, облученных в пучках π^+-мезонов синхроциклотрона ЛЯП ОИЯИ с энергиями 80 и 140 МэВ.

Для выделенных трехлучевых событий в интервале первичных энергий π^+-мезона 72 + 140 МэВ определена эффективная масса вторичных π^--мезона и двух протонов.

В спектре этих эффективных масс обнаружен пик в интервале 2060 ÷ 2072 МэВ со средним значением $M_{эфф}$ =(2065,5 ±3,6) МэВ. Полученная величина $M_{эфф}$ находится в хорошем согласии с массой d'-резонанса, наличие которого предполагалось в расчетах по модели струны в квантовой хромодинамике и было подтверждено в экспериментах по измерению зависимости от первичной энергии сечений реакций двойной перезарядки π^+-мезонов на ядрах и в процессе $pp \to pp\pi^-\pi^+$.

Работа выполнена в Лаборатории ядерных проблем им. В. П. Джелепова ОИЯИ.

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Batusov Yu. A. et al. E1-2002-227
Searches for d' Resonance in Double Charge Exchange Reactions of π^+-Mesons on Nuclei in Nuclear Photoemulsion

797 events have been analyzed in double charge exchange (DCX) reactions of π^+-mesons registered in photoemulsion chambers exposed in positive pion beams of the phasotron of the Dzhelepov Laboratory of Nuclear Problems (JINR) at energies of 80 and 140 MeV.

The effective invariant mass of the secondary π^--meson and the two protons was determined for each three-prong event identified within the energy range of the incident π^+-meson between 72 and 140 MeV.

The spectrum of effective masses reveals a peak in the 2060 ÷ 2072 MeV interval with a mean value equal to M_{eff} =(2065.5 ±3.6) MeV. The obtained value of M_{eff} is in a good agreement with the mass of the d' resonance hypothesized in «QCD-string» model calculations and confirmed by measurements of the dependence on the incident energy of the DCX cross sections of π^+-mesons on nuclei and in $pp \to pp\pi^-\pi^+$ process.

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

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