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Production of pentaquarks in pA-collisions

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We suggest a novel mechanism of production of hidden-charm pentaquarks in proton-nuclear collisions. We estimate the production cross-section and find that, due to lack of electroweak intermediaries, it considerably exceeds the total cross-section via weak decays of Λ_b, where pentaquarks were discovered. Additionally, the suggested process allows to check the existence of a neutral pentaquark P_c^0 (an isospin partner of P_c^+), as well as bottom sector analogs predicted in several models. The rapidity and transverse momentum distributions of pentaquarks could provide comprehensive information about the $\bar{c}c$ component of this exotic baryon.

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1. Introduction

The recent discovery of hidden charm pentaquarks, $P_c^+(4380)$ and $P_c^+(4450)$, in weak decays of Λ_b hyperons [1] renewed the interest in the study of exotic baryons predicted by Gell-Mann [3]. The existence of the pentaquarks is in line with existence of other exotic (tetraquark) candidates, early observations of attractive binding Van der Waals like interaction between $\bar{c}c$ and light nucleons [4, 5], and a plausible explanation for the large intrinsic charm of the proton [6, 7]. Experimentally available information on pentaquarks is very limited: we know their mass, decay widths and that $J/\psi\, p$ is one of the possible decay channels. A relatively large phase space available for decay products and narrow decay width suggests that a pentaquark could be a weakly bound state of the D-meson and charmed Λ_c/Σ_c-hyperon [8, 9, 10, 11], χ_c and p [12], J/ψ and light baryon [13], or $\psi(2S)$ and p [14]. From the QCD point of view, these cases differ by dominant component of $\bar{c}c$ wave functions. For the hadrocharmonium scenario, pentaquark has a compact $\bar{c}c$ pair in a color singlet state, separated by a large distance from light quarks. In the $\Sigma_c D$ or $\Lambda_c D$ molecule the c and $\bar{c}$ quarks are uncorrelated by color and separated by a large distance.

In order to clarify the structure of pentaquark, it is important to analyze additional decay channels [15], check for existence of other pentaquarks from $SU(3)$ flavor symmetry octet [17, 18, 19], as well as study other production mechanisms, like photoproduction of pentaquarks in γp [20, 21, 22] or πp collisions [23].

In this paper we suggest that P_c^+ might be produced in proton-nucleus collisions in forward kinematics, as a two-stage process discussed in the next Section 2. Due to absence of electroweak intermediaries, this process has a sizable cross-section which significantly exceeds the cross-section via Λ_b decays. The dynamics of the heavy $\bar{c}c$ pair is described by the perturbative QCD, and is relatively well understood from studies of charmonia and bottomonia production [24, 25, 26]. For this reason, in the suggested method we can directly relate the observed distributions of produced P_c^+ to distribution of $\bar{c}c$ pairs inside a pentaquark.

2. Pentaquark production via $\bar{c}c + p \to P_c^+$ subprocess

We argue that in pA collisions pentaquarks can be formed without electroweak intermediaries, via direct fusion of diffractively produced $\bar{c}c$ pairs with nucleons. The dynamics of a heavy $\bar{c}c$ pair is described by perturbative QCD and is reasonably well understood from quarkonium production. For this reason the process can be used to study the dynamics of a $\bar{c}c$ pair in P_c^+. For the sake of brevity and simpicity, in this proceeding we will consider only the case of $\chi_c p$ molecule, when the $\bar{c}c$ pair inside a pentaquark is in a color singlet P-wave and is separated by small distance (results for other scenarios may be found in our recent [27]). The Feynman diagram corresponding to this process is shown schematically in the Fig 1. A $\bar{c}c$-pair produced via a gluon splitting has a negative invariant mass, so in order to be able to produce a near-onshell $\bar{c}c$, it should interact at least once with the target. The cross-section for the diagram in the Figure 1 is given by

$$\begin{aligned} \frac{d\sigma^{(a)}}{dy} &= \frac{1+x_1}{x_1} x_1 g(x_1) \int d^2R_{cc}^{(1)} d^2R_{cc}^{(2)} d\alpha_c^{(1)} d^2r_{cc}^{(1)} d\alpha_c^{(2)} d^2r_{cc}^{(2)} \Phi_{\bar{c}c}^{\bar{\mu}\mu}\left(\alpha_c^{(1)}, \vec{r}_{cc}^{(1)}\right) \Phi_{\bar{c}c}^{\bar{\nu}\nu*}\left(\alpha_c^{(2)}, \vec{r}_{cc}^{(2)}\right) \\ &\times \Phi_D\left(-\frac{M_{P_c}}{M_{P_c}-2m_c}\vec{R}_{cc}^{(1)}\right) \Phi_D^*\left(-\frac{M_{P_c}}{M_{P_c}-2m_c}\vec{R}_{cc}^{(2)}\right) \mathscr{H}^{\bar{\mu}\mu}\left(\alpha_c^{(1)}, x_1, \vec{r}_{cc}^{(1)}, \vec{R}_{cc}^{(1)}\right) \mathscr{H}^{\bar{\nu}\nu}\left(\alpha_c^{(2)}, x_1, \vec{r}_{cc}^{(2)}, \vec{R}_{cc}^{(2)}\right)^* \end{aligned} \tag{2.1}$$

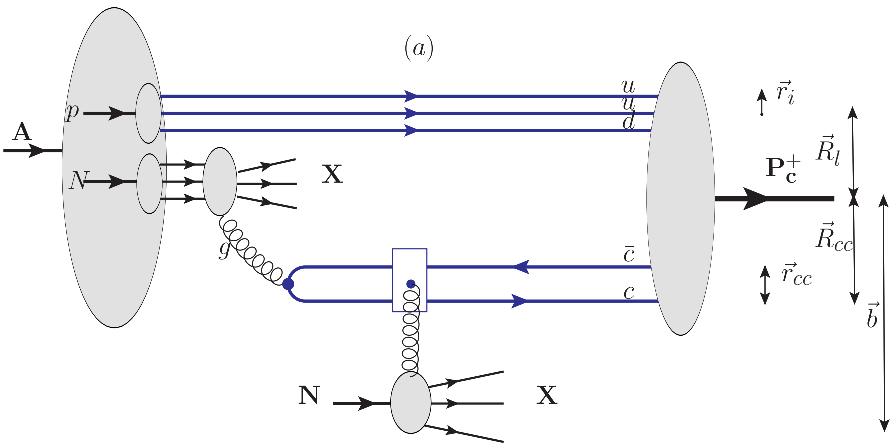

Figure 1: Lowest order perturbative diagram contributing to the pentaquark production if the $\bar{c}c$ pair is in color singlet P-wave state. The square block stands for a sum of diagrams with all possible attachments of t-channel gluons with heavy quarks. In order to probe the color singlet S-wave or color octet components of the $\bar{c}c$ pair, additional emission of a gluon is required.

$$\times\ \frac{1}{16}\left[\sigma\left(\alpha_c^{(1)}\vec{r}_{cc}^{(1)}+\bar{\alpha}_c^{(2)}\vec{r}_{cc}^{(2)}\right)+\sigma\left(\bar{\alpha}_c^{(1)}\vec{r}_{cc}^{(1)}+\alpha_c^{(2)}\vec{r}_{cc}^{(2)}\right)-\sigma\left(\alpha_c^{(1)}\vec{r}_{cc}^{(1)}-\alpha_c^{(2)}\vec{r}_{cc}^{(2)}\right)-\sigma\left(\bar{\alpha}_c^{(1)}\vec{r}_{cc}^{(1)}-\bar{\alpha}_c^{(2)}\vec{r}_{cc}^{(2)}\right)\right]$$

where x_1 is the light-cone fraction of the nucleon carried by the gluon, and is related to pentaquark rapidity y as

$$y=\ln\left(\frac{\sqrt{s}}{m_N}\right)=\frac{1}{2}\ln\left(\frac{P_c^+}{P_c^-}\right)=\ln\left(\frac{(1+x_1)\sqrt{s}}{\sqrt{M_{P_c}^2+P_\perp^2}}\right); \tag{2.2}$$

$x_1 g(x_1)$ is the gluon density in a projectile proton; superscript indices 1 and 2 refer to the normal and complex conjugate amplitudes; α_c and $\vec{r}_{cc}$ are the light-cone fraction and dipole size of the c-quark in a $\bar{c}c$ pair, and we also use variables $\vec{R}_{cc}$ for the distance between the center of mass of the pentaquark and the $\bar{c}c$ pair; $\vec{r}_i$ for the distance between the light quarks w.r.t. its center of mass. The notation $\mathscr{H}^{\bar{\mu}\mu}$ in (2.1) stands for the overlap of proton and pentaquark wave functions,

$$\begin{aligned}\mathscr{H}^{\bar{\mu}\mu}\left(\alpha_c,\xi,\vec{r}_{cc},\vec{R}_{cc}\right) &= \int\prod_{i=1}^{3}(d\alpha_i dr_i)\,\delta^2\left(\sum_i\vec{r}_i\right)\delta\left(1-\sum_i\alpha_i\right)d\alpha_c \\ &\times\ \Psi_{P_c}^{\dagger}\left(\frac{\alpha_i}{1+\xi},\vec{r}_i+\vec{R}_l;\ \frac{\alpha_c\xi}{1+\xi},\vec{R}_{\bar{c}c}-\alpha_c\vec{r}_{\bar{c}c},\ \frac{\bar{\alpha}_c\xi}{1+\xi},\vec{R}_{\bar{c}c}+\bar{\alpha}_c\vec{r}_{\bar{c}c}\right)^{\nu_1\nu_2\nu_3\bar{\mu}\mu}\Psi_p^{\nu_1\nu_2\nu_3}(\alpha_i,r_i),\end{aligned} \tag{2.3}$$

where Ψ_p and Ψ_{P_c} are the light-cone wave functions of the proton and pentaquark, $\bar{\mu}/\mu$ are spinor indices of the c and $\bar{c}$, and $\xi=\left(P_c^+-p^+\right)/p^+$ is the ratio of light-cone momenta of $\bar{c}c$ pair and light quarks. The antisymmetry of the expression in the third line of (2.1) under swap of coordinates of $\bar{c}$ and c quarks, $\alpha_i,\vec{r}_i\leftrightarrow\bar{\alpha}_i,-\vec{r}_i$, combined with a smallness of the produced $\bar{c}c$ dipoles, implies that this mechanism probes a $\bar{c}c$ pair in a P-wave in $\mathscr{H}^{\bar{\mu}\mu}$. For the wave function $\Phi_{\bar{c}c}^{\bar{\mu}\mu}(\alpha_c,r)$ of heavy $\bar{c}c$ dipole we use the well-known perturbative expression [28, 29]. The dipole cross-section $\sigma(r)$ implicitly depends on Bjorken variable x_2, for which we take a value $x_2\approx M_{cc}^2/(x_1 s)$. In (2.1) we assume that the light cone momentum of the nucleus is equally distributed among the nucleons, which is justified in view of the very narrow width of the light-cone distributions of nucleons inside the nucleus [27].

$\sqrt{s}$	$y_{min}\left(\sqrt{s}, P_c^{\perp}\approx 0\right)$	P-wave	S-wave
200 GeV	3.8	$0.6\,\mu$b	16 nb
7 TeV	7.4	$1.9\,\mu$b	120 nb
13 TeV	8	$2\,\mu$b	163 nb

Table 1: Total pentaquark production cross-sections for the case when $\bar{c}c$ pair inside P_c^+ is in color singlet state with different orbital momenta.

Our estimates of total pentaquark cross-sections are summarized in Table 1 for two cases, when the $\bar{c}c$ pair inside a pentaquark is either in P- or in S-wave (which requires emission of extra gluon from one of the heavy quarks). In both cases we assume that the wave function of $\bar{c}c$ pair inside pentaquark coincides with wave function of a charmonium with proper quantum numbers, which is justified when Van der Waals forces acting on $\bar{c}c$ are weak. Due to existence of a node in radial part, partial cancellation of contributions of large- and small-r_{cc}, and emission of additional gluon, the cross-section for S-wave production is smaller than for the P-wave.

The LHCb collaboration [1] detected $N\approx 10^3$ pentaquarks after analysis of $\mathscr{L}\approx 3\,\mathrm{fb}^{-1}$ data, which gives an estimate for the total cross-section

$$\sigma_{\rm LHCb}^{pp\to\Lambda_b\to P_c^+} = \frac{N}{\mathscr{L}} \sim 0.3\,\mathrm{pb}, \tag{2.4}$$

at least three orders of magnitude smaller than the mechanism which we suggest.

The rapidity dependence of the produced P_c^+ is shown in the Figure 2. The decrease of the curve at small $y - y_{min}(s)$ happens due to small-x suppression of the overlap of pentaquark and proton wave functions, and reflects the fact that the $\bar{c}c$ pair and the proton separated by a large rapidity gap cannot form a bound state. At large y we have a decrease due to suppression in the gluon PDF, which in the limit $x_1\to 1$ behaves as $\sim (1-x_1)^5$. Similar rapidity dependence is observed for all other cases of $\bar{c}c$ quantum numbers.

3. Conclusion

In this paper we suggested a novel mechanism of hidden charm pentaquark P_c^+ production in proton-nucleus collisions. A key advantage of the suggested mechanism is that it does not involve any electroweak intermediaries, and for this reason has a per-nucleon cross-section at least three orders of magnitude larger than the process mediated by weak decays of Λ_b [1]. An additional appeal of the suggested process is that it allows to access parameters of pentaquark wave function. In particular, a rapidity distribution of produced pentaquarks probes a fraction of pentaquark light-cone momentum carried by $\bar{c}c$ pair. A slope of the P_T-distribution is controlled by an average distance between center of mass of P_c^+ and center of the $\bar{c}c$ pair. If P_c^+ has neutral "siblings" with structure $udd\bar{c}c$ as suggested by several models [17, 18, 19], these could be also produced via $\bar{c}c+n\to P_c^0$ subprocess in pA collisions. In view of isospin invariance of strong interactions, the cross-section of such process is related to a P_c^+ production cross-section by a factor $(A-Z)/Z$. Similarly, this method can reproduce pentaquarks from bottom sector.

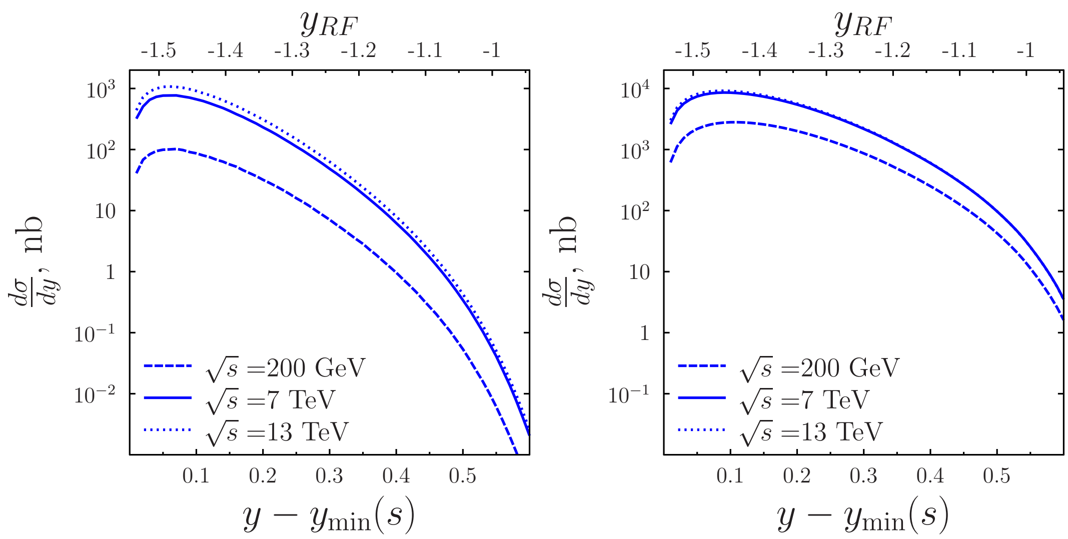

Figure 2: Rapidity dependence of the cross-section $d\sigma/dy$ (if the pentaquark has a $\bar{c}c$ pair in the color singlet S-wave (left) and P-wave (right)). y is a pentaquark rapidity in a nucleon-nucleon center of mass, the minimal rapidity of produced pentaquarks is $y_{\min} = \ln\left(\frac{(1+x_1)\sqrt{s}}{\sqrt{M_{P_c}^2+P_\perp^2}}\right)$, and $y_{RF} \equiv y - \ln\left(\frac{\sqrt{s}}{m_N}\right)$ is a pentaquark rapidity in the nucleus rest frame.

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