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Letter

Charmed hadron production from secondary $\overline{p} + p$ annihilations in p+A reactions at FAIR

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Abstract We present estimates for the production cross sections of charmed states (Λ_c, Σ_c, Ξ_c, D and D_s) from secondary $\overline{B} + B$ annihilations in p+A reactions from $E_{\rm lab} = 10 - 30A$ GeV. We focus specifically on the newly planned hadron physics program of CBM at FAIR. These estimates for the production of charmed states are based on the achievable number of $\overline{B} + B$ annihilations and their invariant mass distributions calculated in the UrQMD transport model.

1 Introduction

The exploration of exotic hadron states of QCD (Quantum-Chromo-Dynamics) has been among the main goals of hadron physics programs around the world. Most notably are the current results from BES III [1,2] in $e^+ + e^-$ reactions on the exploration of the X,Y,Z states, GlueX [3,4] with its investigation of charm production near the threshold in $\gamma + p$ reactions and the observation of the Ξ_{cc} at LHCb [5]. The PANDA experiment [6,7] at FAIR is supposed to contribute to these investigations using an anti-proton beam with initial momenta of up to 15 GeV. A major aim is to explore the properties of exotic (charmed) hadrons and glue-balls with unprecedented precision. With the currently expected delay of the PANDA experiment, a hadron physics program running as part of the CBM collaboration is developed as a bridge towards the program with anti-protons. This calls for a careful re-analysis of what part of the $\overline{p} + p$ program could be achieved in this new set-up.

The CBM experiment's main focus is on reactions of heavy nuclei to create compressed baryonic matter. Unfortunately, the collision energies for heavy nuclei are limited due to their small Z/A (Z is the proton number, A is the baryon number of the nuclei) to the range $\sqrt{s_{\rm NN}} = 3-5$ GeV, which is below the charm production threshold of ≈ 5 GeV for the J/Ψ in elementary nucleon-nucleon reactions. Multi-step processes in heavy ion reactions that allow for the accumulation of energy in heavy resonances have been suggested as sources for charm production near or even below the threshold of elementary nucleon-nucleon reactions [11].

However, the collision energy at FAIR can be increased, if one restricts the beam to proton projectiles. Here, beam energies of up to $E_{\rm lab}^{\rm proton} = 30A$ GeV are available, lifting the initial $\sqrt{s_{\rm NN}}$ to ≈ 7.7 GeV. Pioneering studies on charm production in this energy range have been performed e.g. in [9] based on production channels in $N + N$ and $\pi + N$. The cross section for open charm production has been estimated to be in the order of a few $10^{-2} \mu b$ in $N + N$ around $\sqrt{s_{\rm NN}} = 7.7$ GeV.

The production of charmed hadrons in $p + p$ reactions is still limited by their threshold energy and it is strongly suppressed even above the threshold [8–10], as the effective energy available for particle production in NN reactions is low, due to the large longitudinal motion of the outgoing baryons.

In the present work, we want to point to an alternative production mechanism that was intensely explored for PANDA, namely the production of charmed states in $\overline{B} + B$ annihilations. For the PANDA program, the anti-protons would have been produced in separate $p + A$ reactions with much higher collision rates, then collected and subsequently brought to collision with protons or nuclei. We suggest to use the same target nucleus for both, the production of the anti-baryons

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and their annihilation. This will allow to include our present knowledge on the production of charmed hadrons in $\overline{p}+p$ annihilations into the $p+A$ program and will further allow to scrutinize the high gluon densities reached in the annihilation process.

2 The case for $\overline{B}+B$ annihilations

As discussed above, the production of new quarks in color fields is usually strongly suppressed. Also in $\overline{p}+p$ annihilations a similar observation is expected naively, because according to the Okubo–Zweig–Iizuka (OZI) rule, processes that require quark annihilation followed by the creation of a disconnected quark pair should be highly suppressed. This suppression arises because the process relies on an intermediate state composed purely of gluons, which does not directly couple to the initial valence quarks. Consequently, the expected cross section for these reactions, based on OZI rule arguments, are usually very small (e.g. in the case $\overline{p}+p \rightarrow \phi+\phi$ on the order of nb). However, experimental results from the JETSET collaboration [12] contradict this expectation. JETSET observed an anomalously large cross section of $2-4\,\mu b$ for incoming anti-proton momenta corresponding to center-of-mass energies $\sqrt{s} \approx 2.12$ GeV (slightly above the threshold), which is approximately two orders of magnitude larger than the OZI rule prediction. This substantial violation of the OZI rule suggests the presence of additional dynamical effects beyond simple two-gluon exchange in $\overline{p}+p$ annihilations.

Several theoretical mechanisms have been proposed to explain the unexpectedly large cross sections in $\overline{p}+p$ annihilations:

- Glueball resonance production [13,14]: The intermediate gluonic state may form a resonant glueball, a bound state of gluons predicted by quantum chromodynamics (QCD). Such a state would naturally couple strongly to gluonic processes, leading to an enhancement in production. Since gluons are massless spin-1 particles, possible quantum numbers for a two-gluon system include 0^{++}, 0^{-+}, 2^{++}. Lattice QCD calculations predict glueball masses in the range of $2.39-2.56$ GeV, making them accessible in near-threshold production experiments.
- Coupling to broad four-quark states [15,16]: In the case of strangeness, the reaction may proceed via intermediate tetraquark states with significant strangeness content, such as the $\phi(2170)$ and the $X(2239)$. These states can act as intermediate resonances, enhancing production.
- Hidden strange or charm quark content in the proton and anti-proton [17]: If the proton and anti-proton wavefunctions contain a significant hidden strange or charm component, the reaction could occur with less suppression than traditionally expected.
- Baryon/meson exchange in the t- and u-channel [18,19]: Additional contributions from mesonic and baryonic exchange diagrams in the t- and u-channel could provide alternative reaction pathways, further increasing the cross section.

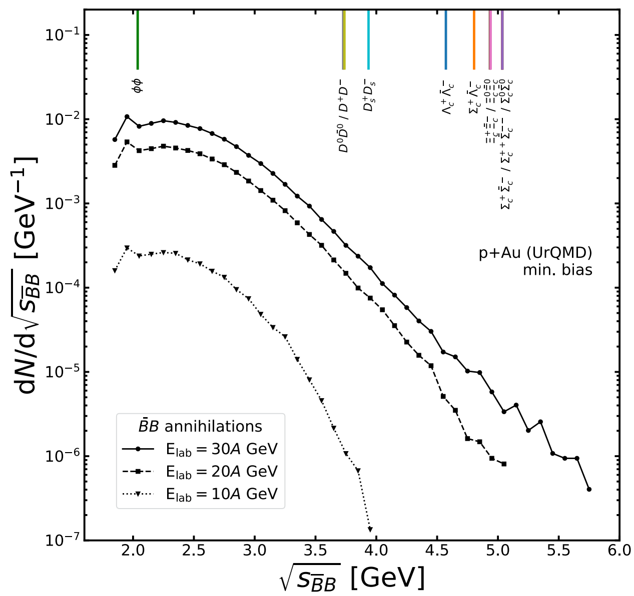

Fig. 1 [Color online] Differential distribution of center-of-mass energies $\sqrt{s_{\overline{B}B}}$ in $\overline{B}+B$ annihilations produced per min. bias p+Au reaction

Thus, a key to obtain these novel states is the creation of a gluon-rich environment. This makes anti-baryon+baryon annihilations a much better environment for the creation of charmed states in comparison to proton+proton reaction. In addition, the full annihilation energy is concentrated in a small volume in contrast to a longitudinally stretched color flux tube created in proton+proton reactions. Another advantage is that quantitative estimates for the production of these novel states in $\overline{p}+p$ annihilations are available [18,19], in contrast to $p+p$ reactions at low energies.

Therefore, we explore here the possibility to use secondarily produced anti-baryons, which annihilate in the same collision system to create the desired gluon-rich environment. We than fold the energy spectrum of the $\overline{B}+B$ annihilations with the previously obtained production cross sections of hitherto unexplored hadron channels and predict estimates for the experimental reach within the parameters of the CBM experiment (i.e. $E_{lab}^{proton}=10-30A$ GeV). One should note that we focus here only on the secondary anti-baryons and do not include the production of charmed states from (potentially possible) proton+nucleon interactions, thus, we obtain a lower limit.

Table 1 Threshold energies for the different charm and strangeness channels in proton-anti-proton annihilations

Reaction	Threshold [GeV]
$p\overline{p} \to \Lambda_c^+ \overline{\Lambda_c^-}$	4.572
$p\overline{p} \to \Sigma_c^+ \overline{\Lambda_c^-}$	4.804
$p\overline{p} \to \Sigma_c^+ \overline{\Sigma_c^-}$	5.036
$p\overline{p} \to \Sigma_c^{++} \overline{\Sigma_c^{--}}$	5.036
$p\overline{p} \to \Sigma_c^0 \overline{\Sigma_c^0}$	5.036
$p\overline{p} \to \Xi_c^+ \overline{\Xi_c^-}$	4.934
$p\overline{p} \to \Xi_c^0 \overline{\Xi_c^0}$	4.940
$p\overline{p} \to D^0 \overline{D^0}$	3.728
$p\overline{p} \to D^+ D^-$	3.738
$p\overline{p} \to D_s^+ D_s^-$	3.936
$p\overline{p} \to \phi\phi$	2.038

Table 2 Charmed baryon production cross sections, taken from [19], and charmed meson production cross sections, taken from [18], both at $\varepsilon = 25$ MeV above threshold

Reaction	$\sigma^{p\overline{p}\to x+y}$ [μb] at $\varepsilon = 25$ MeV		
	M/B exch	Quark model	Ref
$p\overline{p} \to \Lambda_c^+ \overline{\Lambda_c^-}$	3.33	0.97	[19]
$p\overline{p} \to \Sigma_c^+ \overline{\Lambda_c^-}$	0.41	0.015	[19]
$p\overline{p} \to \Sigma_c^+ \overline{\Sigma_c^-}$	0.24	0.001	[19]
$p\overline{p} \to \Sigma_c^{++} \overline{\Sigma_c^{--}}$	0.86	0.001	[19]
$p\overline{p} \to \Sigma_c^0 \overline{\Sigma_c^0}$	0.33	0.001	[19]
$p\overline{p} \to \Xi_c^+ \overline{\Xi_c^-}$	0.51	0.004	[19]
$p\overline{p} \to \Xi_c^0 \overline{\Xi_c^0}$	0.22	0.004	[19]
$p\overline{p} \to D^0 \overline{D^0}$	0.025	0.009	[18]
$p\overline{p} \to D^+ D^-$	0.03	0.007	[18]
$p\overline{p} \to D_s^+ D_s^-$	0.02	0.025	[18]
$p\overline{p} \to \phi\phi$	3	–	[12]

The double ϕ production cross section is taken from the JETSET data [12]

3 Simulations of the collision spectrum of $\overline{B} + B$ annihilations

We employ the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model [22,23] (v. 3.4) to calculate minimum bias[1] $p+Au$ reactions. The simulations are performed in cascade mode. UrQMD includes the production of anti-baryons via diquark-pair creation in the strings created in the individual proton+proton reactions. The production of anti-baryons in the planned CBM energy region has been investigated in the past (for the reaction $p + p \to \overline{p} + X$, see [20], for the production in nuclear systems, see [21]) and compares well to the experimental data. The anti-proton annihilation cross section is fitted to available experimental data. We observe that approx. 25% of the produced anti-protons are annihilated in the target nucleus in minimum bias p+Au reactions.

Let us start with the analysis of the spectrum of $\bar{B} + B$ annihilations in these proton+Au reactions at three different beam energies. The annihilations stem from anti-baryons that where initially produced and then annihilate within the same target nucleus. Figure 1 shows the distribution of the center-of-mass energy of all individual anti-baryon+baryon annihilations $\sqrt{s_{\bar{B}B}}$ per $p + Au$ event. One observes that the majority of annihilations is at energies below 3 GeV, however the spectrum stretches (especially in the case of 30 GeV initial proton energy) up to center of mass energies of $5-6$ GeV. Comparing these energies to the threshold energies for the production of charmed states, shown in Table 1, one can understand that these annihilations allow for the production of the Λ_c baryon and $D\overline{D}$ as well as more exotic final states.

[1] We define min. bias proton+Au reactions in the model as those with an impact parameter of $b \leq 6$ fm.

4 Production rates for charmed hadron production

To translate the simulated annihilation spectrum of anti-baryon+baryon annihilations, $dN/d\sqrt{s_{\bar{B}B}}$, into an estimate for the production cross section of charmed hadrons, we will use the cross sections for charm hadron production in $\overline{p}+p$. These cross sections have been explored intensively by Haidenbauer and Krein [18,19] and are shown in Table 2. As can be seen, the expected cross sections for charmed hadron production in annihilation differ drastically, depending on whether one employs the M/B exchange or quark model. We will use both scenarios to obtain the corresponding yields of charmed states from annihilations in the p+Au reactions. The cross section for ϕ production is taken from the JETSET data [12]. The charmed (hidden strange) hadron production cross sections can be transformed into a yield per annihilation via $N(x) = \sigma(\overline{p}p \to x)/\sigma(\overline{p}p)^{\text{ann}}$, assuming that $\sigma(\overline{p}p)^{\text{ann}} \approx 50$ mb, in the energy range considered. This yield per annihilation depends only weakly on the invariant mass, when starting about 25 MeV above the threshold. We assume that the charm (strangeness) production cross sections in anti-baryon+baryon annihilations are the same as in anti-proton+proton annihilations at the same center-of-mass energy.

With the simulated annihilation energy spectrum and for a typical running campaign of 90 days, we obtain the following estimates: Multiplying the number of $B\overline{B}$ annihilations per $p + Au$ event above the threshold (plus $\varepsilon = 25$ MeV) with the production rate of hadron species h_i per annihilation with the design collision rate of 10 MHz ($R = 10^7/s$) for $p + Au$ with the number of seconds in 90 days ($\Delta t_{90\,\mathrm{d}} \approx 7.8 \cdot 10^6 s$)

Table 3 Charmed (hidden strange) hadron yields per 90 days at full luminosity in min bias p+Au reactions at $E_{lab} = 30A$ GeV (left columns) and $E_{lab} = 20A$ GeV (right columns)

Hadron	Rate per 90 days p+Au			
	$E_{lab} = 30A$ GeV		$E_{lab} = 20A$ GeV	
	M/B exch	Quark model	M/B exch	Quark model
$\Lambda_c^+ \overline{\Lambda_c^-}$	$3.1 \cdot 10^4$	$9.0 \cdot 10^3$	$4.9 \cdot 10^3$	$1.4 \cdot 10^3$
$\Sigma_c^+ \overline{\Lambda_c^-}$	$2.2 \cdot 10^3$	$8.0 \cdot 10^1$	$2.7 \cdot 10^2$	$1.0 \cdot 10^1$
$\Sigma_c^+ \overline{\Sigma_c^-}$	$5.8 \cdot 10^2$	$2.0 \cdot 10^0$	$4.0 \cdot 10^1$	$0.2 \cdot 10^0$
$\Sigma_c^{++} \overline{\Sigma_c^{--}}$	$2.1 \cdot 10^3$	$2.0 \cdot 10^0$	$1.4 \cdot 10^2$	$0.2 \cdot 10^0$
$\Sigma_c^0 \overline{\Sigma_c^0}$	$8.0 \cdot 10^2$	$2.0 \cdot 10^0$	$5.5 \cdot 10^1$	$0.2 \cdot 10^0$
$\Xi_c^+ \overline{\Xi_c^-}$	$1.5 \cdot 10^3$	$1.2 \cdot 10^1$	$1.5 \cdot 10^2$	$1.2 \cdot 10^0$
$\Xi_c^0 \overline{\Xi_c^0}$	$6.5 \cdot 10^2$	$1.2 \cdot 10^1$	$6.5 \cdot 10^1$	$1.2 \cdot 10^0$
$D^0 \overline{D^0}$	$3.1 \cdot 10^3$	$1.1 \cdot 10^3$	$1.3 \cdot 10^3$	$4.6 \cdot 10^2$
$D^+ D^-$	$3.8 \cdot 10^3$	$8.8 \cdot 10^2$	$1.5 \cdot 10^3$	$3.6 \cdot 10^2$
$D_s^+ D_s^-$	$1.2 \cdot 10^3$	$1.6 \cdot 10^3$	$4.9 \cdot 10^2$	$6.0 \cdot 10^2$
$\phi\phi$	$3.9 \cdot 10^7$	–	$1.7 \cdot 10^7$	–

and obtain the rates in Table 3 for $E_{lab} = 30A$ GeV (left columns) and $E_{lab} = 20A$ GeV (right columns). For $E_{lab} = 10A$ GeV, the obtained yields are too low to be accessible by the experiment.

$$N^{90\,\mathrm{days}}(x) = R\ \Delta t_{90\,\mathrm{d}}\ \frac{\sigma^{\bar{p}p\to x}}{\sigma^{\bar{p}p}_{\mathrm{ann.}}} \int\limits_{\sqrt{s_{\mathrm{thr}}}+\varepsilon}^{\infty} \mathrm{d}\sqrt{s}\, \frac{\mathrm{d}N^{p+Au}_{\bar{\mathrm{B}}\mathrm{B}}}{\mathrm{d}\sqrt{s_{\bar{B}B}}} \qquad (1)$$

Thus, the rates do allow for exploratory studies of a multitude of charmed mesons and baryons. Even rather heavy charmed states like the D_s and the Ξ_c are in experimental reach.

5 Conclusion

Predictions for charmed hadron and double ϕ production in p+Au reactions in the FAIR energy range, $E_{lab} = 30A$ GeV and $E_{lab} = 20A$ GeV, were presented, assuming secondary charm and ϕ production by anti-baryon-baryon annhilations. These annihilations may provide a higher yield of charm states and double ϕ states than p+p reaction due to the gluon-rich environment created in annihilation events. Our simulations predict a small but still measurable amount of heavy charmed hadrons (e.g. D_s^+ and Ξ_c^+), which have never been observed at such low collision energies and which should be explored at FAIR.

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Code availability statement Code/software will be made available on reasonable request. [Author's comment: The model is available from the corresponding author on reasonable request.]

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