Pion-induced production of $\Lambda(1520)$ hyperons on nuclei near threshold

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Abstract

We study the pion-induced inclusive $\Lambda(1520)$ hyperon production from nuclei near threshold within a nuclear spectral function approach accounting for incoherent primary π^- meson-proton $\pi^-p \to K^0\Lambda(1520)$ production processes. We calculate the absolute differential and total cross sections for the production of $\Lambda(1520)$ hyperons off carbon and tungsten nuclei at laboratory angles of $0^{\circ}-10^{\circ}$, $10^{\circ}-45^{\circ}$ and $45^{\circ}-85^{\circ}$ by π^- mesons with momentum of 1.7 GeV/c as well as their relative (transparency ratio) differential and integral yields from these nuclei within four scenarios for their total in-medium width. We demonstrate that these absolute observables, contrary to the relative ones, reveal some sensitivity to the $\Lambda(1520)$ in-medium width. Therefore, their measurement in a dedicated experiment at the GSI pion beam facility will allow to shed light on this width.

1 Introduction

The study of the renormalization of the properties, masses and widths, of light vector mesons ρ , ω , ϕ , kaons and antikaons, η , η' and J/ψ mesons in nuclei has received considerable interest in recent years (see, for example, [1–9]). The in-medium properties of hyperons at finite density have also become a topic of intense current theoretical investigations [10–16]. Thus, for instance, the medium modifications of $\Sigma(1385)$ and $\Lambda(1520)$ hyperons have been studied within chiral unitary hadronic theory [10, 11]. Very small mass shifts of about -40 and -20 MeV have been predicted for the $\Sigma(1385)$ and $\Lambda(1520)$ hyperons, respectively, at rest at normal nuclear matter density ρ_0 . Moreover, a moderate increase of the width of $\Sigma(1385)$ by the factor ~ 2 –3 at density ρ_0 compared to the free width ~ 35 MeV and appreciable increase of the width of $\Lambda(1520)$ hyperons at this density by the factor ~ 5 with respect to the free width of 15.6 MeV has been calculated. The influence of the $\Lambda(1520)$ hyperon in-medium width on its yield from pA and γA reactions has been analyzed within collisional models [17–19] using an eikonal approximation. It has been shown that both the momentum dependence of the absolute $\Lambda(1520)$ hyperon yield and the A dependence of its relative yield are quite sensitive to the $\Lambda(1520)$ in-medium width.

Valuable information on the in-medium properties of $\Lambda(1520)$ hyperons, complementary to that from proton-nucleus and photon-nucleus collisions, can be inferred from pion-nucleus reactions. In this context, the main aim of the present study is to give the predictions for the absolute differential and total cross sections for production of $\Lambda(1520)$ hyperons in $\pi^{-12}C \to \Lambda(1520)X$ and $\pi^{-184}W \to \Lambda(1520)X$ reactions at 1.7 GeV/c incident pion momentum as well as for their relative (transparency ratio) differential and integral yields from these reactions within different scenarios for $\Lambda(1520)$ total in-medium width. These nuclear targets and this initial beam momentum were adopted in recent measurements [20] of π^- meson-induced ϕ meson production at the GSI pion beam facility using the HADES spectrometer and, therefore, can be employed in studying the $\pi^-A \to \Lambda(1520)X$ interactions here. The calculations are based on a first-collision model, developed in [21] for the analysis of the inclusive ϕ meson production data [20] and extended to account for different scenarios for the $\Lambda(1520)$ in-medium width. These calculations can be used as an important tool for determining the width from the data which could be taken in a dedicated experiment at the GSI pion beam facility.

2 Direct $\Lambda(1520)$ hyperon production mechanism

The $\Lambda(1520)$ hyperons can be produced directly in $\pi^- A$ ($A=^{12}\mathrm{C}$ and $^{184}\mathrm{W}$) reactions at incident momentum of 1.7 GeV/c in the following $\pi^- p$ elementary process with the lowest free production threshold momentum (1.68 GeV/c) $^{1)}$

$$\pi^- + p \to K^0 + \Lambda(1520).$$
 (1)

Taking into consideration that the in-medium threshold energy $^{2)}$ of the process (1) looks like that for the free final particles due to the cancelation of nuclear scalar potentials $U_{K^0} \approx +20$ MeV [5] and $U_{\Lambda(1520)} \approx -20$ MeV [10], felt by the K^0 mesons and low-momentum $\Lambda(1520)$ hyperons at saturation density ρ_0 , as well as for the reason of reducing the possible uncertainty of our calculations due to use in them of the model $\Lambda(1520)$ self-energy [10] at finite momenta studied in the present work, we will ignore here the medium modification of the outgoing hadron masses at these momenta.

¹⁾ We can neglect the processes $\pi^- N \to K\Lambda(1520)\pi$ with one pion in the final state at the incident pion momentum of 1.7 GeV/c, because they are energetically suppressed due to the fact that this momentum is less than their production threshold momentum of 1.98 GeV/c in vacuum $\pi^- N$ collisions. Moreover, taking into account the results of the study [21] of pion-induced ϕ meson production on ¹²C and ¹⁸⁴W nuclei at beam momentum of 1.7 GeV/c, we ignore in the present work by analogy with [21] the secondary pion–nucleon $\pi N \to K\Lambda(1520)$ production processes.

²⁾ Determining the strength of the $\Lambda(1520)$ production cross sections in π^-A collisions near threshold (cf. [21]).

Since the $\Lambda(1520)$ -nucleon elastic cross section is expected to be small similar to the ΛN elastic cross section at these momenta [22], we will neglect quasielastic $\Lambda(1520)N$ rescatterings in the present study. Then, accounting for the absorption of the incident pion and $\Lambda(1520)$ hyperon in nuclear matter as well as using the results given in [21], we represent the inclusive differential cross section for the production of $\Lambda(1520)$ hyperons with vacuum momentum $\mathbf{p}_{\Lambda(1520)}$ (or \mathbf{p}_{Λ^*}) on nuclei in the direct process (1) as follows:

$$\frac{d\sigma_{\pi^- A \to \Lambda(1520)X}^{\text{(prim)}}(\mathbf{p}_{\pi^-}, \mathbf{p}_{\Lambda^*})}{d\mathbf{p}_{\Lambda^*}} = I_V[A, \theta_{\Lambda^*}] \left(\frac{Z}{A}\right) \left\langle \frac{d\sigma_{\pi^- p \to K^0 \Lambda(1520)}(\mathbf{p}_{\pi^-}, \mathbf{p}_{\Lambda^*})}{d\mathbf{p}_{\Lambda^*}} \right\rangle_A, \tag{2}$$

where

$$I_{V}[A, \theta_{\Lambda^{*}}] = A \int_{0}^{R} r_{\perp} dr_{\perp} \int_{-\sqrt{R^{2} - r_{\perp}^{2}}}^{\sqrt{R^{2} - r_{\perp}^{2}}} dz \rho(\sqrt{r_{\perp}^{2} + z^{2}}) \exp \left[-\sigma_{\pi^{-}N}^{\text{tot}} A \int_{-\sqrt{R^{2} - r_{\perp}^{2}}}^{z} \rho(\sqrt{r_{\perp}^{2} + x^{2}}) dx \right]$$
(3)

$$\times \int\limits_0^{2\pi} d\varphi \exp \left[- \int\limits_0^{l(\theta_{\Lambda^*},\varphi)} \frac{dx}{\lambda_{\Lambda^*}(\sqrt{x^2 + 2a(\theta_{\Lambda^*},\varphi)x + b + R^2})} \right],$$

$$a(\theta_{\Lambda^*}, \varphi) = z \cos \theta_{\Lambda^*} + r_{\perp} \sin \theta_{\Lambda^*} \cos \varphi, \ b = r_{\perp}^2 + z^2 - R^2, \tag{4}$$

$$l(\theta_{\Lambda^*}, \varphi) = \sqrt{a^2(\theta_{\Lambda^*}, \varphi) - b} - a(\theta_{\Lambda^*}, \varphi), \tag{5}$$

$$\lambda_{\Lambda^*}(|\mathbf{r}|) = \frac{p_{\Lambda^*}}{M_{\Lambda^*}\Gamma_{\Lambda^*}(|\mathbf{r}|)} \tag{6}$$

and

$$\left\langle \frac{d\sigma_{\pi^{-}p\to K^{0}\Lambda(1520)}(\mathbf{p}_{\pi^{-}},\mathbf{p}_{\Lambda^{*}})}{d\mathbf{p}_{\Lambda^{*}}} \right\rangle_{A} = \int \int P_{A}(\mathbf{p}_{t},E)d\mathbf{p}_{t}dE
\times \left\{ \frac{d\sigma_{\pi^{-}p\to K^{0}\Lambda(1520)}[\sqrt{s},M_{\Lambda^{*}},m_{K^{0}},\mathbf{p}_{\Lambda^{*}}]}{d\mathbf{p}_{\Lambda^{*}}} \right\},$$
(7)

$$s = (E_{\pi^{-}} + E_t)^2 - (\mathbf{p}_{\pi^{-}} + \mathbf{p}_t)^2, \tag{8}$$

$$E_t = M_A - \sqrt{(-\mathbf{p}_t)^2 + (M_A - m_N + E)^2}.$$
 (9)

Here, $d\sigma_{\pi^-p\to K^0\Lambda(1520)}[\sqrt{s},M_{\Lambda^*},m_{K^0},\mathbf{p}_{\Lambda^*}]/d\mathbf{p}_{\Lambda^*}$ is the off-shell inclusive differential cross section for the production of $\Lambda(1520)$ hyperon and K^0 meson with free masses M_{Λ^*} and m_{K^0} , respectively. The $\Lambda(1520)$ hyperon is produced with vacuum momentum \mathbf{p}_{Λ^*} in reaction (1) at the π^-p center-of-mass energy \sqrt{s} . E_{π^-} and \mathbf{p}_{π^-} are the total energy and momentum of the incident pion $(E_{\pi^-} = \sqrt{m_{\pi}^2 + \mathbf{p}_{\pi^-}^2}, m_{\pi})$ is the free space pion mass); $\rho(\mathbf{r})$ and $P_A(\mathbf{p}_t, E)$ are the local nucleon density and the spectral function of the target nucleus A normalized to unity; \mathbf{p}_t and E are the internal momentum and removal energy of the struck target proton involved in the collision process (1); $\sigma_{\pi^-N}^{\rm tot}$ is the total cross section of the free π^-N interaction (we use in our calculations the value of $\sigma_{\pi^-N}^{\rm tot} = 35$ mb for initial pion momentum of 1.7 GeV/c [21]); $\Gamma_{\Lambda^*}(|\mathbf{r}|)$ is the total $\Lambda(1520)$ width in its rest frame, taken at the point \mathbf{r} inside the nucleus and at the pole mass M_{Λ^*} ; Z and A are the numbers of protons and nucleons in the target nucleus, and M_A and R are its mass and radius; m_N is the free space nucleon mass; and θ_{Λ^*} is the polar angle of vacuum momentum \mathbf{p}_{Λ^*} in the laboratory system with z-axis directed along the momentum \mathbf{p}_{π^-} of the incoming pion beam.

For the nuclear density $\rho(\mathbf{r})$ of the ¹²C and ¹⁸⁴W nuclei of interest, we have adopted, correspondingly, the harmonic oscillator and the Woods-Saxon distributions given in Ref. [21]. For these target nuclei, the nuclear spectral function $P_A(\mathbf{p}_t, E)$ was taken from Refs. [21, 23–25].

Following [21], we suppose that the off-shell differential cross section $d\sigma_{\pi^-p\to K^0\Lambda(1520)}[\sqrt{s}, M_{\Lambda^*}, m_{K^0}, \mathbf{p}_{\Lambda^*}]/d\mathbf{p}_{\Lambda^*}$ for $\Lambda(1520)$ production in process (1) is equivalent to the respective on-shell cross section calculated for the off-shell kinematics of this process as well as for the final $\Lambda(1520)$ and kaon free space masses M_{Λ^*} and m_{K^0} , respectively. Accounting for Eq. (14) from [21], we obtain the following expression for this cross section:

$$\frac{d\sigma_{\pi^- p \to K^0 \Lambda(1520)}[\sqrt{s}, M_{\Lambda^*}, m_{K^0}, \mathbf{p}_{\Lambda^*}]}{d\mathbf{p}_{\Lambda^*}} = \frac{\pi}{I_2[s, M_{\Lambda^*}, m_{K^0}]E_{\Lambda^*}}$$
(10)

$$\times \frac{d\sigma_{\pi^- p \to K^0 \Lambda(1520)}(\sqrt{s}, M_{\Lambda^*}, m_{K^0}, \theta^*_{\Lambda^*})}{d\Omega^*_{\Lambda^*}}$$

$$\times \frac{1}{(\omega + E_t)} \delta \left[\omega + E_t - \sqrt{m_{K^0}^2 + (\mathbf{Q} + \mathbf{p}_t)^2} \right],$$

where

$$I_2[s, M_{\Lambda^*}, m_{K^0}] = \frac{\pi}{2} \frac{\lambda[s, M_{\Lambda^*}^2, m_{K^0}^2]}{s},\tag{11}$$

$$\lambda(x,y,z) = \sqrt{\left[x - (\sqrt{y} + \sqrt{z})^2\right] \left[x - (\sqrt{y} - \sqrt{z})^2\right]},\tag{12}$$

$$\omega = E_{\pi^{-}} - E_{\Lambda^{*}}, \quad \mathbf{Q} = \mathbf{p}_{\pi^{-}} - \mathbf{p}_{\Lambda^{*}}, \quad E_{\Lambda^{*}} = \sqrt{M_{\Lambda^{*}}^{2} + \mathbf{p}_{\Lambda^{*}}^{2}}.$$
 (13)

Here, $d\sigma_{\pi^-p\to K^0\Lambda(1520)}(\sqrt{s}, M_{\Lambda^*}, m_{K^0}, \theta_{\Lambda^*}^*)/d\Omega_{\Lambda^*}^*$ is the off-shell differential cross section for the production of $\Lambda(1520)$ hyperons in reaction (1) under the polar angle $\theta_{\Lambda^*}^*$ in the π^-p c.m.s. This cross section is assumed to be isotropic in our model calculations of $\Lambda(1520)$ hyperon production in pion–nucleus interactions:

$$\frac{d\sigma_{\pi^{-}p\to K^{0}\Lambda(1520)}(\sqrt{s}, M_{\Lambda^{*}}, m_{K^{0}}, \theta_{\Lambda^{*}}^{*})}{d\Omega_{\Lambda^{*}}^{*}} = \frac{\sigma_{\pi^{-}p\to K^{0}\Lambda(1520)}(\sqrt{s}, \sqrt{s_{\text{th}}})}{4\pi}.$$
(14)

Here, $\sigma_{\pi^- p \to K^0 \Lambda(1520)}(\sqrt{s}, \sqrt{s_{\rm th}})$ is the "in-medium" total cross section of reaction (1) having the threshold energy $\sqrt{s_{\rm th}} = M_{\Lambda^*} + m_{K^0} = 2.017$ GeV. According to the aforesaid, it is equivalent to the vacuum cross section $\sigma_{\pi^- p \to K^0 \Lambda(1520)}(\sqrt{s}, \sqrt{s_{\rm th}})$, in which the free collision energy $s = (E_{\pi^-} + m_N)^2 - \mathbf{p}_{\pi^-}^2$ is replaced by the in-medium expression (8). For the vacuum total cross section $\sigma_{\pi^- p \to K^0 \Lambda(1520)}(\sqrt{s}, \sqrt{s_{\rm th}})$ we have employed the following parametrization suggested in Ref. [19]:

$$\sigma_{\pi^- p \to K^0 \Lambda(1520)}(\sqrt{s}, \sqrt{s_{\rm th}}) = \begin{cases} 123 \left(\sqrt{s} - \sqrt{s_{\rm th}}\right)^{0.47} \left[\mu b\right] & \text{for } 0 < \sqrt{s} - \sqrt{s_{\rm th}} \le 0.427 \text{ GeV}, \\ 26.6 / \left(\sqrt{s} - \sqrt{s_{\rm th}}\right)^{1.33} \left[\mu b\right] & \text{for } \sqrt{s} - \sqrt{s_{\rm th}} > 0.427 \text{ GeV}. \end{cases}$$
(15)

As seen from Fig. 1, the parametrization (15) (solid line) fits well the existing set of experimental data (full circles) [26] for the $\pi^-p \to K^0\Lambda(1520)$ reaction. One can also see that the on-shell cross section $\sigma_{\pi^-p\to K^0\Lambda(1520)}$ amounts approximately to 13 μ b for the initial pion momentum of 1.7 GeV/c and a free target proton being at rest. The off-shell cross section $\sigma_{\pi^-p\to K^0\Lambda(1520)}$, calculated in line with Eqs. (8), (9), (15) for a pion momentum of 1.7 GeV/c and a target proton bound in ¹²C by 16 MeV and having relevant internal momentum of 250 MeV/c, is about 53 μ b. This offers the possibility of measuring the $\Lambda(1520)$ yield in π^-A reactions at the very near-threshold beam momentum of 1.7 GeV/c at the GSI pion beam facility with sizeable strength.

Accounting for the HADES spectrometer acceptance, we will consider the $\Lambda(1520)$ momentum distributions on 12 C and 184 W target nuclei in three laboratory solid angles $\Delta\Omega_{\Lambda^*}=0^{\circ} \leq \theta_{\Lambda^*} \leq 10^{\circ}$, $10^{\circ} \leq \theta_{\Lambda^*} \leq 45^{\circ}$, $45^{\circ} \leq \theta_{\Lambda^*} \leq 85^{\circ}$ and $0 \leq \varphi_{\Lambda^*} \leq 2\pi$. Here, φ_{Λ^*} is the azimuthal angle of the

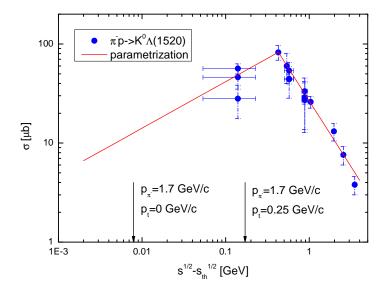


Figure 1: (color online) Total cross section for the reaction $\pi^-p \to K^0\Lambda(1520)$ as a function of the excess energy $\sqrt{s} - \sqrt{s_{\rm th}}$. The left and right arrows indicate the excess energies $\sqrt{s} - \sqrt{s_{\rm th}} = 7.9~{\rm MeV}$ and $\sqrt{s} - \sqrt{s_{\rm th}} = 171~{\rm MeV}$ corresponding to the incident pion momentum of $|\mathbf{p}_{\pi^-}| = 1.7~{\rm GeV/c}$ and a free target proton at rest and a target proton bound in $^{12}{\rm C}$ by 16 MeV and having momentum of 250 MeV/c directed opposite to the incoming pion beam. For the rest of notation see text.

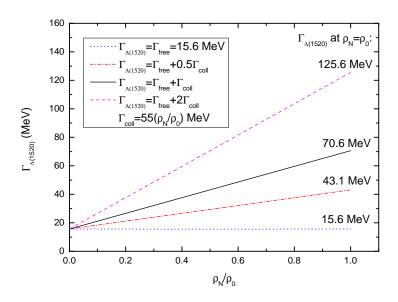


Figure 2: (color online) $\Lambda(1520)$ hyperon total width in its rest frame as a function of the density. For notation see text.

 $\Lambda(1520)$ momentum \mathbf{p}_{Λ^*} in the laboratory system. Integrating the full inclusive differential cross section (2) over these ranges, we can represent the differential cross section for $\Lambda(1520)$ hyperon production in π^-A collisions from the direct process (1), corresponding to the HADES acceptance

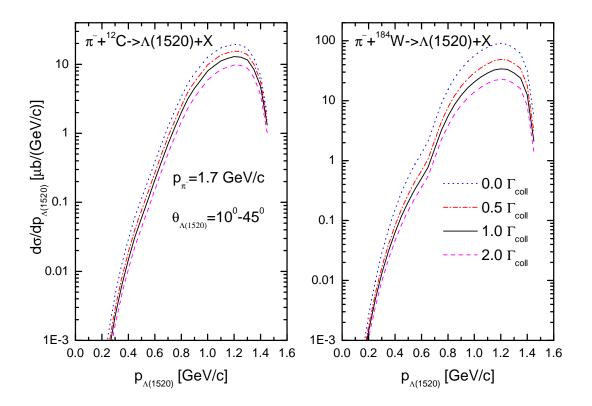


Figure 3: (color online) Momentum differential cross sections for the production of $\Lambda(1520)$ hyperons from the primary $\pi^-p \to K^0\Lambda(1520)$ channel in the laboratory polar angular range of $10^\circ-45^\circ$ in the interaction of π^- mesons of momentum of 1.7 GeV/c with 12 C (left) and 184 W (right) nuclei, calculated within different scenarios for the total $\Lambda(1520)$ hyperon in-medium width in which its collisional width was multiplied by the factors indicated in the inset.

window 3), in the following form:

$$\frac{d\sigma_{\pi^- A \to \Lambda(1520)X}^{(\text{prim})}(p_{\pi^-}, p_{\Lambda^*})}{dp_{\Lambda^*}} = \int_{\Delta\Omega_{\Lambda^*}} d\Omega_{\Lambda^*} \frac{d\sigma_{\pi^- A \to \Lambda(1520)X}^{(\text{prim})}(\mathbf{p}_{\pi^-}, \mathbf{p}_{\Lambda^*})}{d\mathbf{p}_{\Lambda^*}} p_{\Lambda^*}^2$$

$$= 2\pi \left(\frac{Z}{A}\right) \int_{a}^{b} d\cos\theta_{\Lambda^*} I_V[A, \theta_{\Lambda^*}] \left\langle \frac{d\sigma_{\pi^- p \to K^0 \Lambda(1520)}(p_{\pi^-}, p_{\Lambda^*}, \theta_{\Lambda^*})}{dp_{\Lambda^*} d\Omega_{\Lambda^*}} \right\rangle_{A}, \tag{16}$$

where $(a, b) = (\cos 10^{\circ}, 1), (\cos 45^{\circ}, \cos 10^{\circ})$ and $(\cos 85^{\circ}, \cos 45^{\circ})$.

We define now the $\Lambda(1520)$ total in-medium width appearing in Eq. (6) and used in our calculations of $\Lambda(1520)$ production in π^-A reactions. For this width, we employ two different scenarios [19]: i) no in-medium effects and, correspondingly, the scenario with the free $\Lambda(1520)$ width (dotted line in Fig. 2); ii) the sum of the free $\Lambda(1520)$ width and its collisional width Γ_{coll} of the type [10, 11, 17] $55(\rho_N/\rho_0)$ MeV, where ρ_N is the total nucleon density (solid line ⁴⁾ in Fig. 2). In order to study the sensitivity of the $\Lambda(1520)$ hyperon production cross sections from the channel (1) to its total in-medium width we will also adopt in our calculations yet two additional scenarios for this

³⁾ At HADES the $\Lambda(1520)$ hyperons could be identified via the decays $\Lambda(1520) \to K^- p$ with a branching ratio of 22.5%.

⁴⁾ In this scenario the resulting total width of the $\Lambda(1520)$ hyperon reaches the value of about 70 MeV at the normal nuclear matter density ρ_0 , which is a factor of ~ 5 larger than the free one.

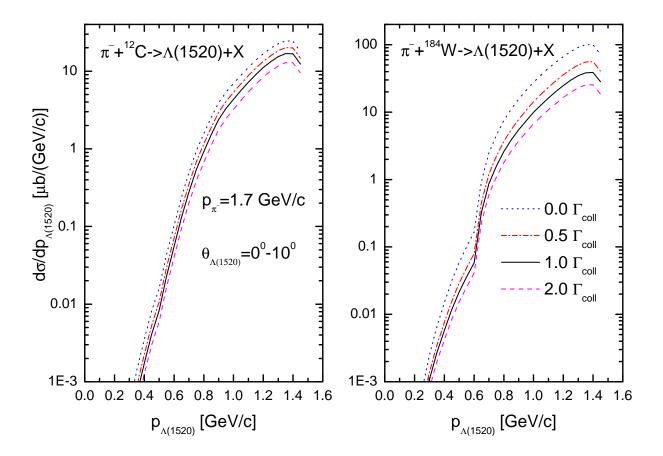


Figure 4: (color online) The same as in Fig.3 but for the laboratory polar angular range of 0°-10°.

width, in which, as compared to the scenario ii), the $\Lambda(1520)$ nominal collisional width $\Gamma_{\rm coll}$ defined above was artificially multiplied by factors f=0.5 and f=2 [17] (dotted-dashed and dashed lines in Fig. 2) ⁵⁾.

The $\Lambda(1520)$ in-medium width can be extracted from a comparison of the calculated (see Eq. (16)) and measured momentum distributions on $^{12}\mathrm{C}$ and $^{184}\mathrm{W}$ target nuclei. Additionally, valuable information concerning the $\Lambda(1520)$ absorption in nuclear matter can be obtained [17, 19] from a comparison of the calculations with the measured transparency ratio of the $\Lambda(1520)$ hyperon, normalized to carbon:

$$T_A = \frac{12}{A} \frac{\sigma_{\Lambda(1520)}^A}{\sigma_{\Lambda(1520)}^C},\tag{17}$$

where $\sigma_{\Lambda(1520)}^A$ and $\sigma_{\Lambda(1520)}^C$ are the inclusive differential (16) or total ⁶⁾ cross sections for $\Lambda(1520)$ production in π^-A and π^-C collisions, respectively.

⁵⁾ Evidently, the first two scenarios for the total $\Lambda(1520)$ in-medium width correspond to the factors f=0 and f=1.

⁶⁾ Obtained by integration of the differential cross sections (16) over $\Lambda(1520)$ momentum.

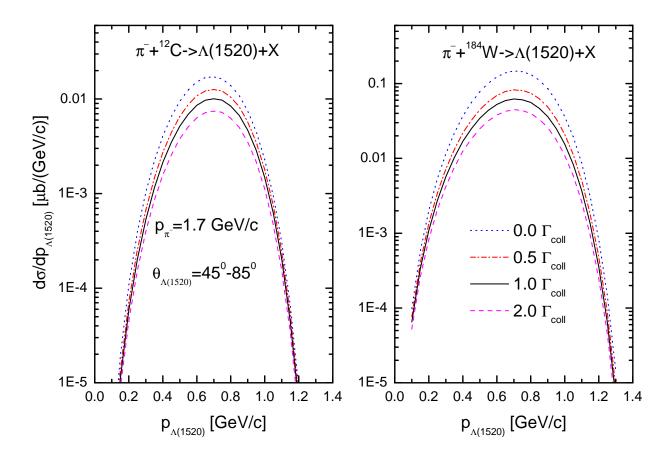


Figure 5: (color online) The same as in Fig.3 but for the laboratory polar angular range of 45°-85°.

3 Results and discussion

At first, we consider the absolute $\Lambda(1520)$ momentum differential cross sections from the direct process (1) in $\pi^{-12}\mathrm{C}$ and $\pi^{-184}\mathrm{W}$ collisions for an incident pion momentum of 1.7 GeV/c. These cross sections were calculated according to Eq. (16) in four considered scenarios for the total $\Lambda(1520)$ in-medium width (see Fig. 2) at laboratory angles of $10^{\circ}-45^{\circ}$, $0^{\circ}-10^{\circ}$ and $45^{\circ}-85^{\circ}$. They are given, respectively, in Figs. 3, 4 and 5. One can see that the $\Lambda(1520)$ hyperons are mainly emitted at laboratory angles $\leq 45^{\circ}$ belonging to the HADES acceptance window. The absolute values of the differential cross sections have at these angles a well measurable strength $\sim 1-100~\mu\text{b}/(\text{GeV/c})$ in the high-momentum region of 0.7-1.4~GeV/c. Here there are a sizeable differences, especially for the heavy target nucleus $^{184}\mathrm{W}$, between the results obtained by using different $\Lambda(1520)$ in-medium widths under consideration. They are $\sim 20-30\%$ for $^{12}\mathrm{C}$ and $\sim 30-50\%$ for $^{184}\mathrm{W}$ between all calculations corresponding to different choices for this width.

To see more clearly the sensitivity of the $\Lambda(1520)$ hyperon yield to its in-medium width, we show in Fig. 6 on a linear scale the ratio between the differential cross sections for $\Lambda(1520)$ hyperon production on 12 C and 184 W nuclei, calculated for different options for its total in-medium width as presented in Figs. 3, 4, and the respective differential cross sections, determined in the scenario where the absorption of $\Lambda(1520)$ hyperons in nuclear matter is governed by their free width. It is seen that there are indeed experimentally distinguishable differences between the considered options for the $\Lambda(1520)$ in-medium width for both target nuclei and for both forward laboratory polar $\Lambda(1520)$

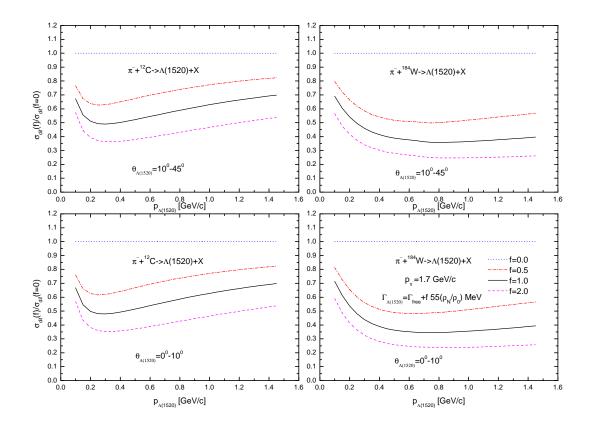


Figure 6: (color online) Ratio between the differential cross sections of $\Lambda(1520)$ production on $^{12}\mathrm{C}$ and $^{184}\mathrm{W}$ target nuclei at laboratory angles of $10^{\circ}-45^{\circ}$ (upper two panels) and $0^{\circ}-10^{\circ}$ (lower two panels) by 1.7 GeV/c π^- mesons in the primary $\pi^-p \to K^0\Lambda(1520)$ reactions calculated within different scenarios for the total $\Lambda(1520)$ hyperon in-medium width in which its collisional width was multiplied by the factors indicated in the inset, and the same cross sections, obtained in the scenario where the absorption of $\Lambda(1520)$ hyperons in nuclear matter is governed by their free width (dotted curve in Fig. 2), as a function of $\Lambda(1520)$ momentum.

angular domains. Thus, for example, the $\Lambda(1520)$ momentum distributions are reduced at collisional width $0.5 \cdot \Gamma_{\rm coll}$ by factors of about 1.3 and 2.0 as compared to those obtained without this width at momentum of 1.0 GeV/c and laboratory angular range of 0°–10° for ¹²C and ¹⁸⁴W target nuclei, respectively. When going from $0.5 \cdot \Gamma_{\rm coll}$ to $1.0 \cdot \Gamma_{\rm coll}$, the corresponding reduction factors are of about 1.2 and 1.4 at these $\Lambda(1520)$ momentum and angular range; while they are about 1.4 and 1.5 when going from $1.0 \cdot \Gamma_{\rm coll}$ to $2.0 \cdot \Gamma_{\rm coll}$.

We, therefore, come to the conclusion that the in-medium properties of $\Lambda(1520)$ hyperons could be in principle studied at the GSI pion beam facility, using the HADES spectrometer, through the momentum dependence of their absolute production cross sections in π^-A interactions at an initial pion momentum of 1.7 GeV/c.

The sensitivity of the $\Lambda(1520)$ production differential cross sections at laboratory angles $\leq 45^{\circ}$ in the momentum range ~ 0.7 –1.4 GeV/c (where they are largest) to its in-medium width, shown in Figs. 3, 4, can be also studied from such integral measurements as the measurements of the total cross sections for $\Lambda(1520)$ production in $\pi^{-12}\mathrm{C}$ and $\pi^{-184}\mathrm{W}$ reactions by 1.7 GeV/c pions in the full-

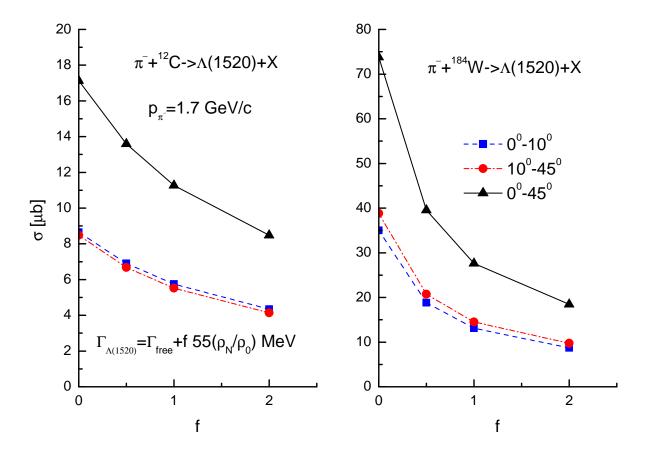


Figure 7: (color online) The total cross sections for the production of $\Lambda(1520)$ hyperons from the primary $\pi^-p \to K^0\Lambda(1520)$ channel on $^{12}\mathrm{C}$ and $^{184}\mathrm{W}$ target nuclei with momenta of 0.1– $1.45~\mathrm{GeV/c}$ in the laboratory polar angular ranges of 0° – 10° , 10° – 45° and 0° – 45° by 1.7 GeV/c π^- mesons as functions of the factor f by which we multiply their collisional width in our model calculations. The lines are to guide the eye.

momentum region of 0.1–1.45 GeV/c. These cross sections, calculated for the $\Lambda(1520)$ laboratory angular ranges of 0°–10°, 10°–45° and 0°–45° by integrating Eq. (16) over the $\Lambda(1520)$ momentum p_{Λ^*} in these ranges, are shown in Fig. 7 as functions of the factor f by which the $\Lambda(1520)$ collisional width [10, 11, 17] was multiplied in our model calculations. One can see that the total cross sections in the angular regions of 0°–10° and 10°–45° are practically the same for both target nuclei. They, as well as the sum of them (angular domain of 0°–45°) reveal some sensitivity to the total $\Lambda(1520)$ in-medium width. Thus, the $\Lambda(1520)$ total cross sections in these three angular domains are reduced at collisional width $0.5 \cdot \Gamma_{\rm coll}$ by factors of about 1.3 and 1.9 as compared to those obtained without this width for $^{12}{\rm C}$ and $^{184}{\rm W}$ target nuclei, respectively. When going from $0.5 \cdot \Gamma_{\rm coll}$ to $1.0 \cdot \Gamma_{\rm coll}$, the corresponding reduction factors are about 1.2 and 1.4; and they are about 1.3 and 1.5 when going from $1.0 \cdot \Gamma_{\rm coll}$ to $2.0 \cdot \Gamma_{\rm coll}$. Therefore, a comparison of the "integral" results, presented in Fig. 7, with the respective experimentally determined total $\Lambda(1520)$ hyperon production cross sections will also allow one to obtain information about its in-medium width.

Fig. 8 shows the momentum dependence of the transparency ratio T_A for the target combination W/C for $\Lambda(1520)$ hyperons produced in the direct reaction channel (1) at laboratory angles of 0°–10° and 10°–45° by 1.7 GeV/c pions. The transparency ratio is calculated on the basis of Eq. (17)

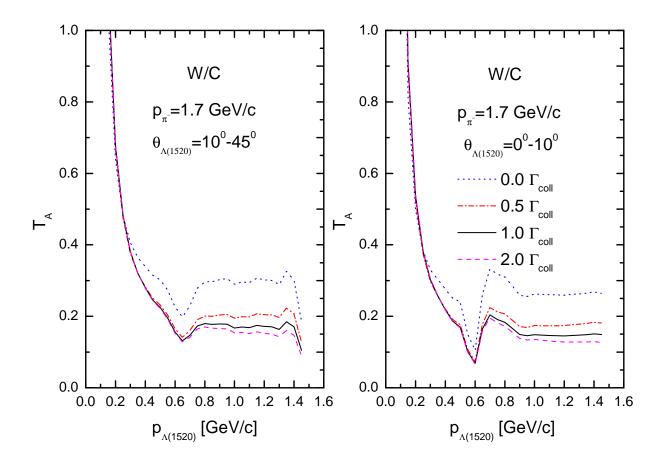


Figure 8: (color online) Transparency ratio T_A as a function of the $\Lambda(1520)$ momentum for combination $^{184}\text{W}/^{12}\text{C}$ as well as for the $\Lambda(1520)$ laboratory polar angular ranges of 10° – 45° (left) and 0° – 10° (right), for an incident π^- meson momentum of 1.7 GeV/c, calculated within different scenarios for the total $\Lambda(1520)$ hyperon in-medium width where its collisional width is multiplied by the factors indicated in the inset.

using the results obtained for the adopted options of the $\Lambda(1520)$ in-medium width and given in Figs. 3, 4. It is seen from this figure that there are measurable changes $\sim 30\%$ in the quantity T_A only between calculations corresponding to the cases when the loss of $\Lambda(1520)$ hyperons in nuclear matter is determined by their free width and by the sum of this width and collisional width of the type $0.5 \cdot \Gamma_{\rm coll}$ at the momenta of interest $\sim 0.7-1.4~{\rm GeV/c}$. On the other hand, the differences between the choices $0.5 \cdot \Gamma_{\rm coll}$ and $1.0 \cdot \Gamma_{\rm coll}$, $1.0 \cdot \Gamma_{\rm coll}$ and $2.0 \cdot \Gamma_{\rm coll}$ for $\Lambda(1520)$ collisional width are almost insignificant. They are $\sim 10-15\%$. This means that the momentum dependence of the transparency ratio cannot be employed for reliable determination of the $\Lambda(1520)$ in-medium width from the HADES near-threshold $\Lambda(1520)$ production measurements in π^-A interactions. The transparency ratio T_A exhibits dips at momenta $\sim 0.6-0.7~{\rm GeV/c}$. This can be explained by the fact that the differential cross sections for $\Lambda(1520)$ production on ¹⁸⁴W target nucleus "is bent down" at these momenta (see Figs. 3, 4) due to the off-shell kinematics of the first chance π^-p collision and the role played by the nucleus-related effects such as the struck target proton binding and Fermi motion, encoded in the nuclear spectral function $P_A(\mathbf{p}_t, E)$. The spectral functions for ¹²C and ¹⁸⁴W, adopted in the calculations, are different [21, 23–25].

In Fig. 9 we show the "integral" transparency ratio T_A for the target combination W/C for

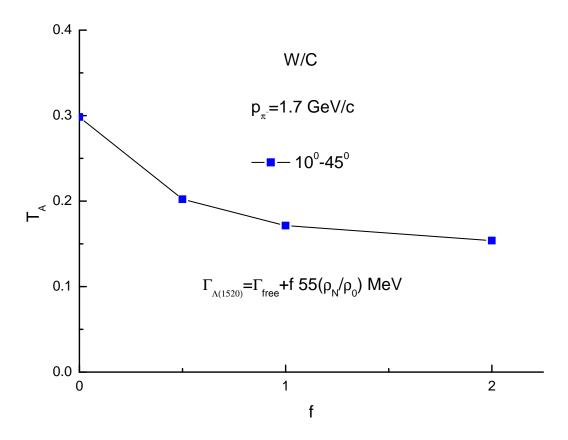


Figure 9: (color online) Transparency ratio T_A for $\Lambda(1520)$ hyperons from primary $\pi^- p \to K^0 \Lambda(1520)$ reactions at incident π^- meson momentum of 1.7 GeV/c for the target combination $^{184}\text{W}/^{12}\text{C}$ as well as for the $\Lambda(1520)$ laboratory polar angular range of $10^{\circ}-45^{\circ}$ and momentum range of 0.1-1.45 GeV/c as a function of the factor f. The line is to guide the eye.

 $\Lambda(1520)$ hyperons produced at laboratory angles of 10°-45° and momenta of 0.1–1.45 GeV/c by 1.7 GeV/c pions as a function of the factor f by which their nominal collisional width predicted in [10, 11, 17] is multiplied in our calculations. This "integral" quantity is calculated according to Eq. (17) using the results for the total $\Lambda(1520)$ production cross sections presented in Fig. 7. One can see that the differences between all calculations corresponding to different choices of the $\Lambda(1520)$ in-medium width are similar to those of Fig. 8.

Taking into account the above consideration, we can conclude that the $\Lambda(1520)$ absolute momentum distribution measurements in near-threshold $\pi^{-12}C$ and $\pi^{-184}W$ reactions might allow one to shed light on the $\Lambda(1520)$ in-medium width. However, its relative yield (both "differential" and "integral") in these reactions cannot serve as reliable tool for determining this width.

4 Conclusions

In the present paper we study the pion-induced inclusive $\Lambda(1520)$ hyperon production from 12 C and 184 W target nuclei near threshold within a nuclear spectral function approach accounting for incoherent primary π^- meson–proton $\pi^-p \to K^0\Lambda(1520)$ production processes. We calculate the

absolute differential and total cross sections for production of $\Lambda(1520)$ hyperons off these nuclei at laboratory angles of 0°-10°, 10°-45° and 45°-85° by 1.7 GeV/c π^- mesons as well as their relative (transparency ratio) differential and integral yields for four scenarios of the $\Lambda(1520)$ total in-medium width. We demonstrate that these absolute observables, contrary to the relative ones, reveal some sensitivity to the $\Lambda(1520)$ in-medium width. Therefore, their measurement in a dedicated experiment at the GSI pion beam facility will allow to shed light on this width.

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References

- [1] R. Rapp and J. Wambach, Adv. Nucl. Phys. 25, 1 (2000).
- [2] R. S. Hayano and T. Hatsuda, Rev. Mod. Phys. 82, 2949 (2010).
- [3] S. Leupold, V. Metag, and U. Mosel, Int. J. Mod. Phys. E19, 147 (2010).
- [4] G. Krein, A. W. Thomas, and K. Tsushima, arXiv:1706.02688 [hep-ph].
- [5] V. Metag, M. Nanova, and E. Ya. Paryev, Prog. Part. Nucl. Phys. 97, 199 (2017).
- [6] A. Gal, E. V. Hungerford and D. J. Millener, Rev. Mod. Phys. 88, 035004 (2016).
- [7] K. Tsushima et al., Phys. Rev. C 83, 065208 (2011);
 G. Krein, A. W. Thomas, and K. Tsushima, Phys. Lett. B 697, 136 (2011).
- [8] E. Ya. Paryev, Yu. T. Kiselev, and Yu. M. Zaitsev, Nucl. Phys. A 968, 1 (2017);
 - E. Ya. Paryev and Yu. T. Kiselev, Nucl. Phys. A **978**, 201 (2018);
 - E. Ya. Paryev and Yu. T. Kiselev, Phys. Atom. Nucl. Vol. 80, No.1, 67 (2017);
 - E. Ya. Paryev and Yu. T. Kiselev, Phys. Atom. Nucl. Vol. 81, No.5, 566 (2018);
 - E. Ya. Paryev, Nucl. Phys. A **988**, 24 (2019).
- [9] S. D. Bass and P. Moskal, arXiv:1810.12290 [hep-ph].
- [10] M. M. Kaskulov and E. Oset, Phys. Rev. C 73, 045213 (2006).
- [11] M. M. Kaskulov and E. Oset, AIP Conf. Proc. **842**, 483–5 (2006).
- [12] M. F. M. Lutz, C. L. Copra and M. Moeller, Nucl. Phys. A 808, 124 (2008).
- [13] D. Cabrera et al., Phys. Rev. C 90, 055207 (2014).
- [14] S. Petschauer *et al.*, Eur. Phys. J. A **52**, 15 (2016).
- [15] E. Ya. Paryev, M. Hartmann, and Yu. T. Kiselev, Chinese Physics C, Vol. 41, No. (12), 124108 (2017).
- [16] Z. Q. Feng, W. J. Xie, and G. M. Jin, Phys. Rev. C 90, 064604 (2014).

- [17] M. Kaskulov, L. Roca and E. Oset, Eur. Phys. J. A 28, 139 (2006).
- [18] E. Ya. Paryev, Phys. Atom. Nucl. Vol. **75**, No.12, 1523 (2012).
- [19] E. Ya. Paryev, J. Phys. G: Nucl. Part. Phys. 37, 105101 (2010).
- [20] J. Adamczewski-Musch et al. (HADES Collaboration), Phys. Rev. Lett. 123, 022002 (2019).
- [21] E. Ya. Paryev, Chinese Physics C, Vol. 42, No. (8), 084101 (2018).
- [22] J. A. Kadyk et al., Nucl. Phys. B 27, 13 (1971);
 J. M. Hauptman, J. A. Kadyk, and G. H. Trilling, Nucl. Phys. B 125, 29 (1977).
- [23] S. V. Efremov and E. Ya. Paryev, Eur. Phys. J. A 1, 99 (1998).
- [24] E. Ya. Paryev, Eur. Phys. J. A 9, 521 (2000).
- [25] E. Ya. Paryev, Eur. Phys. J. A 7, 127 (2000).
- [26] A. Baldini *et al.*, in Total Cross Sections of High Energy Particles, edited by H. Schopper, Landolt-Börnstein, New Series, Vol. I/12a, Springer-Verlag, Berlin (1988).