Exploring kaon induced reactions for unraveling the nature of the scalar meson $a_0(1817)$

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In this work, we investigate the production of isovector scalar meson $a_0(1817)$ by the effective Lagrangian approach. Specifically, we employ the Reggeized t channel Born term to calculate the total and differential cross sections for the reaction $K^-p \to a_0(1817)\Lambda$. Our analysis reveals that the optimal energy range for detecting the $a_0(1817)$ meson lies between $W = 3.4$ GeV and $W = 3.6$ GeV, where the predicted total cross section reaches a minimum value of 112 nb. Notably, the t channel, as predicted by the Regge model, significantly enhances the differential cross sections, particularly at extreme forward angles. Furthermore, we investigate the Dalitz processes of $2 \to 3$ and discuss the feasibility of detecting the $a_0(1817)$ meson in experiments like J-PARC.

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I. INTRODUCTION

The $a_0(1817)$ meson has attracted the attention from the community of hadron physics, as its study provides valuable insights into the intricacies of constructing the light flavor scalar meson family. Recent experimental findings have added to the intrigue surrounding this meson. The *BABAR* Collaboration, through the $\eta_c \to \eta\pi^+\pi^-$ reaction, discovered a new state named $a_0(1700)$, which has a measured mass of $1704 \pm 5(\text{stat.}) \pm 2(\text{syst.})$ MeV and a width of $\Gamma = 110 \pm 15(\text{stat.}) \pm 11(\text{syst.})$ MeV [1]. Additionally, the BESIII Collaboration observed a state denoted as the $a_0(1710)^0$ in the $D_S^+ \to K_S^0 K_S^0 \pi^+$ reaction. However, in this detection process, it was not possible to differentiate between the $a_0(1710)^0$ and $f_0(1710)$, leading to a generalization of both states as $S_0(1710)$ [2]. It was later resolved in a subsequent article using the isospin theorem, which distinguished the isospin $I = 1$ state $a_0(1710)$ from the isospin $I = 0$ state $f_0(1710)$ [3]. Subsequently, the BESIII Collaboration conducted another experiment to study the $a_0(1710)^+$ state with the quantum numbers $I(J^P) = 1^+(0^+)$. The observation of $a_0(1710)^+ \to K_S^0 K^+$ was made through an investigation of the $D_S^+ \to K_S^0 K^+ \pi^0$ decay [4]. This experiment reported the mass and decay width of the newly discovered meson as $M = 1.817 \pm 0.008(\text{stat.}) \pm 0.020(\text{syst.})$ GeV and $\Gamma = 0.097 \pm 0.022(\text{stat.}) \pm 0.015(\text{syst.})$ GeV, respectively. In accordance with the suggestion given by the Lanzhou group *et al.* [5], we adopt the name $a_0(1817)$ for this newly discovered isovector scalar meson in our work.

However, there exist discrepancies in the measured mass and decay width of the $a_0(1817)$ meson as observed by the *BABAR* experiment [1] and the BESIII experiment [3]. Moreover, due to the limited number of relevant experiments and available experimental data, further observations of the $a_0(1817)$ meson in alternative experiments are necessary. These observations would facilitate the measurement of pertinent resonance parameters and provide a more comprehensive understanding of the properties associated with the $a_0(1817)$ meson.

Recent research by the Lanzhou group [5] has indicated that the $a_0(1817)$ meson can be as a scaling point in the construction of scalar meson families. Its primary decay channels include $\pi\eta(1295)$, $\pi\eta'$, $\pi\eta$, $\pi\eta(1475)$, $\pi b_1(1235)$, $K\bar{K}$, and others, with specific details provided in Table I.

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TABLE I. The partial decay widths of the $a_0(1817)$ predicted in Ref. [5].

Channel	$\pi\eta$	$\pi\eta'$	$\pi\eta(1295)$	$\pi\eta(1475)$
Γ (MeV)	$22.4 \sim 24.9$	$27.8 \sim 36.2$	$18.0 \sim 47.5$	$6.2 \sim 34.2$
Channel	$\pi b_1(1235)$	$K\bar{K}$	$\pi f_1(1285)$	$\rho\omega$
Γ (MeV)	$10.8 \sim 19.2$	$7.5 \sim 12.9$	$0.2 \sim 9.5$	$0.1 \sim 3.3$

Theoretical conjectures propose that the $a_0(1450)$ and $a_0(1817)$ represent the first and second radial excitations, respectively, of the $a_0(980)$ meson [6]. Additionally, it is predicted that the $a_0(2115)$ serves as the third radial excitation, contributing to the expanding landscape of the light hadron spectrum [5]. Understanding the inner structure of the $a_0(1817)$ is crucial, as it sheds light on the structural characteristics of scalar mesons in the realm of light quarks, while also addressing other pertinent issues currently under debate in the field of hadron physics [7–10]. The $a_0(980)$ has been extensively studied both theoretically and experimentally [11–13]. Previous studies have considered the possibility of the $a_0(980)$ as a tetraquark candidate [14], and the $a_0(1450)$ as a hybrid state comprising a combination of double and quadruple quarks [15]. The $f_0(1710)$ meson [16,17], serving as the isovector partner of the $a_0(1817)$, does not rule out the possibility of being a scalar glueball. However, given the limited information available on the structure of the $a_0(1817)$, further resonance measurements are imperative. Consequently, the pressing task at hand involves detecting the $a_0(1817)$ in other experimental settings.

Upon consulting the Particle Data Group [18], we find that the K^-p scattering experiment is particularly noteworthy. Since the discovery of K-mesons [19], kaon beams have naturally emerged as a powerful tool for exploring strange hadrons and hypernuclei [20]. Experimental facilities such as J-PARC [21] and OKA@U-70 [22] offer excellent opportunities for such investigations. Several literature sources have presented the production of the $a_0(980)$ in the reaction $K^-p \to \Lambda\eta\pi^+\pi^-$ [23–26]. The discovery of the $\phi(1020)$ meson has been achieved in the reaction $K^-p \to KKn$ [27]. Moreover, the $a_1(1260)$ and $D(1285)$ mesons have been observed in the reactions $K^-p \to \Sigma^-\pi^+\pi^+\pi^-$ [28] and $K^-p \to \Lambda\eta\pi^+\pi^-$ [25], respectively. These examples provide further support for the possibility of observing $a_0(1817)$ in K^-p scattering experiments. In our previous work, we successfully calculated the production of the $\phi(2170)$ meson via the reaction $K^-p \to \phi(2170)\Lambda$ [20], the $X_0(2900)$ state in $K^+p \to \Sigma_c^{++}X_0(2900)$ [29], and the $\eta_1(1855)$ meson through $K^-p \to \eta_1(1855)\Lambda$ [30] using efficient Lagrangian methods and the Regge trajectory model. The numerical results obtained from these calculations provide valuable insights for future experimental endeavors.

In this study, we explore the production mechanism of the scalar meson $a_0(1817)$ in K^-p scattering utilizing an efficient Lagrangian approach, focusing on meson-induced reactions with K-meson exchange solely in the t-channel. Detailed information regarding our methodology will be presented in the subsequent section. The calculation of both the total cross section and differential cross section for the $K^-p \to a_0(1817)\Lambda$ reaction holds significant relevance for future high-precision experimental investigations in this field.

This paper is structured as follows: In Sec. II, we present the efficient Lagrangian method and the Regge trajectory model employed for the analysis of the $a_0(1817)$. The numerical results for the total and differential cross sections are presented in Sec. III. Finally, we summarize our findings and draw conclusions in Sec. IV.

II. FORMALISM

The production of the scalar meson $a_0(1817)$ through kaon-induced reactions on a proton target, with t channel K^+ meson exchange, is illustrated in Fig. 1. In this study, we neglect the contribution from the s channel with nucleon pole, as it is known to be negligibly small. Typically, the contribution of the u channel with nucleon exchange is also minimal and can be neglected at low energies. Moreover, at high energies, the Reggeized treatment of the u channel renders its contribution to the total cross section small and negligible. Therefore, we do not include the contributions from nucleon resonances in the u-channel in the current calculation.

Studying the strong interaction at the quark-gluon level in the energy region where the resonance can be detected poses significant challenges. Therefore, in this study, we employ the effective Lagrangian method to perform the necessary calculations. In the case of kaon-induced production of the $a_0(1817)$, the relevant Lagrangians for the t channel are given by [31–34]

$$\mathcal{L}_{a_0KK} = \frac{f_{a_0KK}}{2m_K} a_0 \partial_\mu \vec{K} \cdot \partial^\mu \vec{K}, \tag{1}$$

$$\mathcal{L}_{KN\Lambda} = ig_{KN\Lambda}\bar{N}\gamma_5\Lambda K + \text{H.c.}, \tag{2}$$

with the isodoublets $K^T = (K^+, K^0)$ and $N^T = (p, n)$. Moreover, the a_0, K, N and Λ stand for the $a_0(1817)$, K, nucleon and Λ fields, respectively.

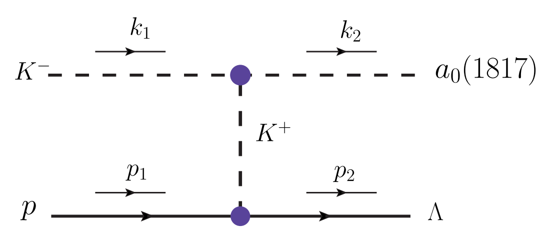

FIG. 1. Feynman diagram for the $K^-p \to a_0(1817)\Lambda$ reaction.

The coupling constant $g_{KN\Lambda}$, which can be determined [34–37] based on the SU(3) flavor symmetry relation.

$$g_{KN\Lambda} = \frac{1}{\sqrt{3}}(1+2\alpha)g_{\pi NN} = -13.24. \quad (3)$$

with $\alpha = 0.365$ and $g_{\pi NN}^2/4\pi = 14.0$. In the present work, this interaction is achieved by pseudoscalar coupling, which is equivalent to pseudovector coupling since the nucleon and Λ are on their mass- shell. Additionally, the coupling constant f_{a_0KK} can be determined from the decay width $\Gamma_{a_0\to\bar{K}K}$.

$$\Gamma_{a_0\to K^+K^-} = \frac{2}{3}\Gamma_{a_0\to\bar{K}K} = \left(\frac{f_{a_0KK}}{2m_K}\right)^2 \frac{(M_{a_0}^2 - 2m_K^2)^2}{32\pi M_{a_0}^2} |\vec{p}_K^{\,\mathrm{c.m.}}|$$

with

$$|\vec{p}_K^{\,\mathrm{c.m.}}| = \frac{\lambda^{1/2}(M_{a_0}^2, m_K^2, m_K^2)}{2M_{a_0}}. \quad (4)$$

Here, λ represents the Källen function, defined as $\lambda(x,y,z) = \sqrt{(x-y-z)^2 - 4yz}$. M_{a_0} and m_K denote the masses of $a_0(1817)$ and the kaon meson, respectively. By considering the decay width $\Gamma_{a_0\to K^+K^-}$ to be 5 MeV, we find that the corresponding coupling constant f_{a_0KK} is determined to be 0.52.

Based on the aforementioned Lagrangians, the amplitude for the production of the $a_0(1817)$ through t channel K^+ exchange in K^-p scattering can be expressed as follows:

$$\mathcal{M}_K = i\frac{f_{a_0KK}}{2m_K} g_{KN\Lambda} F(q^2)\bar{u}_\Lambda(p_2)\gamma_5 \frac{1}{t-m_K^2}(q_\mu \cdot k_1^\mu)u_N(p_1). \quad (5)$$

In the above expression, $\bar{u}_\Lambda$ and u_N represent the Dirac spinors of the Λ hyperon and nucleon, respectively. Considering that the hadron is not a point particle, the introduction of a phenomenological form factor becomes necessary to approximate the influence of its internal structure on the cross section. In the case of t-channel meson exchange, one can utilize monopole, dipole, or exponential form factors to describe this effect [30,32,33,38]. It is worth noting that a previous research study [39] has shown that the impact of different form factors on the cross section shape is negligible. Hence, in this present work, we opt for the commonly used monopole form factor as our choice, i.e., $F(q^2) = (\Lambda_t^2 - m^2)/(\Lambda_t^2 - q^2)$. Here, $t = q^2 = (k_1 - k_2)^2$ represents the Mandelstam variable. The parameter Λ_t, the only free parameter in the form factor, will be discussed in detail in Sec. III.

The Regge trajectory model has proven to be successful in analyzing hadron production at high energies [38,40–42]. It provides a framework to study the spectral behavior of traditional light mesons [43]. In this model, the Reggeization procedure is performed by replacing the t channel propagator in the Feynman amplitudes [Eq. (5)] with the Regge propagator, which can be expressed as follows:

$$\frac{1}{t-m_K^2} \to \left(\frac{s}{s_{\mathrm{scale}}}\right)^{\alpha_K(t)} \frac{\pi\alpha_K'}{\Gamma[1+\alpha_K(t)]\sin[\pi\alpha_K(t)]}. \quad (6)$$

Here, the factor s_{scale} is equal to 1 GeV. In addition, the Regge trajectory $\alpha_K(t)$ read as [34],

$$\alpha_K(t) = 0.70(t - m_K^2). \quad (7)$$

It is note that no additional parameter is introduced after the Reggeized treatment applying.

III. NUMERICAL RESULTS

A. Cross section

In the following calculations, we can determine the cross section of the $K^-p \to a_0(1817)\Lambda$ reaction. The differential cross section in the center of mass (c.m.) frame is given by:

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{32\pi s}\frac{|\vec{k}_2^{\,\mathrm{c.m.}}|}{|\vec{k}_1^{\,\mathrm{c.m.}}|}\left(\frac{1}{2}\sum_\lambda |\mathcal{M}|^2\right), \quad (8)$$

where the variable $s = (k_1 + p_1)^2$ represents the squared center of mass energy, and θ represents the angle between the outgoing $a_0(1817)$ meson and the direction of the kaon beam in the center of mass frame. $\vec{k}_1^{\,\mathrm{c.m.}}$ and $\vec{k}_2^{\,\mathrm{c.m.}}$. represent the three-momenta of the initial kaon beam and the final $a_0(1817)$ meson, respectively.

Since there is no available experimental data for the $K^-p \to a_0(1817)\Lambda$ reaction, we provide predictions for the cross section based on our calculations, as shown in Fig. 2. The cutoff parameter in the form factor plays a crucial role as the sole free parameter in our calculations. Previous studies have utilized different values of this cutoff parameter in related processes. For example, in the $\pi^-p \to K^*\Sigma^*$ scattering process, which is based on Reggeized t channel $K^{(*)}$ exchange [33], a value of $\Lambda_t = 1.67 \pm 0.04$ GeV was employed. In another study [38], a value of $\Lambda_t = 1.55$ GeV was chosen for the Reggeized t channel with K and K^* exchange to achieve better agreement with experimental data. Additionally, for the kaon-induced reaction $K^-p \to \eta_1(1855)\Lambda$, a cutoff value of 1.6 ± 0.3 GeV for the t-channel K^+ exchange was considered [30]. In the present work, to ensure a reliable and feasible conclusion, we have adopted the value of $\Lambda_t = 1.6 \pm 0.3$ GeV for our calculations. This choice is informed by previous studies and aims to strike an appropriate balance between theoretical expectations and experimental data.

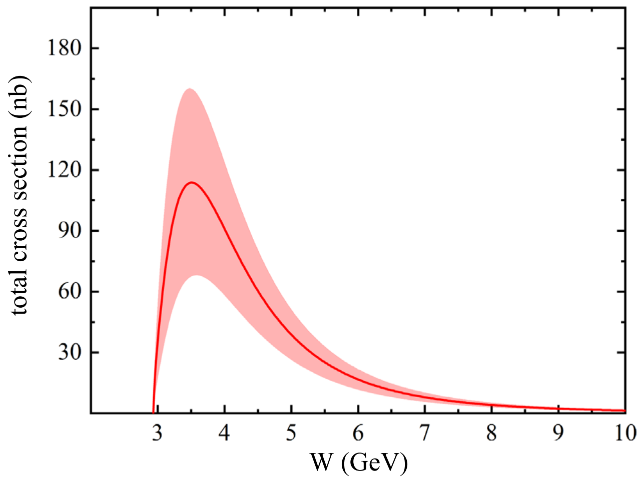

FIG. 2. The energy dependence of the total cross section for production of the $a_0(1817)$ and through t channel with cutoff $\Lambda_t = 1.6 \pm 0.3$ GeV. The Full (red) line is for the $K^- p \to a_0(1817)\Lambda$ reaction. The bands stand for the error bar of cutoff Λ_t.

In Fig. 2, the total cross section exhibits a clear variation trend within the energy range of $W = 2$ to 10 GeV. Notably, there is a prominent peak between $W = 3.4$ and 3.6 GeV, indicating the potential for observing the $a_0(1817)$ resonance through $K^- p$ interactions within this energy range. The increase in the total cross section is steep leading up to the peak, with a value of 113 nb at a center-of-mass energy of 3.5 GeV. Following the peak, the downward trend becomes less pronounced. Taking into account the range of Λ_t as 1.6 ± 0.3 GeV and considering the error band, the total cross section varies by 67 nb from the value at $W = 3.5$ GeV.

In Fig. 3, the predicted differential cross section of the $K^- p \to a_0(1817)\Lambda$ reaction is presented based on the Regge trajectory model, using a cutoff value of $\Lambda_t = 1.6 \pm 0.3$ GeV. It is evident from this work that the differential cross section is highly dependent on the scattering angle θ. As the energy increases, the reaction exhibits a strong forward scattering and gradually strengthens. Therefore, the reinforcement treatment can be effectively validated through forward angle measurements.

Figure 4 shows the t-distribution for the $K^- p \to a_0(1817)\Lambda$ reaction. It can be observed that the differential cross sections gradually decrease with increasing momentum transfer t. However, as t becomes smaller, the differential cross section values continue to increase, and this phenomenon requires further experimental verification.

B. Dalitz process

According to Table I, it is evident that the $a_0(1817)$ meson frequently appears as an intermediate state in various decay processes. The minimum decay width for $a_0 \to K\bar{K}$ is $\Gamma_{a_0 \to K\bar{K}} = 7.5$ MeV, while the minimum decay width for $a_0 \to \pi\eta$ is $\Gamma_{a_0 \to \pi\eta} = 22.4$ MeV. In this study, we aim to

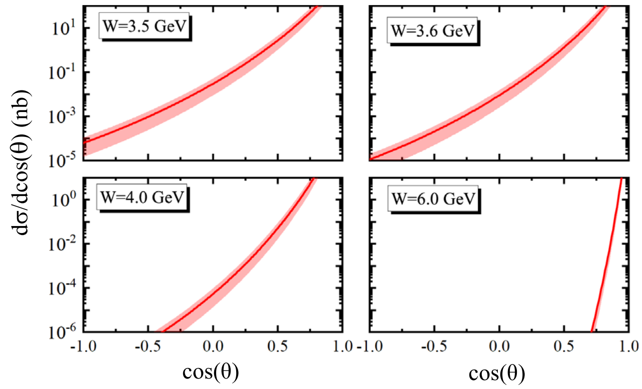

FIG. 3. The differential cross section $d\sigma/d\cos\theta$ of the $a_0(1817)$ and $a_0(1817)$ production at different center-of-mass (c.m.) energies $W = 3.5$, 3.6, 4.0, 6.0 GeV.

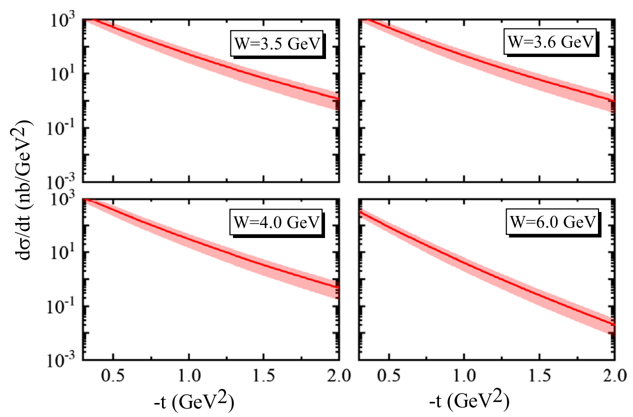

FIG. 4. The t-distribution for the $K^- p \to a_0(1817)\Lambda$ and $K^- p \to a_0(1817)\Lambda$ reactions at different c.m. energies $W = 3.5$, 3.6, 4.0, 6.0 GeV. Here, the notations are as that in Fig. 2.

calculate the Dalitz process for $K^- p \to a_0(1817)\Lambda \to K^+ K^- \Lambda$ and $K^- p \to a_0(1817)\Lambda \to \pi\eta\Lambda$, respectively. The Dalitz process is of great importance and can provide valuable insights for future experimental investigations. Generally, the invariant mass distribution for the Dalitz process[1] can be defined based on the two-body process [44]

$$\frac{d\sigma_{K^- p \to a_0\Lambda \to K^+K^-\Lambda}}{dM_{K^+K^-}} \approx \frac{2M_{a_0} M_{K^+K^-}}{\pi} \times \frac{\sigma_{K^- p \to a_0\Lambda} \Gamma_{a_0 \to K^+K^-}}{(M^2_{K^+K^-} - M^2_{a_0})^2 + M^2_{a_0}\Gamma^2_{a_0}}, \quad (9)$$

[1]Usually, the effective Lagrangian method can also be used to calculate the Dalitz process, but new coupling constants and form factors are needed, which will increase the uncertainty of the results due to the lack of relevant experimental data. Considering that the decay width of resonance $a_0(1817)$ is relatively narrow, we use Breit-Wigner approximation to calculate the invariant mass spectrum of $a_0(1817)$ to ensure the reliability of the results.

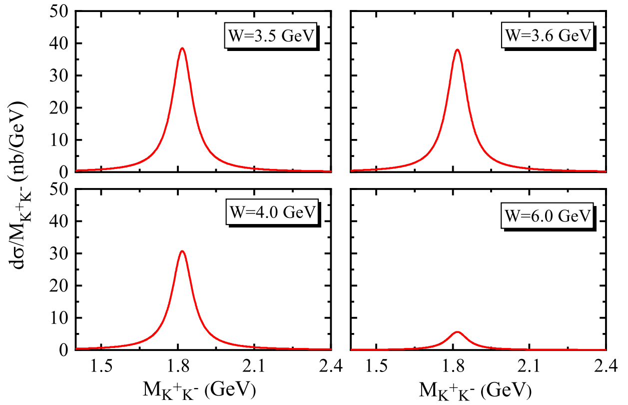

FIG. 5. The invariant-mass distribution $d\sigma_{K^-p\to a_0\Lambda\to K^+K^-\Lambda}/dM_{K^+K^-}$ reactions at different c.m. energies $W = 3.5$, 3.6, 4.0, 6.0 GeV.

$$\frac{d\sigma_{K^-p\to a_0\Lambda\to\pi\eta\Lambda}}{dM_{\pi\eta}} \approx \frac{2M_{a_0}M_{\pi\eta}}{\pi}\frac{\sigma_{K^-p\to a_0\Lambda}\Gamma_{a_0\to\pi\eta}}{(M_{\pi\eta}^2 - M_{a_0}^2)^2 + M_{a_0}^2\Gamma_{a_0}^2}. \tag{10}$$

Here, the total width of a_0 meson, denoted as Γ_{a_0}, is 97 MeV. For the partial width $\Gamma_{a_0\to K^+K^-}$, we consider a value of 5 MeV, and for $\Gamma_{a_0\to\pi\eta}$, we use the value of 22.4 MeV. Based on these parameters, we calculate the invariant-mass distributions $d\sigma_{K^-p\to a_0\Lambda\to K^+K^-\Lambda}/dM_{K^+K^-}$ and $d\sigma_{K^-p\to a_0\Lambda\to\pi\eta\Lambda}/dM_{\pi\eta}$ for center-of-mass energies ranging from $W = 3.5$ GeV to $W = 6$ GeV. The results are shown in Figs. 5 and 6. It can be observed from these figures that there is a peak near the center-of-mass energy of approximately 1.82 GeV, which has direct implications for the experimental detection of the $a_0(1817)$.

To further assess the feasibility of detecting $a_0(1817)$ in K^-p interactions, we calculate the ratio $\sigma(K^-p\to a_0(1817)\Lambda\to K^+K^-\Lambda)/\sigma(K^-p\to K^+K^-\Lambda)$. In Fig. 2, the cross section for $a_0(1817)$ production in K^-p scattering is estimated to be approximately 110 nb at $W = 3.37$ GeV. Assuming a branching ratio of $\mathrm{BR}(a_0(1817)\to K^+K^-)\approx 5.2\%$, we obtain a total cross section of $\sigma_{K^-p\to a_0(1817)\Lambda\to K^+K^-\Lambda}\approx 5.72$ nb at $W = 3.37$ GeV.

In Ref. [45], a total cross section of 35 μb is reported for $W = 3.37$ GeV. Based on this value, the ratio at $W = 3.37$ GeV can be calculated as follows:

$$\frac{\sigma(K^-p\to a_0(1817)\Lambda\to K^+K^-\Lambda)}{\sigma(K^-p\to K^+K^-\Lambda)} \approx 0.016\%. \tag{11}$$

Considering the current experimental landscape, we are optimistic about the potential of the J-PARC experiment in detecting the $a_0(1817)$ in K^-p scattering [21,46]. The experimental conditions at J-PARC are well-suited for this purpose. Based on the specifications of the J-PARC experiment, it is estimated that approximately 42,000 events of $K^+K^-\Lambda$ can be generated in 100 days, among which about several events are expected to involve the $a_0(1817)$. By performing calculations, we find that at $W = 3.37$ GeV, the cross section for $K^-p\to a_0(1817)\Lambda\to\pi\eta\Lambda$ is approximately 25.40 nb, considering a branching ratio of $\mathrm{BR}(a_0(1817)\to\pi\eta)\approx 23.1\%$. These events can be reliably detected at J-PARC every 100 days, with dozens of events specifically related to the $a_0(1817)$. Consequently, the $a_0(1817)$ can be confidently observed from the $K^-p\to a_0(1817)\Lambda\to\pi\eta\Lambda$ reaction under the current experimental conditions. Therefore, with the future upgrade of J-PARC, there is a promising opportunity to discover and study the $a_0(1817)$ in greater detail.

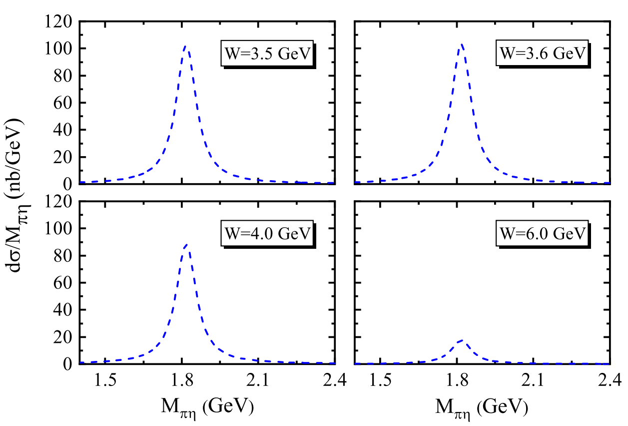

FIG. 6. The invariant-mass distribution $d\sigma_{K^-p\to a_0(1817)\Lambda\to\pi\eta\Lambda}/dM_{\pi\eta}$ reactions at different c.m. energies $W = 3.5$, 3.6, 4.0, 6.0 GeV.

IV. SUMMARY

In the past two years, significant progress has been made in the study of the isovector scalar meson $a_0(1817)$ by the *BABAR* and BESIII Collaborations. However, the measured resonance parameters of the $a_0(1817)$ differ between these experiments, and there is still a lack of sufficient data to fully understand its structure [18]. In order to further investigate the intrinsic properties of the $a_0(1817)$, we propose to explore its characteristics through K^-p scattering.

There are several reasons for choosing the K^-p interaction to search for the $a_0(1817)$. First, the ground state particle of the $a_0(1817)$, $a_0(980)$, has already been observed in the K^-p scattering process. Second, the decay channel $a_0(1817)\to K^+K^-$ plays a significant role in the overall decay of the $a_0(1817)$. By employing the effective Lagrangian method and the Regge trajectory model in quantum field theory, we calculate the total and differential cross sections of $K^-p\to a_0(1817)\Lambda$.

Our results indicate that the total cross section exhibits a peak at a center-of-mass energy of $W = 3.4$–3.6 GeV, suggesting that this energy range is ideal for detecting the $a_0(1817)$ through the $K^-p \to a_0(1817)\Lambda$ reaction. Moreover, the differential cross section is highly sensitive to the scattering angle θ and the minimum momentum transfer t. Therefore, high-precision data from experimental facilities such as J-PARC, OKA@U-70, and SPS@CERN [47], which provide suitable kaon beams, are eagerly awaited.

Based on the current experimental conditions, the detection of the $a_0(1817)$ from $K^-p \to \pi\eta\Lambda$ is considered more feasible compared to $K^-p \to K^+K^-\Lambda$. The theoretical insights obtained in this study will provide valuable information for future experiments aimed at identifying and characterizing the $a_0(1817)$ state.

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