The study of U-boson from π^0-meson decays at HIAF energy

Xiaoyun Wang[1,2], Xurong Chen[1,3], Qi Zeng[1,4], Wei Jiang[1,4], Rong Wang[1,2,5], Baiyang Zhang[1,2]
[1] *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
[2] *University of Chinese Academy of Sciences, Beijing 100049, China*
[3] *Research Center for Hadron and CSR Physics, Institute of Modern Physics of CAS and Lanzhou University, Lanzhou 730000, China*
[4] *School of Nuclear Science and Technology, USTC, Hefei 230022, China and*
[5] *Lanzhou University, Lanzhou 730000, China*

Within the frame of LDM (light dark matter)-model, the LDM exchange particle U-boson (with mass 10-100 MeV) can be produced from many meson decay process so it attracts a lot of attention. Considering the merit of searching the U-boson from π^0 decay, the momentum spectra of light spin-1 vector U-boson from decay channel $\pi^0 \to \gamma U$ and the energy spectra of positron decay from $U \to e^+e^-$ at beam energy of 5-10 GeV are first presented by using a relativistic transport (ART) model. Moreover,the feasibility and rationality of searching the U-boson in the experiment at HIAF energy are discussed, which will be an important promotion to understand and ultimately detect the U-boson, both in theory and experiment.

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I. MOTIVATION

Researchers believe, in our universe, the ordinary matter is less than 5%, which imply that dark matter and dark energy account for the majority [1]. Especially for dark matter (DM), although it is invisible, but it has always been a hot research topic since some astronomical observations suggest that dark matter very likely exists in the universe [2]. For instance, the astronomer observed that many galaxy clusters' mass is much large than that of their constituent galaxies, which have breached the Newton's laws and the extra "mass" maybe caused by the DM [2–4]. In addition to the phenomenon of astronomical observations, researchers also carried out many of the indirect detection of dark matter experiments. One of results is the 511 keV gamma rays streaming from the centre of our galaxy detected by the SPI/INTEGRAL satellite, which was considered as sourcing from the dark matter [5–10]. Moreover, recent C. C. Ting team measured the positron fraction in primary cosmic rays by the Alpha Magnetic Spectrometer on the International Space Station, which is consistent with theoretical prediction about the existence of dark matter [11]. Except the astronomical phenomena and observations, researchers are also trying to use dark matter to explain the contradiction between experimental data and theoretical prediction of the Standard Model (SM). For example, the branching ratio of $\pi^0 \to e^+e^-$ measured by KTeV-E779 Collaboration exceeds the SM theoretical calculation [12, 13], which is thought to be caused by the DM particles [14].

Despite there are many studies about DM, until now we are ignorant of the nature of DM [4]. Accordingly, physicist proposed a lot of candidate particles of DM. Of these, most agree that particles are the weakly interacting massive particles (WIMP) and light dark matter (LDM) [4, 14]. WIMPs (its mass can range from about 50 GeV to a few TeV) arise naturally from the supersymmetry theory which is a new theory beyond the SM [4]. However, the WIMP was still not been detected by the Large Hadron Collider at CERN and it is difficult to consider it as the source of 511 keV γ-rays. Therefore, the LDM (with mass 1-100 MeV) which was proposed by Boehm *et al*. [15] has attracted much attention recently, which is consistent with all laboratory data [15–18].

LDM annihilation process $\chi\chi \to e^+e^-$ were related to the source of the 511 keV γ-ray line from the galactic bulge. Correspondingly, a neutral light spin-1 gauge U-boson was proposed which is a exchange particle and mediate the LDM annihilation process [15]. The U-boson is derive from supersymmetry model with an extra U (1) symmetry, which also have essential influence in nuclear and particle physics [19–21]. Meanwhile, the study of U-boson is conduced to get a deeper understanding of the LDM and the new physics beyond SM [22].

In the LDM model, the light vector U-boson with mass 10-100 MeV can be produced from the decays of the ψ or the K^+, or of the π^0, η or η' mesons etc [14, 23], which provides a possibility of detecting the U-boson in the Lab. Based on the consideration of experimental practical and theoretical calculation, recently researchers proposed two suggested U-boson search channels: $\eta \to \gamma U$ ($U \to e^+e^-$) and $\pi^0 \to \gamma U$ ($U \to e^+e^-$). The advantage of the suggested channels is that all final state particles in the η and π^0 decays can be measured. Therefore, it is less background comparing to other method, such as electro-production experiments. In this paper, we mainly focus our research on the U-boson production decay from π^0, which need to produce enough π^0 first. Based on the above reasons, we studied the π^0 production by proton collision with the light target (^{12}C and ^{9}Be) at HIAF energy, which will have relatively larger π^0 and U-boson production and smaller background particles. The future HIAF accelerator at IMP can make the proton beams energy to achieve about 10 GeV.

In this paper, on the basis of LDM model and the consideration about actual experiment, the U-boson production from decay channel $\pi^0 \to \gamma U$ at HIAF energy are discussed by using a relativistic transport (ART) model [24–26]. In Sec. II the analytic model and method are introduced and described in detail. In Sec. III we investigate the π meson yields via p + ^{9}Be and p + ^{12}C at different beam energies. In Sec. IV. A the momentum spectra of U-boson and the energy spectra of positron from U-boson decays ($U \to e^+e^-$) are given and discussed. In Sec. IV. B the total cross section of U-boson production are calculated and the invariable mass spectra of signals and background are presented, which will be an important basis for the experiment of searching for the U-boson at HIAF energy.

II. INVESTIGATIVE METHOD AND MODEL

Within the framework of the LDM-model, We study the U-boson production and get the relevant predict results by using a relativistic transport (ART) model. The ART-model was developed by B. A. Li *et al*. [24–26], which is based on the very successful BUU transport model [27–29]. Some noticeable new physics and techniques have been added in the ART-model so that it can simulate collisions at higher energies.

More specifically, the phase space distribution functions of mesons $(\pi, \rho, \omega, \eta, K)$ and baryons $(N, \Delta(1232), N^*(1440), N^*(1535), \Lambda, \Sigma)$ with all possible charge states and their isospin degrees of freedom are included in the ART model by considering the influence of hadron-hadron scatterings and also an optional mean field for baryons. Meanwhile, most elastic and inelastic hadron-hadron collisions also are embedded in this model [24–26].

For baryon-baryon inelastic interactions, the following reaction channels are included:

$$NN \longleftrightarrow N\Delta, NN^*(1440), NN^*(1535), \quad (1)$$
$$NN \longleftrightarrow \Delta\Delta, \Delta N^*(1440), \quad (2)$$
$$NN \longleftrightarrow NN\rho, NN\omega, \Delta\Delta\pi, \quad (3)$$
$$NN \longleftrightarrow \Delta\Delta\rho, \quad (4)$$
$$N\Delta \longleftrightarrow NN^*(1440), NN^*(1535), \quad (5)$$
$$\Delta\Delta \longleftrightarrow NN^*(1440), NN^*(1535), \quad (6)$$
$$\Delta N^*(1440) \longleftrightarrow NN^*(1535) \quad (7)$$

For meson-baryon elastic interactions, they are included by adopt the formation of baryon resonances,

$$\pi N \longleftrightarrow \Delta, N^*(1440), N^*(1535), \quad (8)$$
$$\eta N \longleftrightarrow N^*(1535), \quad (9)$$

and the direct reactions,

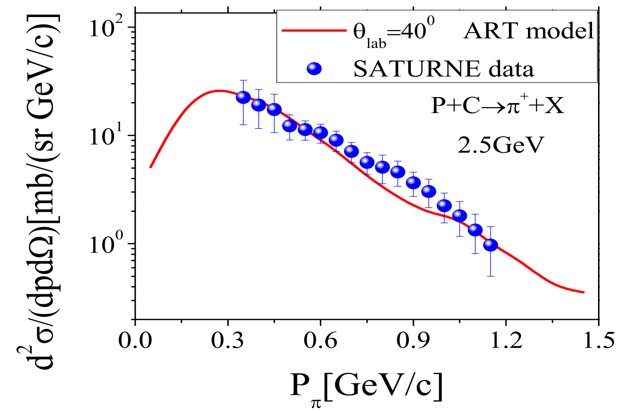

FIG. 1: (Color online) Differential cross section as a function of P_π for π^+ in p + ^{12}C collisions at incident beam energy of 2.5 GeV at $\theta_{lab} = 40^0$. The solid line show the calculations within the ART-model. The full dotted are the experimental data taken from Ref. [36].

$$\pi + N(\Delta, N^*) \longrightarrow \pi + N(\Delta, N^*), \quad (10)$$
$$\rho + N(\Delta, N^*) \longrightarrow \rho + N(\Delta, N^*), \quad (11)$$
$$K^+ + N(\Delta, N^*) \longrightarrow K^+ + N(\Delta, N^*). \quad (12)$$

For the meson-meson interactions, such as for the pion-pion elastic, they are modeled via the formation of a ρ meson, i.e.,

$$\pi + \pi \longleftrightarrow \rho, \quad (13)$$

as well as direct reaction

$$\pi + \pi \longrightarrow \pi + \pi. \quad (14)$$

In addition, this model has been quite successful in studying various hadrons at AGS energy, which include the light creation of light particles as well as the production of π, K and η etc. In particular, it has already been proven that the results about π meson at AGS energies calculated by ART model can reproduce the experiment data well [24, 30–32], which means that this model is well suited for investigating the pion and U-boson production at HIAF energy.

III. PION SPECTRA AND YIELDS VIA PROTON WITH LIGHTWEIGHT TARGETS (^{9}BE, ^{12}C) REACTIONS

Study on the π meson has always been a hot research topics both theoretically and experimentally. One typical example is that π production is a effective means of studying the high density behavior about symmetry energy [33–35]. Besides, recently study found that the cross section of $\pi^0 \to e^+e^-$ measured in experiment excess 3.3σ than the SM calculation, which may well be

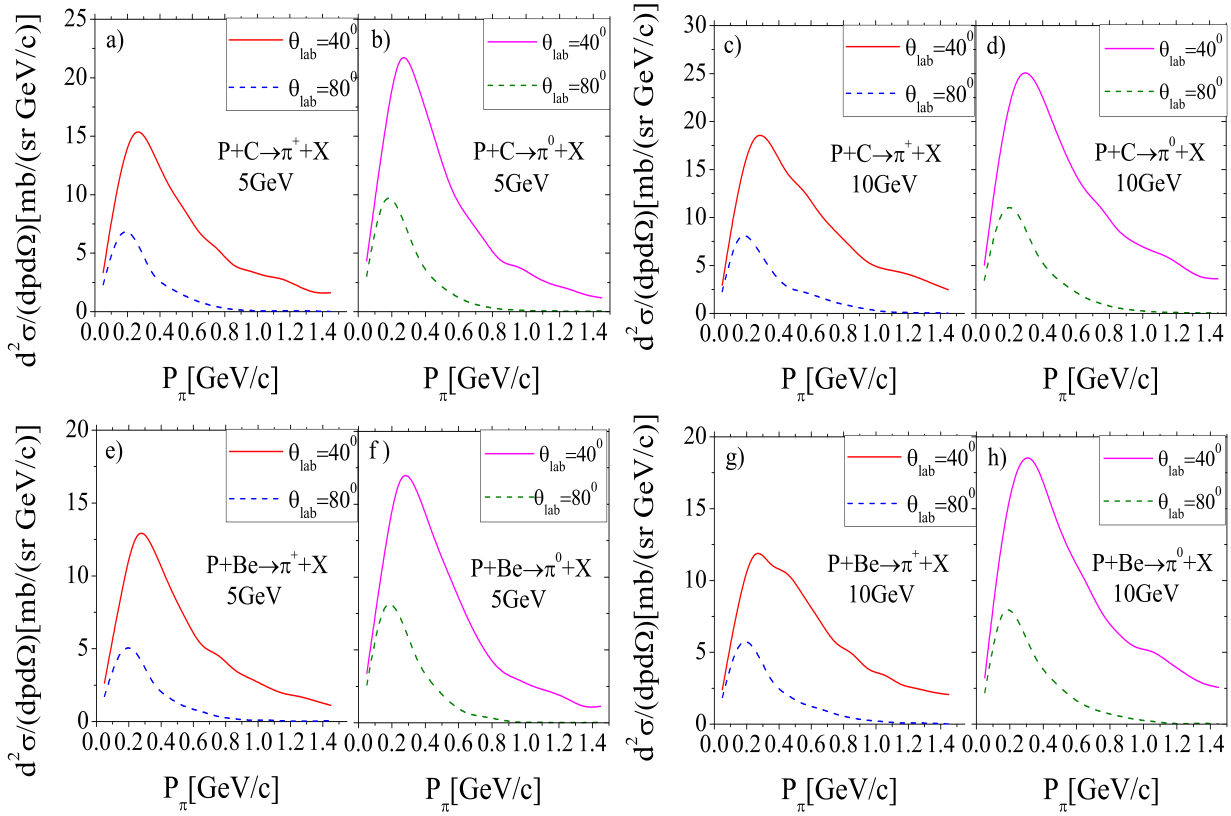

FIG. 2: (Color online) The π^+ and π^0 momentum spectra from p + ^{12}C and p + ^{9}Be collisions at T$_p$ = 5 and 15 GeV for emission angles $\theta_{lab} = 40^0$ (solid line) and 80^0 (dashed line).

an evidence for the exist of LDM particles [12–14]. In this section, we mainly research the π meson production in proton-carbon/beryllium collisions at beam energies from 2.5-15 GeV, which is necessary and essential for the studying of the U-boson from $\pi^0 \to \gamma U$ decays. In order to test the reliability of the ART-model for studying the pion production, we firstly need to compare the results calculated by ART-model with experiment data. Fig. 1 show the double differential cross section of π^+ from p + ^{12}C collision at beam energy of 2.5 GeV and $\theta_{lab} = 40^0$. From this graph, we can see that the result calculated by ART-model is consistent with the SATURNE data well [36], which indicate that the ART-model is reliable for studying the pion production in proton with lightweight target collisions. Moreover, Altogether two main system about pion production have been studied: p + ^{12}C at 2.5-15 GeV and p + ^{9}Be at 2.5-15 GeV beam energy. Fig. 2 present that the differential π^+ and π^0 momentum spectra for p + ^{12}C and p + ^{9}Be at incident energies from 5 to 10 GeV at a diverse range of emission angles, which will redound to achieve a full understanding of the pion production from proton-lightweight target interactions. Specifically, From Fig. 2(a)-(d) we can conclude that, for p + ^{12}C case, the differential cross section of π^+ or π^0 meson have a modest increase with the bombarding energy increases. Besides, we find that the peak value of pion momentum spectra at low emission angle is about twice times larger than the calculation at high angle $\theta_{lab} = 80^0$, which mean that the emission angle has a great effect on the shapes of pion momentum spectra. Fig. 2(e)-(h) also show the differential pion momentum spectra but for p + ^{9}Be, which exhibit the similar characteristics and properties comparing with case of p + ^{12}C. Furthermore, we notice that the double differential cross

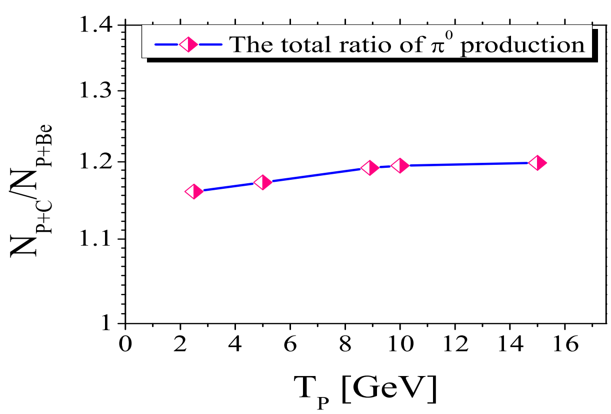

FIG. 3: (Color online) The total ratio of the number of π^0 production as a function of incident beam energy for p+ ^{12}C and p+ ^{9}Be.

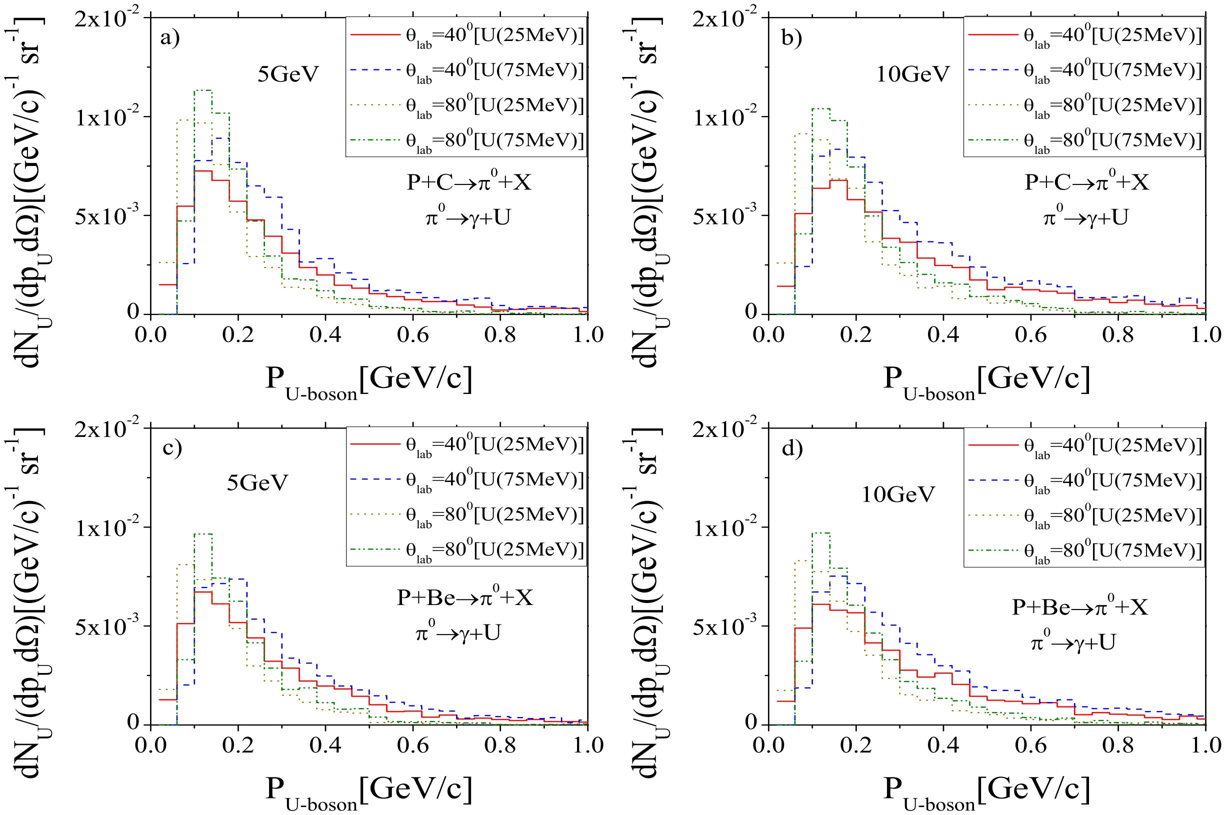

FIG. 4: (Color online) (a)-(b): The momentum spectra of U-boson (with mass 25 and 75 MeV) from $\pi^0 \to \gamma U$ decays in p + ^{12}C reaction for high and low emission angles at T$_p$ = 5, and 10 GeV. (c)-(d) are same as (a)-(b), but for p + ^{7}Li.

section of π^0 is higher than the cross section of π^+ at the same beam energy and emission angle, which may be caused by the elementary branching ratios of single π production in NN collisions [37].

Fig. 3 show the total ratio of π^0 production from p + ^{12}C and p + ^{9}Be at various beam energies from 2.5-15 GeV. It is seen that the average ratio of total π^0 production R(C/Be) at different bombarding energies is about 1.2, which is consistent with the Glauber theory predicted value [38]. Meanwhile, we find that the ratio of π^0 yields R(C/Be) is almost "steady" at the beam energies from 8.9-15 GeV, which may infer that the π^0 production in the range of this energies is also "steady". Besides, just as we have mentioned above, the increase of cross section of π^0 is small at the beam energy from 5-10 GeV, which can be deduced that the π^0 production in proton-carbon/beryllium collisions can become saturation at beam energies from 5-10 GeV. To sum up the above situation, we can conclude that to produce the π^0 meson at HIAF energy is reasonable and desirable, which can achieve the relatively larger π^0 meson production and smaller background.

IV. U-BOSON PRODUCTION FROM $\pi^0 \to \gamma U$

A. The spectra of U-boson and its decay

As previously mentioned, the LDM particle-χ annihilation process $\chi\chi \to e^+e^-$ needs to be mediated by the neutral vector U-boson, which annihilation process is regarded as the source of 511keV γ-ray line from the central region of galaxy. Therefore, study on the U-boson will help us better understand the LDM. Besides, In the frame of LDM-model made by Boehm *et al.* [15], the light spin-1 vector U-boson (m$_U$ = $10 - 100$ MeV) can yield from many meson decays, which is an effective way to investigate the U-boson in detail.

In this subsection, we mainly focus on the yields and spectra of U-boson from decay channel $\pi^0 \to \gamma U$ as well as energy spectra of positron from U-boson decays ($U \to e^+e^-$), which will provide a great deal of insight into the properties and distributions of U-boson. Fig. 4 show the momentum spectra of U-boson from π^0 decay at different incident beam energy and various emission angle for the cases of p + ^{12}C and p + ^{9}Be, respectively. With the LDM-model theory [15], the mass of U-boson is from 10-100 MeV. In order to clarify what the U-boson with different mass impact on the distribution of its momentum spectra, we selected two types of U-boson with mass of 25 MeV and 75 MeV respectively. From Fig. 4(a)-(b), for the case of p + ^{12}C, we find that, except the

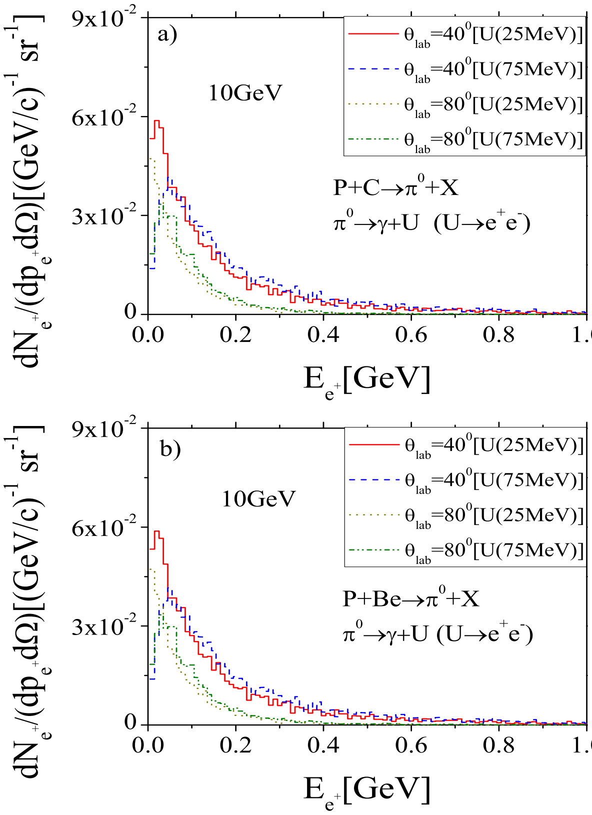

FIG. 5: (Color online) (a): The energy spectra of e^+ from $U \to e^+e^-$ decays in $p + {}^{12}\mathrm{C} \to \pi^0 + X$ collisions for $\theta_{lab} = 40^0$ and 80^0 at beam energy of 10 GeV. (b)is same as (a), but for $p + {}^9\mathrm{Be} \to \pi^0 + X$.

location of peak value of U-boson momentum spectra has a little backward with the increase of mass of U-boson, the U-boson's mass has little effect on the shapes of momentum spectra of U-boson. Besides, with the increase of the beam energy, the number of U-boson has a limited increase, which is similar with the situation of π^0 meson yields. Meanwhile, it is seen that, at the low momentum region, the number of U-boson at high emission angle $\theta_{lab} = 80^0$ is larger than the value at low emission angle $\theta_{lab} = 40^0$, and vice versa. From Fig. 4(c)-(d), for the instance of $p + {}^9\mathrm{Be}$, we achieved the same essential calculation as the case of $p + {}^{12}\mathrm{C}$.

Considering the fact that the U-boson as a neutral particle is difficult to be detected in the experiment, so it is necessary to continue to research U-boson's two body decay $U \to e^+e^-$. Accordingly, we plot the distributions of e^+ energy spectra from U-boson (with mass 25 and 75 MeV) decay in $p + {}^{12}\mathrm{C} \to \pi^0 + X$ and $p + {}^9\mathrm{Be} \to \pi^0 + X$ reaction with $\mathrm{T}_p = 10$ GeV at different emission angles, which are presented in Fig. 5. Besides, we notice that the energy spectra of electron from $U \to e^+e^-$ will be same as the spectra of positron because they have almost the same intrinsic properties. Therefore, we do not need to give the energy spectrum of electron from U-boson decay. From Fig. 5(a) it is seen that the number of positron are mainly gathered at the low energy region and tend to zero at higher energy range. In addition, at the positron energies range from 0-1.0 GeV, the number of positron at low emission angle $\theta_{lab} = 40^0$ all are higher than the positron's value at high emission angle $\theta_{lab} = 80^0$. accordingly, at the same emission angle, the shapes of energy spectra of positron with 25 MeV is similar with the energy spectra of positron with 75 MeV. Which indicate that the distributions of positron energy spectra are largely influenced by the emission angle but not the U-boson's mass. Fig 5(b) is related to the case of $p + {}^9\mathrm{Be}$, which show the same situation with Fig. 5(a).

B. The feasibility study of searching the U-boson in the experiment at HIAF energy

In this subsection, we mainly discuss the feasibility and rationality of searching the U-boson from π^0 decay by proton with lightweight targets (^{9}Be, ^{12}C) reactions at HIAF energy. Firstly, we know that $\pi^0 \to \gamma U$ as the suggested U-boson search channels have some significant advantages compared to other meson decays, which will increase the chance of detected the U-boson in the experiment. Moreover, there are two significant factors play important role in the feasibility of searching the U-boson in the experiment: the total amount of U-boson and the separability of the signal in the background.

As had been done in the previous study, a large number of π^0 meson can be produced by proton beam colliding with lightweight targets (^{9}Be, ^{12}C) at HIAF energy, which is essential to obtain enough U-boson. Based on this, the total cross section of U-boson from π^0 decay can be calculated by using the ART-model, which are presented in Fig. 6. From Fig. 6 it is seen that the total cross section of U-boson increase with the increasing of incident beam energy. Besides, the total cross section of U-boson produced from $p + {}^{12}\mathrm{C}$ are larger than the

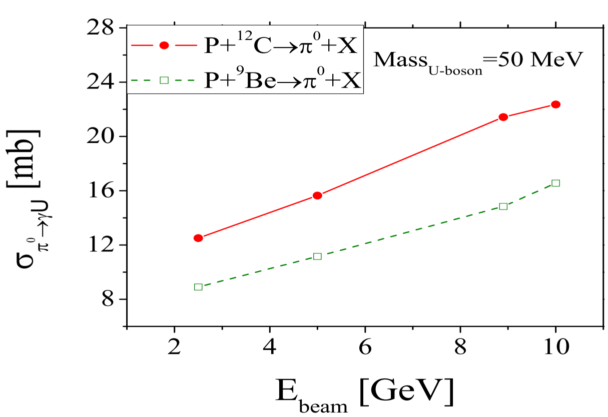

FIG. 6: (Color online) The total cross section of U-boson (with mass 50 MeV) as a function of incident beam energy from $\pi^0 \to \gamma U$ in $p + {}^{12}\mathrm{C}$ (solid line) and $p + {}^9\mathrm{Be}$ (dashed line) collisions.

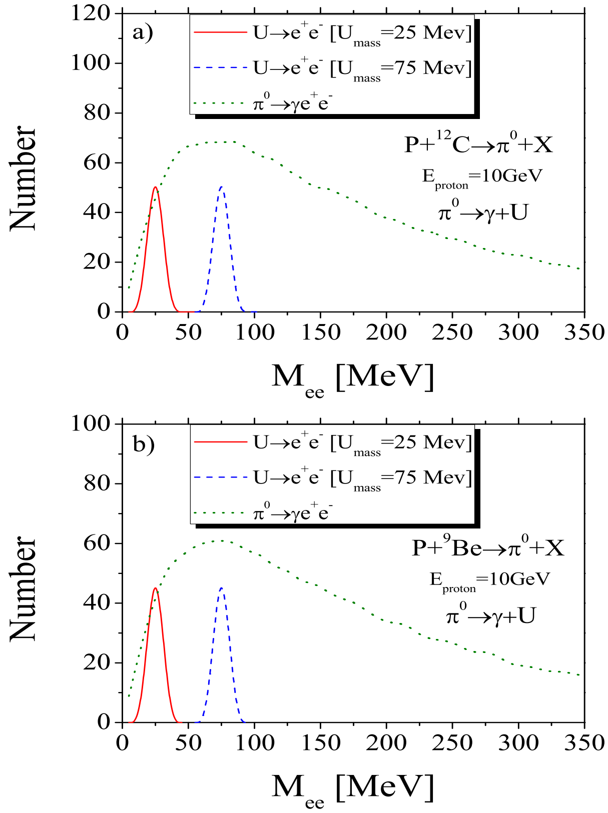

FIG. 7: (Color online) (a): The invariable mass spectrum of signals (from $U \to e^+e^-$) and background ($\pi^0 \to \gamma e^+e^-$).The solid related to the U-boson with mass of 25 MeV and the dashed line correspond to the U-boson with 75 MeV mass. The dotted line refers to the background. (b) is same as (a), but for p + ^{9}Be.

calculations from p + ^{9}Be. Since the ART-model can not predict the branching ratio, the $BR(\pi^0 \to \gamma U)$ and $BR(\pi^0 \to \gamma e^+e^-)$ have not been taken into account in the Fig. 4-Fig. 7. $\pi^0 \to \gamma e^+e^-$ has been measured with a branching ratio $(1.174 \pm 0.035) \times 10^{-2}$ [39]. According to the previous theory [23, 40], for light mass U-boson, the upper limit for its branching ratio is

$$BR(\pi^0 \to \gamma U) < 2 \times 10^{-4}. \quad (15)$$

Combine the total cross section as shown in Fig. 6 and the $BR(\pi^0 \to \gamma U)$, the total signal number of U-boson can be estimated based on the future HIAF accelerator at IMP. We select the case of p + ^{12}C $\to \pi^0 + X$ at beam energy of 10 GeV, which can produce about 22 mb cross section of U-boson with 50 MeV mass. Moreover, the luminosity of HIAF will reach to the 10^{33} and the total accumulated luminosity of one year will be about 5 fb^{-1}. We assume that the detection efficiency is about 10%, according to the formula, the total signal number of U-boson $N_S = 10\% \times 5\ fb^{-1} \times 22\ mb \times 10^{-4} = 11 \times 10^8$ events. It means that we can observe at least 11×10^8 event of U-boson during one year on the HIAF, which is sufficient and reasonable number for the experiment of searching for U-boson.

On the other hand, it is essential to discuss the separability of the signal in the background. For the U-boson from $\pi^0 \to \gamma U$, if the U-boson were to decay into e^+e^-, the corresponding background particles would mainly come from the $\pi^0 \to \gamma e^+e^-$ process. Fig. 7 present the invariable mass spectrum of signal (from $U \to e^+e^-$) and background (from $\pi^0 \to \gamma e^+e^-$). By comparing the Fig. 7(a) and Fig. 7(b), we find that the distribution of invariable mass spectrum are similar for the case of p + ^{12}C and p + ^{9}Be at same incident beam energy. From Fig. 7 it is seen that the height and width of signal related to U-boson with 25 MeV is almost the same as the situation of signal for the U-boson with 75 MeV. However, the distribution of background is not a static line but a variable function with invariable mass M$_{ee}$ and its peak position is mainly at the range of M$_{ee}$ = 70 − 80 MeV. Therefore, since the distribution of background is uneven, the signals of U_{mass} = 25 MeV will be easier to be detected than the signals of U_{mass} = 75 MeV. Certainly, the degree of difficulty of detecting the signals of U-boson with different mass can be calculated. Finally, we notice that the signals come from two-body decay ($U \to e^+e^-$) and the background mainly come from three-body decay ($\pi^0 \to \gamma e^+e^-$), which mean that the signals can be distinguish from a larger amount of background because the producing mechanism from two-body decay and from three body-decay are different in the experiment.

V. CONCLUSIONS

The U-boson from $\pi^0 \to \gamma U$ decays in proton-carbon/beryllium collisions at HIAF energy has been studied systematically. By analyzing the momentum spectra of U-boson from π^0 decay as well as energy spectra of positron from U-boson decays ($U \to e^+e^-$) which were first presented, we found that the shapes of distribution of U-boson momentum spectra and positron energy spectra all are sensitive to the angle θ_{lab} but almost independent of the mass of U-boson. Furthermore, the feasibility and probability searching the U-boson in the experiment at HIAF energy were discussed in depth. The analytical results show that a substantial number of U-boson can be produced by proton collision with the light target (^{12}C and ^{9}Be) at HIAF energy and the separability of the signal in the background is desirable, which indicate that to search the U-boson from π^0 decay in HIAF energy proton light-target collisions is reasonable and feasible.

As of now, the U-boson still not be detected in experiment. Alternatively, there are many debate on whether the U-boson exist in the universe. Recently, some encouraging studies indicate that the U-boson affects the equation of state of dense neutron-rich matter, thus properties of neutron stars [41], which will provide a new evidence for the existence of U-boson.

In the future, our study will mainly focus on the another suggested U-boson search channels $\eta \to \gamma U$, which will enable us to have a more comprehensive understanding of the properities and the producing mechanism of the U-boson.

VI. ACKNOWLEDGMENTS

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