Letter of Intent for J-PARC

A new approach to study the $X(1835)$ via the $d(\overline{p}, n)$ reaction

∼ towards $\overline{p}$ bound nuclear system ∼

submitted on 12 / 12 / 2012

Masahiko Iwasaki, Hiroaki Ohnishi and Yue Ma
Nishina Center, RIKEN, Saitama 351-0198, Japan

Abstract

At present, $\overline{p}p$ sub-threshold resonances, $\eta(1760)$ and $X(1835)$ found by B-factories, attract many interests. To study those resonances, we are intended to perform an experimental study by $d(\overline{p}, n)X$ reaction, at the initial $\overline{p}$ momentum around 700 $\sim$ 1000 MeV/c, at K1.8BR beam area by upgrading the present spectrometer for E15 experiment. We wish to perform an experimental study based on 1) formation of sub-threshold resonances analysis by the missing-mass spectrum of $d(\overline{p}, n)$ reaction, and 2) exclusive decay channel focusing on the charged decay channel of $X \to \rho\rho$ and $X \to K^*K$ (including $\overline{K}K$), whose final state can be consists of all charged particles.

1 Introduction

In an experimental point of view, sub-threshold particle and anti-particle baryon system has never been produced and studied the property. On the other hand, the interaction of $\overline{p}p$ system is expected to be very strongly attractive, including the region where huge short-range repulsion exist in the normal NN system. Therefore, theoretical studies have been done to study what can be done experimentally [1, 2, 3, 4]. However, experimental study is very difficult because of the strong annihilation process, even if such state can exist. Therefore, it would be reasonable to start from the most simplest system such as two-body $\overline{N}N$ system.

On the other hand, the invariant mass study of the decay channel $J/\Psi \to \gamma\pi\pi\eta'$ revealed the existence of $\overline{p}p$ sub-threshold resonance, $X(1835)$, which has the energy of $1835^{+5.0}_{-3.2}$ MeV having the decay width of 99 ± 55 MeV, as shown in Fig. 1 [5, 6]. It is pointed out that the $X(1835)$ could be interpreted as $\overline{p}p$ bound state, or it would have substantial contribution to this resonance, because the resonance locates just below the $\overline{p}p$ threshold, and the fact that the decay channel of J/Ψ to $\overline{p}p\gamma$ is observed upto the threshold energy, which implies strong coupling between the resonance and the $\overline{p}p$ state. However, it is also pointed out that the $\eta(1760)$ and $X(1835)$ can be a radial

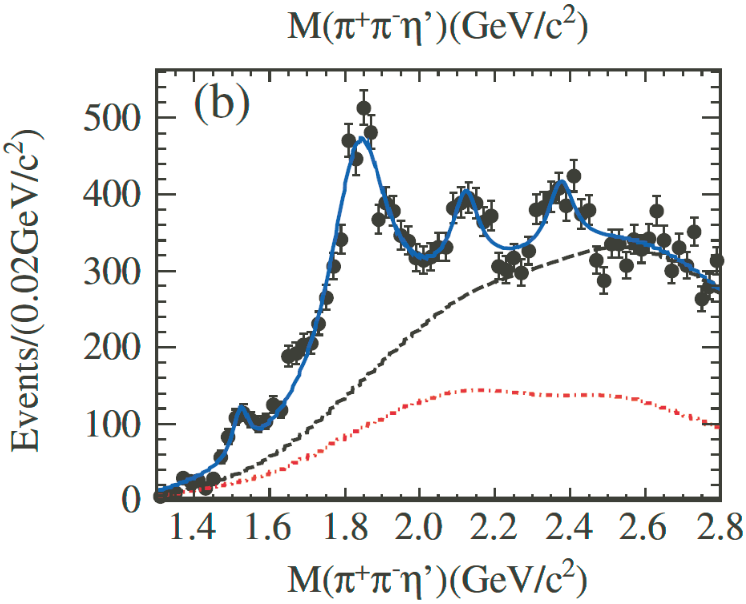

Figure 1: Invariant mass of $\pi^+\pi^-\eta'$ observed in J/Ψ decay [5]. Dashed line is the evaluated back ground by the experimental group.

excited states of η and η', or admixture of those states, so one need to study the properties of those $\bar{p}p$ sub-threshold resonances.

Therefore, we are intended to study those states via the strong interaction at recoilless condition, without forming an atomic state, where the strong annihilation process exist and produce huge backgrounds. Another key is full reconstruction of reaction kinematics focusing on the all charged-particle decay processes of the resonance (except for the high-momentum forward neutron produced at the formation reaction) to substantially reduce the background channels. We are also aiming to study the property of the resonance by means of relative branching ratio of those exclusive channels.

2 Production channel and the event tagging

Within the strong interaction, the most promising direct formation reaction is $d(\bar{p}, n)$ reaction. Because the masses of incident anti-proton and projectile neutron are almost equal, so the $\bar{p}n$ head-on collision produce at-rest $\bar{p}$ near spectator "p" within the strong interaction range, namely side-by-side $\bar{p}$-"p" system produced at-rest in Laboratory frame as illustrated in Fig.2. This forward neutron can be momentum analyzed by mean of time-of-flight (TOF) between reaction point identified as a vertex, between $\bar{p}$ beam trajectory and that of the decay charged particles, and neutron-counter hit position and its timing. When illustrated intermediate state is formed, the forward neutron should have specific momentum according to the binding energy.

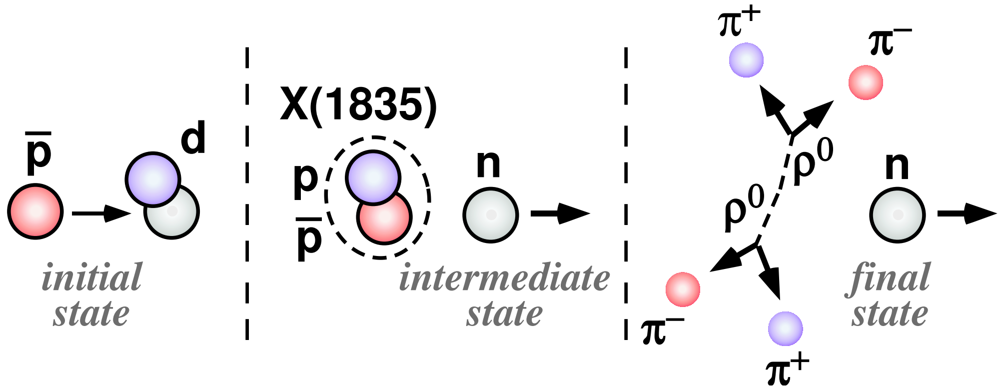

Figure 2: A cartoon of the reaction to illustrate one of the intended sub-threshold resonance formation to be detected.

Energetic neutron emission in the forward direction is not sufficient to remove all the background events, because the annihilation release 2 GeV in energy and may produce high momentum neutron in various reaction channels. Even if the anti-proton knocking out a neutron in the forward direction without annihilating in primary reaction, resulting quasi-free $\overline{p}$ ($\overline{p}$-QF) can stop in the target volume rather easily, and will annihilate with other nuclei, which will produce many particles around the target. Fortunately, associated neutron in the forward direction should be less energetic than that of the signal neutron, the these two are momentum separated by the $\overline{p}p$ thereshold. It is known that the neutron produced by the $\overline{p}$-QF process forms a specific structure in the neutron momentum spectrum in the unbound energy region.

More severe backgrounds come from $\overline{p}$ annihilation in the primary reaction, in which a part of the released energy transferred to the neutron in the target, such as meson absorption. Therefore, we shall focus on the specific decay channels from the sub-threshold resonance, and fully reconstruct the event kinematics. As it is described above, known decay channels of $X(1835)$ are limited to $\overline{p}p$ and $\pi\pi\eta'$. However, those decay channels are not idealistic or not easy to detect. Because the former decay channel can happen only up to the $\overline{p}p$ threshold, and $\overline{p}p$ produced in $d(\overline{p}, n)X$ reaction is low energy and it is extremely difficult to detect these particle. The latter channel requires large acceptance γ-ray detector to solve the kinematics, it is also not feasible to discriminate from none-resonant $\pi\pi\eta' n$ production channel.

To realize the experiment in short term, we propose to focus on other decay channels consists of all charged particles, alternatively to prepare very expensive γ-ray detector. If these channels exist, we can detect those decay particles by covering the target region with the large acceptance spectrometer. The two body decay of the resonance is the most promising channel to discriminate signal from backgrounds, because the two particles from the decay should have back-to-back event topology in the recoilless reaction. Another important point is to make the spectrometer system having an excellent particle-identification (PID) capability to fully solve the event kinematics, so as to suppress the background events.

In fact, if sub-threshold resonances decay through $\frac{1}{\sqrt{2}}\ |\overline{u}u + \overline{d}d >$, $|\overline{s}s >$, or these admixture, as it is naively expected, then the large fraction of the decay branch should have $\rho\rho$ and/or K^*K (including K^+K^-) channels. We will focus on these channels, because 1) these channels have all charged final state in the decay process, and easy to reconstruct its kinematics, 2) initial two body decay allows us to evaluate whether the event kinematics is consistent with "at-rest" back-to-back decay event topology of the sub-threshold resonance, and 3) one can evaluate the mixing angle between $\frac{1}{\sqrt{2}}\ |\overline{u}u + \overline{d}d >$ and $|\overline{s}s >$ from the relative ratio of these channels.

3 K1.8BR spectrometer and required upgrade

The J-PARC K1.8BR multi-purpose spectrometer has quite unique feature having large acceptance high-resolution neutron detector system in the forward direction [7]. K1.8BR spectrometer is originally designed for E15 experiment to search for deeply bound $\overline{K}$ state in nuclei by substituting one of the neutron by injecting K^- [8], collaborating with KEK hadron group. Isospin of injected particle and knocked-out neutron is $|\frac{1}{2}, -\frac{1}{2} >$. so that the spectrometer is quite efficient for the study of isospin unchanged reaction channel. The $\overline{p}$ isospin is same as K^- so that it is also suitable for the isospin 0 intermediate resonance study for $d(\overline{p}, n)$ reaction channel. Neutron detection is difficult, so that the experiment focusing on forward neutron has not been done extensively, and it makes this spectrometer quite unique.

Fig. 3 shows the K1.8BR experimental apparatus. To study both formation and decay processes, we designed the K1.8BR spectrometer consisting of the forward neutron counter (NC) and the cylindrical detector system (CDS) surrounding the target cell operated by the cryogenic system (liquid ^{3}He target, in the case of E15). To detect charged particles produced around the target region, the CDS is consist of cylindrical drift chamber (1180 mmϕ (diameter) and 1170 mm (length)) operated at 0.7 T, and cylindrical plastic hodoscope counters to trigger decay particles. Un-reacted beam particles, kaons and pions, are swept out using dipole magnet (0.7 T·m) placed after the cryogenic target system, and guided to the caved-shape beam dump specific to the K1.8BR spectrometer. The cave is $\sim$ 4 m long surrounded by $\sim$ 300 mm thick iron block, to avoid unfavorable irradiation of neutron, produced at the beam dump, to the neutron counter array. The neutron counter (NC) is located at 15 m apart from the target, which is consists of 16 segments and 7 layers array of plastic scintillation counter (200 (width) $\times$ 1500 (hight) $\times$ 50 (thick)). The acceptance of the NC is $\sim$ 20 msr and the detection efficiency of $\sim$ 30 %, and has momentum resolution of $\Delta p/p \sim 1\%$. The solid angle of NC-array is covered by charge-veto counters, which is used as TOF-stop confer for the beam through run, to calibrate the absolute beam momentum. This charge-veto / TOF-stop is extended to opposite to the caved beam dump, and utilized as proton counter to study the isospin dependence. Most of these experimental setup can be utilized by the present experimental study, by replacing the

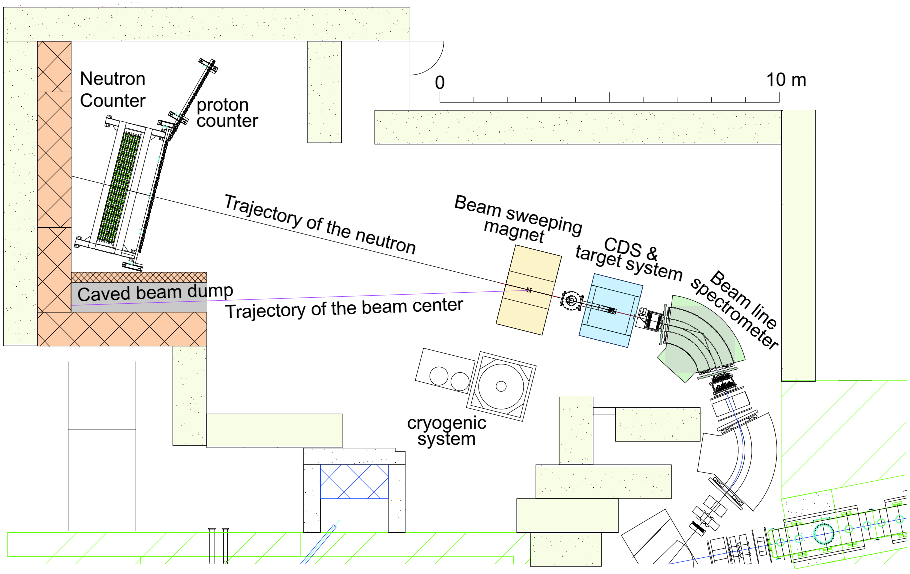

Figure 3: The J-PARC K1.8BR sprctrometer. The setup consists of beam line spectrometer (D5). liquid ^{3}He cryogenic target system, cylindrical spectrometer system (CDS), beam sweeping dipole magnet, caved beam dump equipped with beam monitor hodoscopes, neutron counter (NC) made of array of plastic scintillation counters equipped with charged veto counters (TOF stop counter for beam sweep), and the proton counter hodoscopes extended to the right-hand side of NC array.

target from ^{3}He to deuteron.

As it is described above, ideal experiment can be done when we cover the target region by large acceptance γ-ray detector system, which is not quite easy to realize. Alternatively, we are focusing on the two body mesonic decay of the $\bar{p}p$ sub-threshold resonance, namely $\rho\rho$ and K^*K channels, and successive decay of the two mesons into all-charged decay modes. To accomplish the event kinematic reconstruction efficiently, we need higher PID capability and larger solid angle coverage for our CDS system. Therefore, we are planning to replace the cylindrical drift chamber in CDS to cylindrical time projection chamber with highly segmented readout pads ($\sim$ 10,000 channels) to fulfill these two experimental requirements at the same time.

3.1 reaction kinematics

In general, the formation probability of resonance / bound state become large, when the momentum transfer is minimum. Fig. 4 (left) shows the momentum transfer of $d(\bar{p}, n)X(1835)$ reaction at $\theta_n = 0$. Because $X(1835)$ mass locates 40$\sim$ 50 MeV below the $\bar{p}p$ threshold, the momentum transfer has small but finite value, and decrease at the higher momentum. It start saturating around 500 MeV/c, and the momentum transfer around this region is as small as $\sim$ 60 MeV/c, which is much smaller than the typical Fermi motion in nuclei, so one can expect large formation probability. As

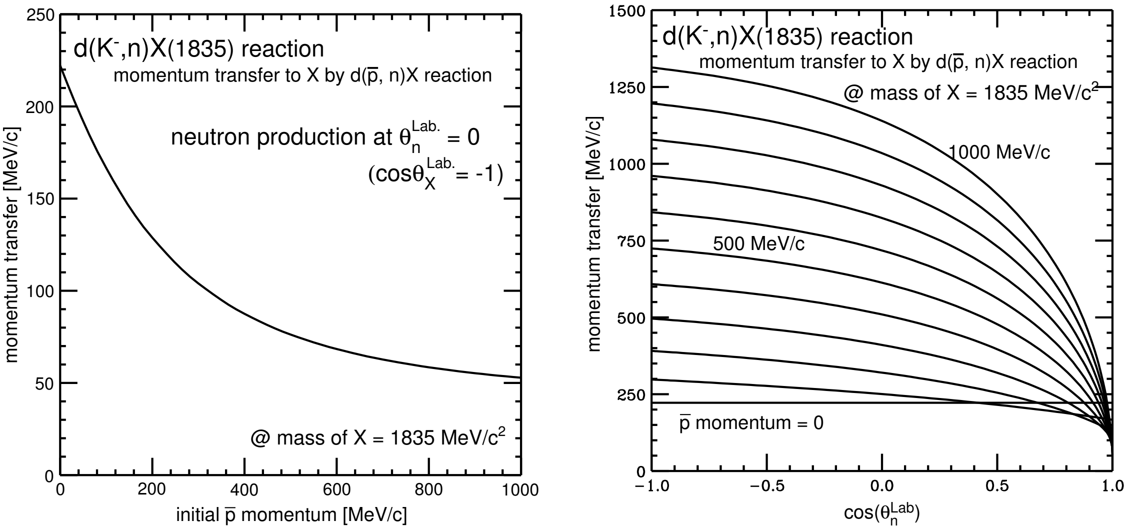

Figure 4: Left: The momentum transfer q of $d(\overline{p}, n)X(1835)$ reaction for neutron production in the forward direction. Right: Same for the neutron emission to finite angle at the initial $\overline{p}$ momentum from 0 to 1 GeV/c in 100 MeV/c step.

shown in Fig. 4 (right), small momentum transfer is realized only for the event having forward neutron emission, where we have 2 tons of NC at K1.8BR.

Fig. 5 (left) shows the $\overline{p}p$ elastic-scattering cross section (right scale), and the differential cross section of $\overline{p}$ backward-scattering of this reaction (left scale). As shown in the figure, the elementary elastic-scattering does not change largely in this momentum region, although the backward-scattering sharply drops in higher momentum region compared to the total cross section. Thus the signal to noise ratio (S/N) is expected to be better in the lower momentum region, because the background will be proportional to the total cross section.

On the other hand, available anti-proton yield at J-PARC, evaluated by Sanford-Wang empirical formula, has opposite momentum dependence, as shown in Fig. 5 (right). As shown in the figure, the $\overline{p}$ yield drops quite rapidly at low momentum, so that the higher momentum is preferable in terms of statistics at J-PARC. We need detailed simulation study for the final decision of the initial anti-proton momentum to determine the optimum $\overline{p}$ beam momentum, although it is clear that we shall run the experiment at around 700 $\sim$ 1000 MeV/c.

3.2 formation probability

To evaluate the experimental feasibility, the formation cross section of $d(\overline{p}, n)X(1835)$ reaction is needed. Because there is no theoretical calculation on this process, we apply very crude estimation. Let us assume that the backward differential cross-section of the $\overline{p}p$ and $\overline{p}n$ elementary processes are equal, $d\sigma_{\overline{p}n}/d\Omega \approx d\sigma_{\overline{p}p}/d\Omega$. The sticking

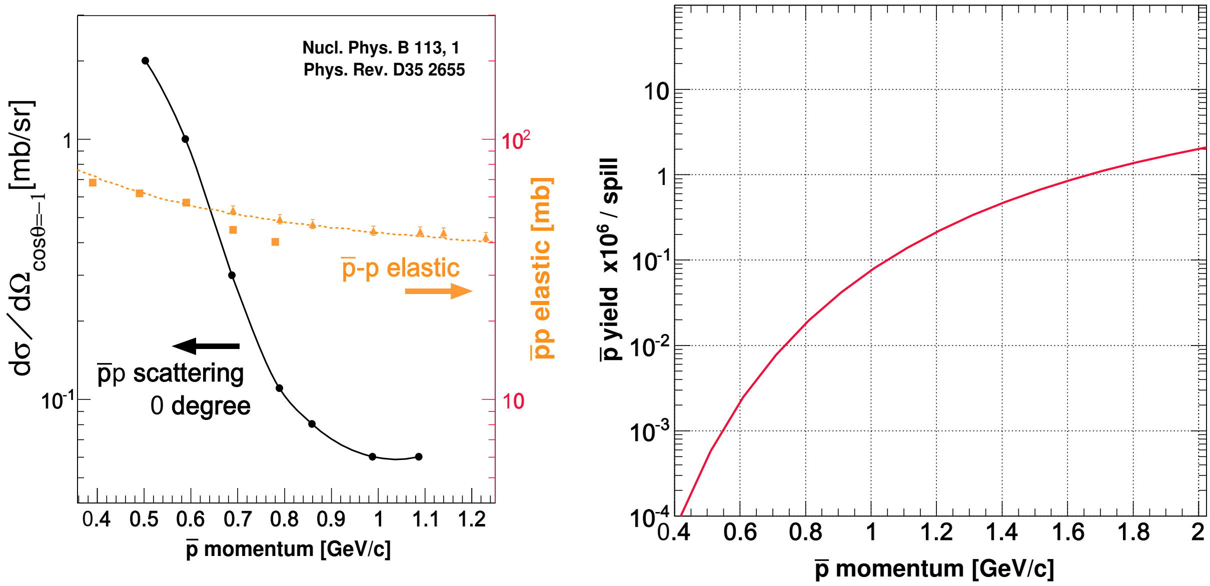

Figure 5: Left: total (right scale) and differential (left scale) cross section of elastic $\overline{p}p$ scattering. Right: expected $\overline{p}$ yield per spill (present SX provides a beam spill every 6 seconds) at J-PARC K1.8BR at 30 GeV and 30kW operation.

probability of backward $\overline{p}$ and spectator "p" can be roughly estimated by square of the form factor $F(q)$ viewed by the recoiled anti-proton at the momentum q at $l = 0$, namely by neglecting d-wave component in Ψ_D

$$P_{stick} \approx |F(q)|^2 \approx |\int j_0(qr)\Psi_D(\vec{r})\Psi_X(\vec{r})d\vec{r}\,|^2, \tag{1}$$

where the $\Psi_D(\vec{r})$ and the $\Psi_X(\vec{r})$ are the deuteron and X wave functions, respectively. Then the formation probability of $X(1835)$ can be written as

$$\frac{d\sigma_X}{d\Omega} = \frac{d\sigma_{\overline{p}n}}{d\Omega} P_{stick} \approx \frac{d\sigma_{\overline{p}p}}{d\Omega}|F(q)|^2. \tag{2}$$

For the present very rough estimation, we replace these wave functions by that of simple square well potential, adjusting the size and the binding energy of deuteron ("pn") and $X(1835)$ ("$\overline{p}p$"). Fig. 6 shows the sticking probability $P_{stick} \approx |F(q)|^2$. For the calculation, we used 2.0 MeV binding with radius of 2 fm for deuteron, and we fixed the $X(1835)$ radius to be 0.9 fm and changing the binding energy. In the estimation, the momentum transfer q is calculated, assuming the initial $\overline{p}$ momentum at 1 GeV/c, according to the binding energy.

Naturally, the sticking probability depends on the size of X. Because we do not know the size, we simply assumed that it is much compact than deuteron having a range of strong interaction of about 0.9 fm. For the comparison, we also plotted the

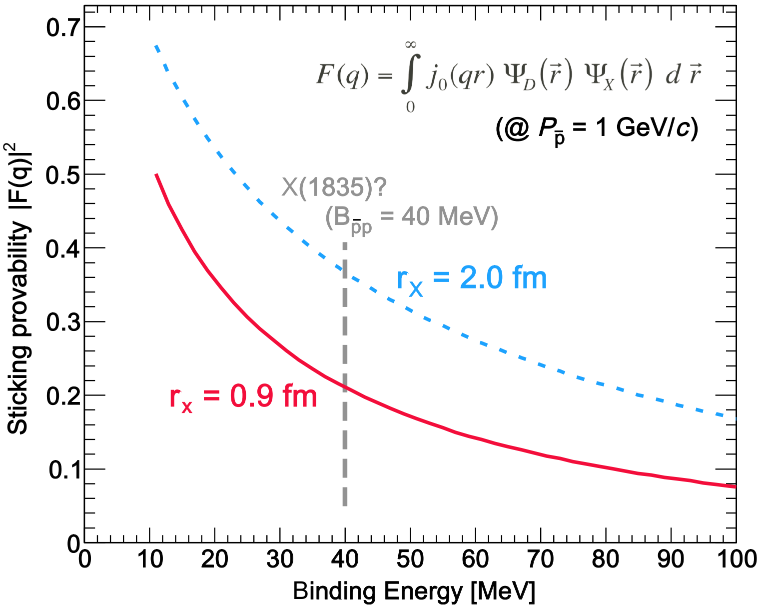

Figure 6: The sticking probability of "$\bar{p}p$" to form $X(1835)$ estimated by the square of the form factor $|F(q)|^2$ at initial $\bar{p}$ momentum of 1 GeV/c, as a function of its binding energy. The square-well size (r_X) for X is assumed to be 0.9 fm. For the comparison, sticking probability at $r_X = 2$ fm is also plotted in dotted curve.

probability when we assume that the X is as large as deuteron (2 fm), where the overlap becomes maximum.

Thanks to the recoilless kinematical condition of the $d(\bar{p}, n)X(1835)$ reaction, the sticking probability is as large as ~ 0.2 at the region of interest, even if the size of the $\bar{p}p$ system is as small as 0.9 fm. As it is described, the present evaluation of the formation probability is very crude, however we believe that it is good enough for the rough feasibility check of the experiment, at present.

3.3 beam time estimation

At present, J-PARC main ring is quite unique machine in the world, which can provide slow extraction (SX) beam. We are planning to do this experiment at K1.8BR experimental area. Because of the required cylindrical TPC preparation, it is not feasible to start experiment right at the moment. It is also true that we already have several experimental programs at K1.8BR and 30 GeV machine are expecting to have long shutdown for the lineac upgrade. Thus, the present experiment could be done only after 2015, and one can expect that the J-PARC slow extraction beam power is at least more than 30 kW.

Let us estimate the event rate and the required beam time, focusing on the decay branch of $X \to \rho^0\rho^0 \to 2$ "$\pi^+\pi^-$"-pairs. Assuming the initial anti-proton momentum at 1 GeV/c, we made a very rough estimation of the signal event rate by using following equation.

$$N = I_{beam} \times N_{target} \times \frac{d\sigma_X}{d\Omega} \times \Delta\Omega_{NC} \times \varepsilon_{NC} \times Br_{\rho\rho} \times \varepsilon_{CDS} \times \varepsilon_{analysis}, \qquad (3)$$

where I_{beam} and N_{target} are $\bar{p}$ beam intensity and the number of target nuclei, respectively. The $\Delta\Omega_{NC}$ is the solid angle of NC, and ε_{NC} is the detection efficiency of neutron. The $Br_{\rho\rho}$ is the branching ratio to $X \to \rho^0\rho^0 \to 2$ "$\pi^+\pi^-$" channel. The ε_{CDS} represents for the acceptance of the charged particles of the final state including the detection efficiency from the decay of X, $\bar{p}p$ sub-threshold resonance. Finally, $\varepsilon_{analysis}$ is the analysis efficiency.

The anti-proton beam intensity, I_{beam}, is expected to be $\sim 1 \times 10^5$ per spill (6 seconds) at 1 GeV/c with 30kW J-PARC MR operation at 30 GeV. Assuming target system developed for J-PARC E31 (deuteron target-cell thickness along the beam axis is 1.4g/cm^2), the number of target nuclei is 4.1×10^{23}/cm^2. The solid angle of the neutron counter array $\Delta\Omega_{NC}$ at K1.8BR (prepared for J-PARC E15 experiment) is 20 msr, and the neutron detection efficiency ε_{NC} is expected to be ~ 0.3.

The backward $\bar{p}p$ elastic cross section is about 70 μb/sr in CM system, and the conversion factor from the CM to the Lab. frame is about 4.9. Thus, the cross section in the Lab. frame is about 350 μb/sr. Therefore, the formation cross section $d\sigma_X/d\Omega$ is estimated to be about 50 μb/st. The decay branch $Br_{\rho\rho}$ including charge ρ decay modes is theoretically predicted to be at around 0.1 [9]. Assuming that the isospin of $X(1835)$ is zero, then the neutral decay channel $\rho^0\rho^0$ should be 1/3. Based on the simple Monte Carlo simulation, the acceptance of CDS (ε_{CDS}), to detect all pions produced in the decay $X \to \rho^0\rho^0 \to 2$ "$\pi^+\pi^-$" reaction, is about 90% with the upgraded cylindrical TPC. At last, we assumed the analysis efficiency, $\varepsilon_{Analysis}$, to be about 0.8.

As a result, we can expect that the neutron missing mass spectrum of $X \to \rho^0\rho^0 \to 2$ "$\pi^+\pi^-$" events would be almost background-free, and $\sim 9 \times 10^2$ events of this decay mode can be detected by 360 shifts of beam time at K1.8BR (at 1000 [spill/hour] , 8 [hours/shift] and 30kW operation of J-PARC SX), using the present spectrometer system with upgraded CDS. We can also study K^*K mode analogous to $\rho\rho$ mode, and the relative branching ratio will give us a mixing angle between $\frac{1}{\sqrt{2}} \ |\bar{u}u + \bar{d}d >$ and $|\bar{s}s >$. This event yield would be feasible in 2015, when we can expect proton beam power more than 30 kW.

4 Conclusion

At present, $\bar{p}p$ sub-threshold resonances, $\eta(1760)$ and $X(1835)$ found by B-factories, attract many interests. Especially, it is pointed out that the $X(1835)$ could be a $\bar{p}p$ bound state, or has substantial $\bar{p}p$ contribution in it. Therefore, we propose to perform an experimental study via $d(\bar{p}, n)X$ reaction at the initial $\bar{p}$ momentum around 700 $\sim$

1000 MeV/c. By this reaction channel, we wish to perform an experimental study based on 1) formation of sub-threshold resonances analysis by the missing-mass spectrum of $d(\overline{p}, n)$ reaction, and 2) exclusive decay channel focusing on the charged decay channel of $X \rightarrow \rho\rho$ and $X \rightarrow K^*K$ (including $\overline{K}K$), whose final state can be consists of all charged particles.

The momentum transfer of the proposed reaction is as small as 60 MeV/c, so we can expect rather large formation cross section of $\overline{N}N$ state formation, especially to the resonance strongly coupled with $\overline{p}p$. This recoilless condition ensures that the initial decay to two mesons should have back-to-back event topology, which can be utilized to tag signal quite effectively. Therefore, it is quite promising to study $\overline{p}p$ sub-threshold resonances by $d(\overline{p}, n)X$ reaction channel.

References

[1] I. N. Mishustin *et al.*, Phys. Rev. C 71 (2005) 035201.

[2] A. B. Larionov *et al.*, Phys. Rev. C 78 (2008) 014604.

[3] A. B. Larionov *et al.*, Phys. Rev. C 80 (2009) 021601(R).

[4] A. B. Larionov *et al.*, Phys. Rev. C 82 (2010) 024602.

[5] M. Ablikim *et al.*, Phys. Rev. Lett. 106 (2011) 072002.

[6] J. Beringer *et al.*, Phys. Rev. D86 (2012) 010001.

[7] Keizo Agari *et al.*, Prog. Theor. Exp. Phys. (2012) 02B011.

[8] M. Iwasaki *et al.*, J-PARC E15 proposal, http://j-parc.jp/NuclPart/pac_0606/pdf/p15-Iwasaki.pdf

[9] De-Min Li and Bing Ma, arXiv:0801.4821v3.