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Feasibility study for measurement of beta-decay rates of Λ hypernuclei

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Abstract. The baryon structure may be modified in nuclear medium. The quark meson coupling model predicts that the beta decay rate of a Λ hyperon in Λ hypernuclei decreases by 20% at maximum. We propose an experiment to precisely measure the beta-decay rate of ${}^{5}_{\Lambda}\mathrm{He}$ at J-PARC via the (π^+, K^+) reaction. A feasibility study via GEANT4 simulation has been done, showing that the background can be suppressed down to ~ 3.9% of the beta-decay electron yield, using a calorimeter covering the whole solid angle around the target. The measurement of the beta-decay of a Λ in a nucleus is found to be feasible.

1 Modification of the baryon structure in nuclear medium

Since a nucleon is a composite particle made of quarks and gluons, it is natural to consider that the properties and the structure of the nucleon may be modified in a nucleus via the interactions with other nucleons. The only clear evidence for the nucleon modification is the EMC effect [1]. The EMC effect indicates a change of the momentum distribution of quarks in the nucleon in nuclear matter, but the mechanism of the change has not been clarified very well. We thought of an idea that possible modification of baryon structure in a nucleus may be clearly detected by using a Λ hypernucleus. A promising probe for the baryon modification are weak decay properties of a Λ in a nucleus. It has been conjectured that the size of a nucleon (baryon) may be swelled since the spatial distribution of u and d quark wavefunctions in a baryon may be spread due to their interaction with the meson field in the nucleus. Figure 1 shows a schematic view of a Λ in the free space and in the nucleus. It is expected that the spatial distribution of u and d quarks is spread and that of s quarks is almost unchanged because the coupling of s quarks with the meson field is much smaller than that of u and d quarks. When the beta-decay of Λ takes place in the nucleus, the spatial overlap between the u quark wavefunction and the unchanged s quark wavefunction is expected to decrease. This structure change of Λ results in reduction of the axial charge g_A, and then the beta decay-rate of Λ, Γ_β in a nucleus. According to a calculation by the quark meson coupling model, g_A is predicted to be reduced by 10 % at maximum, which corresponds to a reduction of Γ_β by 20% at maximum in a nucleus [2]. The g_A/g_V value of a Λ in the free space was

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measured to be $g_A/g_V = -0.718 \pm 0.015$ [3]. However, there is no experimental data on beta decay of Λ in a nucleus and the in-medium g_A value.

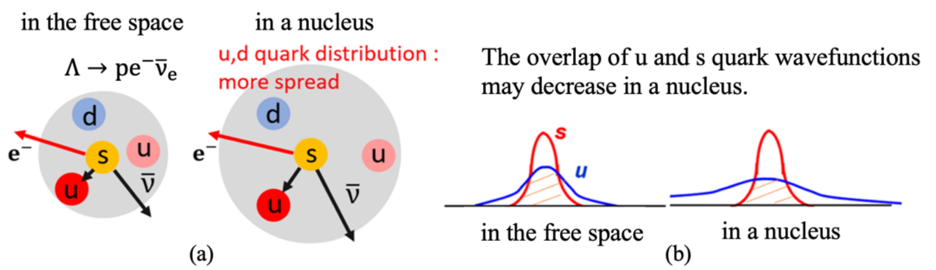

Fig. 1(a). Conceptual illustration for beta-decay of Λ in the free space (left) and in a nucleus (right).
Fig. 1(b). Illustration for wavefunctions of the initial state s quark and the final state u quark in the free space (left) and in a nucleus (right).

2 Experiment for measuring beta-decay rate of Λ

When measuring g_A reduction of Λ from the baryon modification via measurement of the beta-decay rate, other effects which cause the reduction of the beta-decay rate become a problem. In the beta-decay of ordinary nuclei, nuclear many-body effects as well as hadronic effects such as meson exchange current are known to reduce the beta-decay rate of Gamow Teller transition. Such reduction is ascribed to quenching of the effective g_A value in nuclei [3]. To measure the change of g_A from the baryon modification clearly, these quenching effects should be small. The quenching effects become larger in heavier nuclei, and they are small enough (<~5%) for the s-shell ($A \leq 4$) nuclei [4,5]. Thus, we propose an experiment to measure the beta-decay rate of ${}^5_\Lambda$He. In the proposed experiment, ${}^5_\Lambda$He will be produced by the ^{6}Li$(\pi^+, K^+){}^6_\Lambda$Li, ${}^6_\Lambda$Li $\to {}^5_\Lambda$He + p reaction at J-PARC K1.1 beam line with a setup as shown in Fig. 2. Momenta of beam π^+'s and scattered K^+'s are measured by the K1.1 beam line spectrometer and the SKS spectrometer. After producing ${}^5_\Lambda$He hypernuclei, the beta-decay rate, Γ_β, will be obtained by measuring the branching ratio of the beta-decay, BR_β, and the lifetime of ${}^5_\Lambda$He, τ_Λ. Considering the available beam time at J-PARC K1.1 beam line, we expect that the BR_β can be measured within a 4% statistical error and τ_Λ can be measured within a 2% statistical error. Then we will be able to confirm the reduction of Γ_β (20% at maximum) with more than 3σ confidence level. The lifetime τ_Λ was previously measured with a 4% statistical error in the KEK E462 experiment [6]. In our proposed experiment, we will use a similar setup as the E462 and achieve a statistical error of 2% [7].

When measuring the BR_β, the beta-decay electron from ${}^5_\Lambda$He should be measured by suppressing the background from other decay modes of Λ. The expected background comes from mesonic weak decay, $\Lambda \to p\pi^-$ ($BR_{\pi^-} = 0.4$) and $\Lambda \to n\pi^0$ ($BR_{\pi^0} = 0.2$), and nonmesonic weak decay, $\Lambda n \to nn$ and $\Lambda p \to np$ ($BR_{nm} = 0.4$), where the BR values were measured for ${}^5_\Lambda$He [6]. The ^{6}Li target is surrounded by plastic counters, lucite Cerenkov counters and a BGO calorimeter, as shown in Fig. 3. The plastic counters distinguish the beta-decay electron from neutral particles such as γ and neutron. The lucite Cerenkov counters distinguish the beta-decay electron from charged particles such as $\pi^-$and proton. The BGO calorimeter separates the beta decay-electron from π^0 and π^- by using the number of clusters in the BGO.

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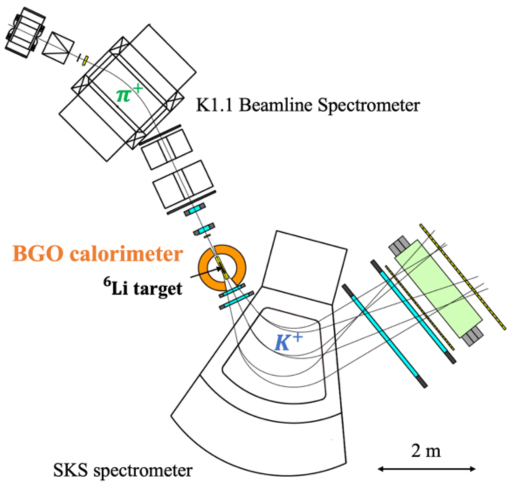

Fig. 2. Setup at the K1.1 beam line at J-PARC.

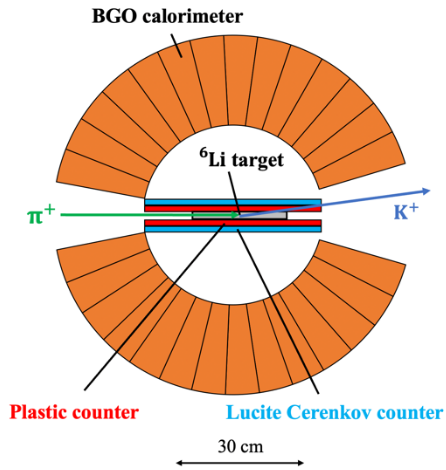

Fig. 3. Apparatus around the ^{6}Li target.

3 Background reduction study for measuring the branching ratio

In this section, we report simulation results for the background reduction study by the GEANT4 simulation code, and discuss feasibility of the beta decay measurement.

3.1 The cluster analysis via the BGO calorimeter

The background from π^0 and π^- from mesonic weak decay of Λ can be greatly suppressed via the cluster analysis in the BGO calorimeter. Figure 4 shows simulated distributions of the number of clusters in the BGO calorimeter. A cluster is identified when one or several adjacent segments in the BGO calorimeter have an energy deposit more than 1 MeV each. As shown in Fig. 4, a beta-decay electron produces one cluster. A π^0 mainly produces two clusters since π^0 mainly decays to 2γ, and one cluster events of π^0 are caused by the escape of one γ from the upstream or downstream hole of the BGO calorimeter. A π^-produces many clusters caused by many neutrons and nuclear γ-rays from interaction between π^- and nuclei in BGO. It was found that, by selecting one cluster events, 97% of π^0 and 92.8% of π^- events are rejected. Thus, the π^0 and π^- backgrounds are reduced down to $BR_{\pi^0} \times (1-0.97) = 0.006$ and $BR_{\pi^-} \times (1-0.928) = 0.028$, respectively.

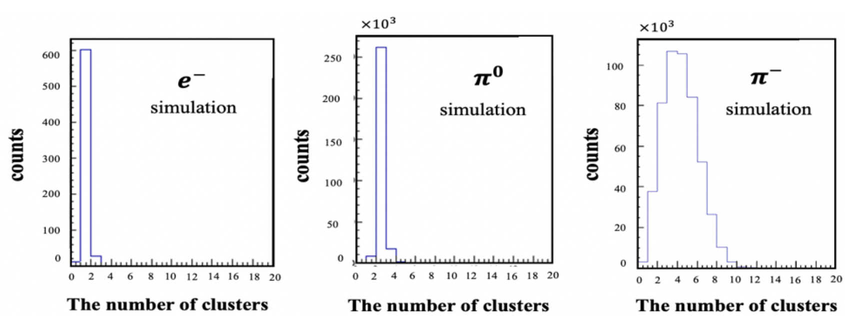

Fig. 4. The number of clusters in the BGO for the beta-decay electron, π^0 and π^- from $^{5}_{\Lambda}$He decay.

3.2 Analysis in the plastic counter and the lucite Cerenkov counter

Figure 5 shows a simulated distribution of the energy deposit per path length. The path length of particles in the plastic counter is determined by the vertex point in the target and the hit position at the BGO calorimeter. The distribution of the beta-decay electron has a minimum ionization peak at 0.2 MeV as shown in Fig. 5. The distribution for π^0 has two peaks corresponding to either of e^-or e^+, and to both $e^-$and e^+. The distribution for π^- has a peak at 0.5 MeV due to the pion velocity of $\beta\sim0.6$. By selecting $0.12 - 0.25$ MeV/mm in the energy deposit per path length and requiring a hit of the lucite Cerenkov counter, the π^0 and π^- backgrounds are reduced down to 0.006×0.12 (Plastic) $\times$ 0.1 (Lucite) $=$ 7.2×10^{-5} and 0.0288×0.001 (Plastic) $\times$ 0.045 (Lucite) $= 1.3 \times 10^{-6}$, respectively.

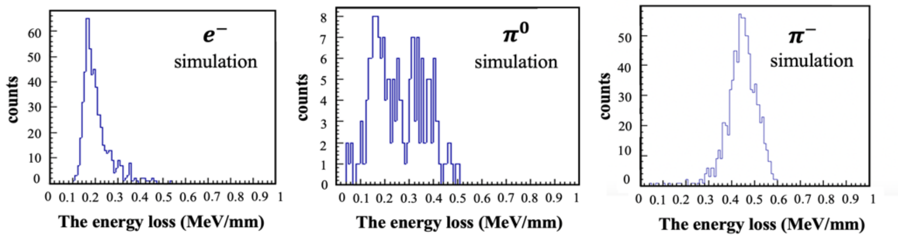

Fig. 5. The energy deposit per path length in the plastic counter for the beta-decay electron, π^0 and π^-.

3.3 Simulation results

Besides the analysis of each detector described above, the π^0 and π^- backgrounds can be further suppressed by analysis in photon veto counters to be installed at the exit of the downstream hole of the BGO calorimeter. Via all the analyses, the remaining π^0 and π^- backgrounds are reduced down to branching ratios of 7.2×10^{-5} and 1.3×10^{-6} , respectively. These values correspond to 3.6 % and 0.26% of the branching ratio of the beta-decay electron. The systematic error from the background is expected to be smaller than the required statistical error (4%) of the beta-decay measurement. Thus, the beta-decay measurement is found to be feasible.

4 Conclusion and future prospects

We found that the measurement of the beta-decay rate of Λ in the ${}^{5}_{\Lambda}$He hypernucleus is feasible. Most of the present results have been reported as a Letter-Of-Intent to J-PARC. In the near future, we will make more realistic simulation considering the performance of each detector and prepare a full proposal to J-PARC.

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