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Binding Energy of ${}^{7}_{\Lambda}$He and Test of Charge Symmetry Breaking in the ΛN Interaction Potential

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Abstract.
The binding energy of ${}^{7}_{\Lambda}$He has been obtained for the first time with reaction spectroscopy using the $(e,e'\mathrm{K}^+)$ reaction at Jefferson Lab's Hall C. A comparison among the binding energies of the A=7 T=1 iso-triplet hypernuclei, ${}^{7}_{\Lambda}$He, ${}^{7}_{\Lambda}$Li* and ${}^{7}_{\Lambda}$Be, is made and possible charge symmetry breaking (CSB) in the ΛN potential is discussed. For ${}^{7}_{\Lambda}$He and ${}^{7}_{\Lambda}$Be, the shifts in binding energies are opposite to those predicted by a recent cluster model calculation, which assumes that the unexplained part of the binding energy difference between ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He, is due to the CSB of the ΛN potential. Further examination of CSB in light hypernuclear systems is required both experimentally and theoretically.

1. Introduction

The masses of iso-multiplet light Λ hypernuclei provide us with basic information on their structure and the characteristics of the ΛN potential. In particular, they are expected to shed light on possible Charge Symmetry Breaking (CSB) in the potential. The possible CSB has been suggested based on the binding energy difference of the A=4, T=1/2 Λ hypernuclei, ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He. The differences, Δ=B(${}^{4}_{\Lambda}$He)-B(${}^{4}_{\Lambda}$H), for the ground and the excited 1^+ states have been measured by an emulsion experiment to be 0.35 ± 0.06 MeV and 0.24 ± 0.06 MeV, respectively.[1] However, there remain un-explained differences, even after subtracting the binding-energy shifts due to the Coulomb potential and Λ-Σ^0 mixing, ΛN-ΣN coupling and/or ΛNN three body forces. Even recent theoretical calculations for the system do not successfully account for the differences which are often attributed to CSB of the ΛN potential.

The A=7 hypernuclear system forms a T=1 iso-triplet with ${}^{7}_{\Lambda}$He as one of the multiplet members. Prior to the present work, the experimental data for the A=7 hypernuclear system have been obtained by emulsion measurements, but only for ${}^{7}_{\Lambda}$Li and ${}^{7}_{\Lambda}$Be.[2] The T=1 ${}^{7}_{\Lambda}$Li ground state binding energy was derived from the γ-ray energy for the T=1 $1/2^+$ state at 3.88 MeV to the T=0 $1/2^+$ ground state transition[3] and the ground state binding energy. The binding energy of the ${}^{7}_{\Lambda}$Be ground state was determined by measuring the 5 decay particles associated with pionic decay, also in emulsion. On the other hand, the ground state mass of the ${}^{7}_{\Lambda}$He has not been determined due to the poor emulsion spectrum.[2] The peak corresponding to the ground state is broad and the existence of an isomeric state is suggested[4] though it has not been confirmed yet.

$(e,e'\mathrm{K}^+)$ hypernuclear spectroscopy[5] offers a new opportunity to measure hypernuclear masses and thus determine the binding energies of Λ hypernuclei independently from emulsion experiments. Two of the characteristics of the $(e,e'\mathrm{K}^+)$ reaction for hypernuclear spectroscopy play key roles in the opening of this technique of determining binding energies. One is, that with high-quality electron beams used to produce Λ hypernuclei, precision spectroscopy with sub-MeV(FWHM) mass resolution can be achieved. The other is that the $(e,e'\mathrm{K}^+)$ reaction converts a proton in the target to a Λ hyperon and thus allows the use of $p(e,e'\mathrm{K}^+)\Lambda,\Sigma^0$ reactions as a calibration using the well known Λ and Σ masses. These two characteristics are advantages of $(e,e'\mathrm{K}^+)$ hypernuclear spectroscopy over hypernuclear production methods such as (π^+,K^+) and (K^-,π^-) reactions.

Recently, $(e,e'\mathrm{K}^+)$ hypernuclear spectroscopy was successfully carried out at JLab and has become an indispensable part of hypernuclear physics.[6, 7] This paper reports a preliminary result of the first mass determination of ${}^{7}_{\Lambda}$He and binding energies using the $(e,e'\mathrm{K}^+)$ reaction from JLab experiment E01-011.

2. E01-011: Hypernuclear spectroscopy experiment at JLab Hall C

The advantages of using high-quality GeV electron beams for the investigation of Λ hypernuclei have been recognized since the construction of CEBAF at JLab.[5] However, despite the

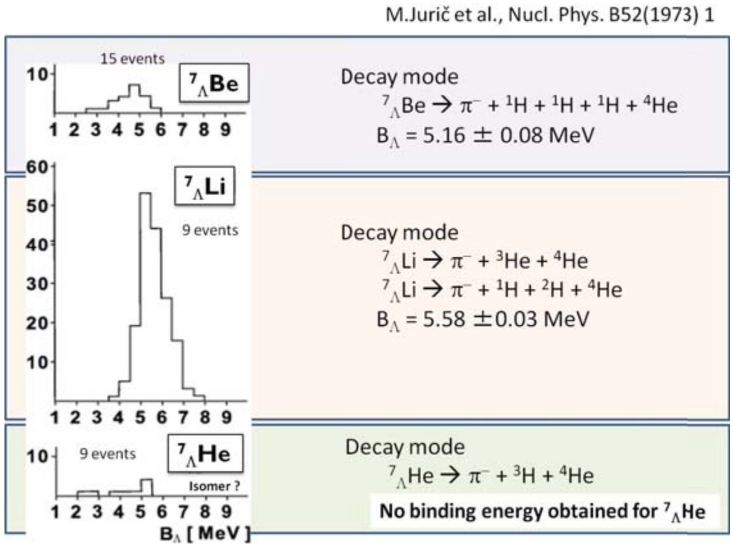

Figure 1. Measured binding energies of A=7, T=1 Λ hypernuclei.

advantages of electron beams over K^- and π hadron beams, experiments using electron beams have been difficult to realize. $(e, e'\mathrm{K}^+)$ spectroscopy experiments require two high resolution spectrometers, one for kaons and the other for scattered electrons. Moreover, the very high backgrounds from electromagnetic processes require a careful design of experiments. High accidental coincidence rates of a two arm spectrometer system limit the luminosity and thus the hypernuclear yield.

The JLab Hall C hypernuclear program was originally proposed in 1989. Since then this program has undergone three stages[8, 9, 10], with the last generation successfully completing data taking in the fall of 2009.

In $(e, e'\mathrm{K}^+)$ spectroscopy, both scattered electrons and kaons should be measured at very forward angles. The angular distributions of Bremsstrahlung electrons and electron-positron pairs are much more forward peaked than the distribution of scattered electrons associated with hypernuclear production. In addition, electrons from Møller scattering for a given momentum range also peak at very forward angles, though this depends on the beam energy. For the Hall C 2nd generation E01-011 experiment, a new High-resolution Kaon Spectrometer (HKS) was constructed and installed. In addition, the so called "tilt method" was employed, which was invented in order to considerably suppress background electrons at very forward angles due to electromagnetic processes proportional to $\sim Z^2$.

In the E01-011 experiment, Λ hypernuclei in a wide mass range were strategically investigated achieving a sub-MeV resolution for the ground state of $^{12}_{\Lambda}\mathrm{B}$ by tuning the two spectrometer system.[11] Among the hypernuclei studied, a preliminary result for $^{7}_{\Lambda}\mathrm{He}$ is described in the following sections.

3. Binding energy of $^{7}_{\Lambda}$He and comparison with other members of A=7, T=1 iso-triplet

In the present analysis, the absolute mass scale of hypernuclear spectra was carefully examined with the aim to reliably determine hypernuclear masses. Momenta of kaons and scattered electrons were calculated by backward transfer matrices that convert focal plane observables of particle trajectories to initial momenta of scattered electrons and kaons. The matrices were tuned using data with sieve slits located between the splitter magnet and the first quadrupole

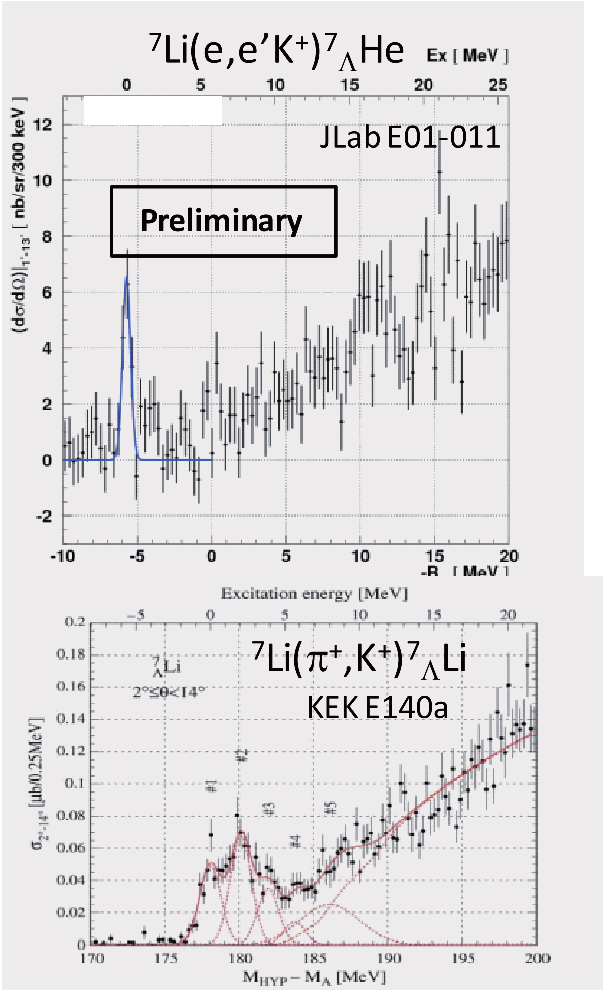

Figure 2. The $(e, e'\mathrm{K}^+)$ hypernuclear spectrum measured by the JLab E01-011 experiment

magnets, and with proton target data (CH_2, H_2O) starting from a matrix obtained using Monte Carlo simulation data generated with a 3-dimentional field map. In the Hall C setup, both Λ and Σ peaks are simultaneously observed as the large momentum acceptances for both scattered electrons and kaons gives a large missing mass acceptance. The proton target data also serves to constraint the absolute mass scale. A resolution of better than 0.5 MeV and hypernuclear yield rate of 8 counts/hour for the ground state of $^{12}_{\Lambda}$B were achieved with a beam intensity of 30 μA and target thickness of 100 mg/cm^2, as reported in [11].

The systematic errors due to the matrix tuning process were evaluated by analyzing full Monte Carlo data with arbitrarily chosen hypernuclear masses and various signal-to-noise ratios. The simulation data were analyzed using the same software as for the actual data. The analyzed peak positions differed from the input masses by $<$ 100 KeV for major peaks with a S/N ratio $>$ 1, but by $<$ 400 KeV for smaller peaks with a S/N ratio $<$ 1. In addition, errors due to the uncertainty of kinematic variables such as absolute beam energy, central momenta of kaons and scattered electrons were also examined and their contribution to the systematic error was found to be at most 150 keV. In E01-011, the overall errors of absolute binding energies were estimated to be less than 250 keV, taking into account the systematic and statistical errors. Further examination of these errors is under way.

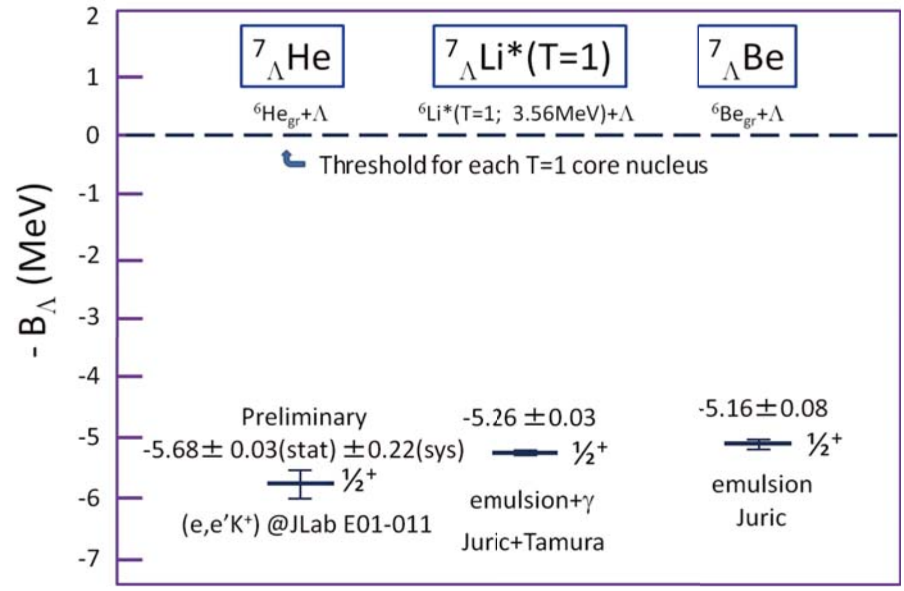

Figure 3. Binding energies of A=7 iso-triplet hypernuclei. The value for the $^7_\Lambda$He is the preliminary result from the E01-011 experiment. The data for $^7_\Lambda$Li was obtained by combining the emulsion data and γ-ray data, while that for $^7_\Lambda$Be was given by the emulsion experiment.

A preliminary excitation spectrum of $^7_\Lambda$He measured in experiment E01-011 is shown in Fig. 2 above a spectrum measured using the ^{7}Li(π^+, K$^+$) reaction using the SKS spectrometer at the KEK PS. This preliminary $^7_\Lambda$He spectrum shows a mass resolution of 510 keV(FWHM) and an absolute binding energy of -B$_\Lambda$ = -5.68 ± 0.03(stat.) ± 0.22(sys) MeV. The systematic error arises from ambiguities of the optical tuning of momentum reconstruction and from kinematic uncertainties such as beam energy. The spectrum is undergoing analysis before the binding energy and errors are finalized. We also note that the present preliminary spectrum does not agree with that of the E89-009 experiment which had one order of magnitude poorer statistics.[7]

In Fig. 3, the experimental binding energies of A=7, T=1 Λ hypernuclei are shown together with the preliminary one for $^7_\Lambda$He from this experiment. The errors on experimental binding energies for $^7_\Lambda$Li*(T=1) and $^7_\Lambda$Be are taken from emulsion data. It is shown in the figure that A=7 hypernuclear systems with fewer protons are bound deeper.

Hiyama *et al.* recently calculated the binding energies of A=7 Λ hypernuclei based on an α+N+N+Λ four body cluster model, renormalizing the three body ΛNN force and assuming that the unexplained mass difference between $^4_\Lambda$He and $^4_\Lambda$H can be attributed to the charge symmetry breaking.[12] They made a comparison of the T=1 ground states for $^7_\Lambda$He, $^7_\Lambda$Li and $^7_\Lambda$Be, and discussed hypernuclear mass shifts due to charge symmetry breaking in the A=7 system phenomenologically. It is suggested that the calculated binding energies are shifted and that the differences are enhanced more by taking into account the phenomenological CSB effect, although the size of the shifts, around 200 keV, are comparable to that of the experimental error for $^7_\Lambda$He obtained by the $(e, e'$K$^+)$ reaction.

It was mentioned that the core state of $^7_\Lambda$Be hypernucleus, ^{6}Be, is known to be unbound and that the calculation suffers from the structure ambiguity of the core nucleus. On the other hand, it is believed that the calculation for $^7_\Lambda$He is more reliable and that a precision binding energy measurement with the $(e, e'$K$^+)$ reaction can give clearer

information on possible charge symmetry breaking. In the case of the A=7 system, it was suggested there could also be a contribution from an odd CSB potential, which does not contribute in the case of A=4 $s-$ shell hypernuclei. The present result offers a possible opportunity to investigate the odd term contribution of CSB by comparing the CSB effects between A=4 and A=7 hypernuclear systems.[13]

4. Summary

JLab Hall C hypernuclear spectroscopy program has evolved from the 1st pioneering experiment, E89-009, to the 2nd generation hypernuclear spectroscopy experiment, E01-011, which achieved the highest resolution ever, < 0.5 MeV, for the ground state of ${}^{12}_{\Lambda}$B. In E01-011, a high precision ${}^{7}_{\Lambda}$He spectrum was also measured, determining the Λ binding energy to be $B_{\Lambda} = 5.68$ MeV with a precision better than 250 keV including both statistical and systematical errors.

A comparison was made for the binding energies of the T=1 iso-triplet Λ hypernuclei with A=7, ${}^{7}_{\Lambda}$He, ${}^{7}_{\Lambda}$Li* and ${}^{7}_{\Lambda}$Be. The present result suggests that the contribution of the CSB effect, which was predicted by the recent cluster model calculation, may shift the binding energies in the opposite direction for ${}^{7}_{\Lambda}$He and ${}^{7}_{\Lambda}$Be. The present result for the A=7 iso-triplet system is expected to provide us with information on charge symmetry breaking and reinforces the importance of further investigation of CSB in the ΛN potential. We state that it is worthwhile to re-visit the A=4 emulsion data which have been the basis of discussion of CSB in hypernuclear systems and also to measure the binding energies of other iso-multiplet systems of light hypernuclei by the precision $(e, e'K^{+})$ spectroscopy.

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