**CREST Research Project 3:** Study of hyperon-hyperon, hyperon-nucleon, and high energy nucleon-nucleon interactions
(Igor Filikhin - project PI, V. M. Suslov and B. Vlahovic, NCCU, Physics)

**Activity:**

- Spectroscopy of the $^7_{\Lambda}$He hypernucleus


- Spectroscopy of the $^9_{\Lambda}$Be and $^9$Be nuclei

  - B.Vlahovic, I. Filikhin, V.M. Suslov, Faddeev calculations for the $^9_{\Lambda}$Be, European Physical Journal (EPJ Conferences) 2009.

- Three body model for $^6_{\Lambda}$He and $^{12}_{\Lambda}$Be hypernuclei (in progress)
Spectroscopy of the $^7_{\Lambda}$He hypernucleus

Third Generation Exp. at JLab
E05-115 (Hall C)

Low-lying levels of $^7_{\Lambda}$He and $^6$He nuclei

First reliable observation of $^7_{\Lambda}$He w/ good statistics (Prof. Satoshi Nakamura, 2010)

Faddeev calculation: $-6.23$ meV
Spectroscopy of the $^7\Lambda\text{He}$ hypernucleus

Our findings are:

• The calculations using OBE simulating potential for NSC97f model of NY-interaction give the $^7\Lambda\text{He}$ binding energy (5.35 MeV) which is close to the preliminary experimental value (5.4 MeV or 5.74 MeV ?).

• We discussed the receipt for extracting hyperon binding energy from the three-body calculation. The value obtained in previous calculation by E. Hiyama et al. has to be corrected. The new corrected value agrees with our consideration.

• We predicted new value for He6L ground state energy of 0.25 MeV (compare with the E.Hiyama at al. result of .36 MeV)

• We have found that the ground band of the $^7\Lambda\text{He}$ spectrum can be classified as an analog of the 6He ground band
Cluster model for $^{9}_{\Lambda}\text{Be}$

$\alpha\alpha$–potential


$$V_{\alpha\alpha}^l(r) = V_{\text{rep}}^l \exp\left(-r/\beta_{\text{rep}}^l\right)^2 - V_{\text{att}}^l \exp\left(-r/\beta_{\text{att}}^l\right)^2,$$

$\alpha\Lambda$–potential

$\Lambda$ hyperon energy:

$$B_{\Lambda}(\Lambda^5\text{He}) = 3.12 \pm 0.02 \text{ MeV}$$


Gibson, Tang – Herndon (TH) potentials have a form of one range Gaussian

$$V(x) = V_o \exp\left(-\alpha x^2\right)$$
Numerical results

Low-lying levels of $\alpha\alpha\Lambda$ system: calculation with the $ABe+TH(M)$ potential model

Cal. 1 - our calculation
Exp. - experimental data for $(\pi^+, K^+)$ reaction From “Spectroscopy of $\Lambda$ hypernuclei” O. Hashimoto, H. Tamura, Progress in Particle and Nuclear Physics, 2006
Calculated (Cal.) and experimental (Exp.) spectrum of $^9$Be and $^9\Lambda$Be. Orbital and total momentum of each levels are shown. Energy is measured from $a+ a+L$ and $a+ a+n$ thresholds, respectively.

Calculated energy levels of $^9\Lambda$Be for three cluster configurations. A band corresponding to genuine hypernuclear states appears as an $\alpha - \alpha - \Lambda(p\Lambda)$ configuration.
Our findings are:

- **We found the set of phenomenological potentials to reproduce the ground state $\frac{1}{2}^+$ binding energy and excitation energy of the $5/2^+$ and $3/2^+$ states, simultaneously.**

- **Our calculations reproduce well the experimental data for excitation energies**

- **For $^9\Lambda$Be we found the set of local phenomenological potentials that reproduces well the ground state binding energy and reasonable -- the energies of low-lying resonances. Also we give classification of experimental data for low-lying spectrum as a set of spin-flip doublets.**

- **It is shown that for each energy levels of $^9\Lambda$Be one can establish a correspondence to the $^9$Be spectrum with the exception of several "genuine hypernuclear states", that agrees qualitatively with previous studies.**

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Three-body model for $^6_{\Lambda}He$ hypernucleus (in progress)

$^6_{\Lambda}He$ is typical P-shell nuclei, due to Pauli blocking between n and alpha-particle.


There are no experimental data for the 2$^-$ level

The system of three non-identical particles

Configuration space Faddeev equations:

$$\{ H_0 + V_\alpha(u_\alpha) - E \} \Psi_\alpha(u_\alpha, v_\alpha) = -V_\alpha(u_\alpha) \sum_{\beta \neq \alpha} \Psi_\beta(u_\beta, v_\beta),$$

where $V_\alpha$ is a short-range pair interaction in the channel $\alpha$, $H_0 = -\Delta_{u_\alpha} - \Delta_{v_\alpha}$ is the internal kinetic energy operator, $E$ is the total energy and the wavefunction of the three-body system is given as a sum $\Psi = \sum_{\alpha=1}^3 \Psi_\alpha$ over the three Faddeev components, corresponding to the two-body rearrangement channels.
Three-body models for other hypernucleus (in progress)

Figure 3: Cluster models for light Hypernuclei. The red arrows mean that three-body models are obtained from corresponding two-body models by including one nucleon. a) The \(^{6}\_\Lambda\)He and \(^{7}\_\Lambda\)Li hypernuclei as two-body and three-body systems. b) Systems \((\Lambda + k \times \alpha) + N\) and \((\Lambda + k \times \alpha) + N + N\), \(k = 1, 2, 3\) (two- and three-body systems). The core nucleus is shown for each \(k\). The nuclei, which will be predicted in proposed work, are also shown. The case shown in Figure (a) is obtained with \(k = 1\).
Figure 4: Hypernuclear chart. The hypernuclei which will be involved in the work on the present project marked by colored backgrounds. The arrows show the nuclei for which the binding energy will be predicted in proposed work. Blue background corresponds to two-body calculations of the type Core+N; the green background corresponds to three-body calculations of the type Corenucleus+N+N; red background corresponds to four-body calculations for the 3α + Λ system.
Cluster calculations for the $^{12}_{\Lambda}$Be ($^{12}_{\Xi}$Be) hypernucleus

In this section we propose to consider hypernuclear systems $^{10}_{\Lambda}$Be+$n+\Lambda$ and $^{10}_{\Xi}$Be+$n+\Xi$ as cluster model for the $^{12}_{\Lambda}$Be and $^{12}_{\Xi}$Be hypernuclei. The experimental evidence for existence of $^{12}_{\Xi}$Be was reported in [47] (see also K. Ikeda, et al, Prog. Theor. Phys. 91 (1994) 747; Y. Yamamoto, et al, Prog. Theor. Phys. Suppl. 117 (1994) 281). The phenomenological potential for $^{10}_{\Lambda}$Be+$n$ interaction was obtained in [\*]. For $^{10}_{\Xi}$Be+$\Xi$ interaction different type of potentials will be proposed (Woods-Saxon and Isasi potentials). Note that new experiments for $^{12}_{\Xi}$Be are planed at the J-PARC 50 GeV Proton Synchrotron (see T. Nagae, Spectroscopic Study of $\Xi$-Hypernucleus $^{12}_{\Xi}$Be, via the (K$^-$,K$^+$) Reaction, HYP06 at Mainz).

JLab Hall A

$^{12}_{\Lambda}$Be

\[
^{12}_{\Lambda}C(e, e'K^+)^{12}_{\Lambda}B
\]

Experimental data for bound states of $^{10}_{\Lambda}$B given from H. Tamura (\gamma-Ray Detector Symposium, December 27, 2004)

John Millener:

5 theory peaks: $^{11}_{\Lambda}$B($\frac{3}{2}^-$; g.s) $\otimes$ $s_{\Lambda}(1^-/2^-)$, $^{11}_{\Lambda}$B($\frac{1}{2}^-$; 2.12) $\otimes$ $s_{\Lambda}(1^-)$, $^{11}_{\Lambda}$B($\frac{3}{2}^-$; 5.02) $\otimes$ $s_{\Lambda}(1^-/2^-)$, $^{11}_{\Lambda}$B($\frac{3}{2}^-$; g.s) $\otimes$ $p_{\Lambda}(2^+/3^+)$, $^{11}_{\Lambda}$B($\frac{1}{2}^-$; 2.12) $\otimes$ $s_{\Lambda}(1^+/2^+)$