Residual Interaction Effects on Deeply Bound Pionic $1s$ states in Sn isotopes

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Deeply bound pionic states in heavy nuclei were predicted to be quasistable by Toki and Yamazaki [1] and were actually observed experimentally in 1996 in (d,^{3}He) missing mass spectra [2]. Recently, K. Suzuki *et al.* performed the (d,^{3}He) reactions on the Sn targets and succeeded to observe deeply bound $1s$ pionic states in Sn isotopes very precisely [3]. Experimental errors for the binding energies of the $1s$ state are around $\Delta E \sim 20$keV .

It is extremely interesting to study the s-wave part of the pion-nucleus interactions, since the s-wave strength provides both information on the pion mass excess in the nuclear medium and pion decay constant f_π through the Tomozawa-Weinberg theorem. The f_π^2 is the order parameter of chiral symmetry breaking of QCD, and is connected to the quark condensate through the Gell-Mann-Oakes-Renner relation. Thus, it is very interesting to determine the s-wave potential parameters from deeply bound pionic atoms. For this purpose, it is highly required to observe the pionic s-states precisely because the s-states depend nearly entirely on the s-wave potential [4] and, thus, the $1s$ states in heavy nuclei ($N > Z$) provide key information on the isovector part of the s-wave potential. According to this line, K. Suzuki *et al.* performed an experiment based on the theoretical prediction [4] and obtained excellent new data of the deeply bound pionic $1s$ states in Sn isotopes as described above [3].

However, since we make use of the single neutron pickup (d,^{3}He) reaction, the final pionic states are the one-pion-particle-one-neutron-hole $[\pi \otimes n^{-1}]_J$ states with respect to the target nuclei [5]. So far all theoretical calculations and analyses of the data postulate that the residual interaction effect is small and can be neglected except for the evaluation in Ref. [6]. This was actually true for Pb case since errors of data are significantly larger than the estimated residual interaction effects [6]. In present cases for the $1s$ states in Sn isotopes, it is not trivial at all whether the effects are negligible or not since the sizes of the experimental error for Sn cases are comparable to the calculated residual interaction effects for Pb. Thus, it is very important to evaluate the residual interaction effects for $1s$ states in Sn isotopes to deduce physical quantities related to pion behaviors in the nuclear medium from the observed spectra. In this report we evaluate the residual interaction effects on pionic states in Sn isotopes.

We apply the same theoretical model described in Ref. [6] to evaluate the residual interaction effects here, which includes only s-wave terms for the residual πN interaction. We will report more comprehensive results including p-wave terms in Ref. [7]. The matrix elements of the residual interaction can be written as [6],

$$\begin{aligned}
&\langle(\ell'_\pi \otimes j_\beta^{-1})^J \mid V_{N\pi} \mid (\ell_\pi \otimes j_\alpha^{-1})^J\rangle \\
= \; & -\frac{2\pi}{m_\pi}\frac{b_0+b_1}{4\pi}(-1)^{J+j_\alpha+j_\beta+\ell_\beta+\ell_\alpha-1/2} \\
&\times\sqrt{(2j_\alpha+1)(2j_\beta+1)(2\ell_\alpha+1)(2\ell_\beta+1)(2\ell'_\pi+1)(2\ell_\pi+1)} \\
&\times\left[\int_0^\infty dr r^2 R^*_{\ell_\beta}(r)R_{\ell_\alpha}(r)R_{\ell'_\pi}(r)R_{\ell_\pi}(r)\right]
\end{aligned}$$

$$\times \sum_L \left\{ \begin{array}{ccc} \ell'_\pi & j_\beta & J \\ j_\alpha & \ell_\pi & L \end{array} \right\} \left\{ \begin{array}{ccc} \ell_\alpha & j_\alpha & \frac{1}{2} \\ j_\beta & \ell_\beta & L \end{array} \right\} (\ell_\beta 0 \ell_\alpha 0 \mid L0)(\ell_\pi 0 \ell'_\pi 0 \mid L0),$$

where m_π is the pion mass. We fix the interaction strength as $b_0 = -0.0283 m_\pi^{-1}$ and $b_1 = -0.12 m_\pi^{-1}$, which are taken from the pion-nucleus optical potential parameters [8] and considered to be an effective πN interaction strength in nucleus. We include the neutron-hole states $s_{1/2}^{-1}$, $d_{3/2}^{-1}$, and $h_{11/2}^{-1}$, and pion orbits $1s$, $2s$, $2p$, $3s$, $3p$, and $3d$. We can evaluate the residual interaction effects by diagonalizing the matrix elements of the whole Hamiltonian describing the pion-nucleus system.

The calculated preliminary results are shown in Table 1 for the $(1s)_\pi \otimes (s_{1/2}^{-1})_n$ configuration for Sn isotopes. We found that the complex eigenenergies vary about 10-15 keV in the present cases. These effects are relatively smaller than the natural widths of the deeply bound pionic $1s$ states. However, the shifts are comparable to the experimental errors [3] and hence, should be evaluated carefully using better formula.

^{115}Sn	^{119}Sn	^{123}Sn
13.1 + 1.8 i	11.9 + 1.6 i	10.5 + 0.8 i

Table 1: Calculated complex energy shifts due to the residual interaction. The results are shown in units of keV for the $(1s)_\pi \otimes (s_{1/2}^{-1})_n$ configuration for Sn isotopes.

In summary, we have evalauted the complex energy shifts of the deeply bound pionic $1s$ states in Sn isotopes and shown the preliminary results which include only s-wave residual interaction effects and assume the one-neutron-hole configuration in the final open-shell nucleus implicitely. The present preliminary results show that the sizes of the residual interaction effect are comparable to the experimental errors, and hence, we need to evaluate them using realistic theoretical formula, which will be reported in Ref. [7]. We believe that it is essential to evalaute these effects precisely in order to deduce the chiral parameters from the accurate pionic atom data.

References

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