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Abstract:

The Pauli blocking effect on the pionic decay rate of ${}^{5}_{\Lambda}$He is investigated with the Λ-α potential obtained from the hard-core Λ-N potential. The repulsive core of the Λ-N interaction reduces the Pauli blocking effect and enhances the pionic decay rate by about 30%. The lifetime of ${}^{5}_{\Lambda}$He evaluated is in good agreement with the experimental one.

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In recent papers[1] we have shown that a central repulsion appears in the effective Λ-α potential constructed with the Dalitz hard-core Λ-N potential.[2] We call the Λ-α potential the Isle-type one for its characteristic form. As shown in Fig.1, the Isle potential is very different from the single Gaussian (SG) Λ-α potential usually used in studies of light hypernuclei.[3] The central repulsion of the Isle potential must strongly affect the Λ-density distribution in the light hypernuclei. Fig 1

As discussed by Dalitz and Liu[4], the pionic decay of ${}^{5}_{\Lambda}$He is largely suppressed by the Pauli blocking effect, which is very sensitive to the Λ-density distribution in ${}^{5}_{\Lambda}$He. Here, to clarify the importance of the central repulsion of the Isle potential, we investigate the Pauli blocking effect on the pionic decay rate of ${}^{5}_{\Lambda}$He and estimate the lifetime of ${}^{5}_{\Lambda}$He. For comparison we also use the SG potential.

The Isle-type Λ-α potential is parameterized into the two-range Gaussian form;

$$U_{\Lambda\alpha}(r) = V_R \exp(-(r/b_R)^2) - V_A \exp(-(r/b_A)^2), \tag{1}$$

where V_R= 450.4MeV, V_A= 404.9MeV, b_R= 1.25fm and b_A= 1.41fm. The SG Λ-α potential is obtained by folding the Dalitz-Downs single Gaussian Λ-N potential[5] with the shell-model wave function of the α particle and represented with parameters V_R=0, V_A= 43.92MeV and b_A= 1.566fm. With these parameters the Λ-α separation energy is

3.1MeV. The difference between the ranges of two Λ-α potentials is due to that of the intrinsic ranges of the elementary Λ-N potentials.

In a closure approximation with the mean π^- momentum $\bar{q}_-$, the π^- decay rate of ${}^5_\Lambda$He is given by[4]

$$R^- = 2\bar{q}_-\{\, s_-^2 + (\bar{q}_-/q_\Lambda^-)^2\, p_-^2 \,\}(1-\eta_-)/\{\, 1+\omega_-/(5M)\, \}, \qquad (2)$$

with $\omega_- = (\, m_-^2 c^4 + \bar{q}_-^2 c^2 \,)^{1/2}$. Here q_Λ^- is the π^- momentum for the free Λ decay and s_-, p_- are its s and p-wave amplitudes, respectively. The expression for the π^0 decay rate R^0 can be obtained by exchanging $\bar{q}_-$, s_- etc. for the quantities corresponding to the π^0 decay. The values of s_-^2 and p_-^2 are experimentally determined to be 8.72×10^{-15} and 1.17×10^{-15}, respectively, and s_0^2/s_-^2 (or p_0^2/p_-^2) is 0.508. The correction of the Pauli blocking η_- is given by

$$\eta_- = \int \phi_\alpha^*(2,3,4,5)\, u_\Lambda^*(1)\, \exp\{ i\vec{\bar{q}}_- \cdot (\vec{r}_1 - \vec{r}_2)\}\, \phi_\alpha(1,3,4,5)\, u_\Lambda(2)\, d\tau, \qquad (3)$$

where ϕ_α is the ground state wave function of the α-particle and u_Λ the Λ-α relative wave function. With the shell-model wave function of the $(0s)^4$ configuration for ϕ_α, Eq. (3) is reduced to

$$\eta_- = (2b_\alpha\sqrt{\tfrac{\pi}{3}}\,)^{-3}(\tfrac{16}{15})^3 \int d\vec{x}\, d\vec{y}\, \exp(-\frac{2}{75b_\alpha^2}(17\vec{x}^2+16\vec{x}\cdot\vec{y}+17\vec{y}^2))$$

$$\times\exp(\, \tfrac{4}{5}\, i\vec{\bar{q}}_- \cdot (\vec{x}-\vec{y})\,)\; u_\Lambda(x)\; u_\Lambda(y), \qquad (4)$$

where b_α (=1.358fm) is the size parameter of the α particle. For simplicity we omit the suffix - or 0 of all quantities hereafter when we need not identify the pionic decay mode of ${}^5_\Lambda$He.

The Λ-α relative wave function u_Λ is given by solving the Schrödinger equation with the Isle-type and SG Λ-α potentials. As shown in Fig.2, the Λ-density distribution in ${}^5_\Lambda$He with the Isle potential is extremely suppressed at the center by the central repulsion and the Λ particle is spreaded outside. The rms radii of the Λ particle for the Isle and SG potentials are 2.43 and 2.12 fm, respectively. As the Pauli blocking effect is proportional to the overlapping between the Λ and nucleon wave functions, it must be reduced for the spreaded distribution of the Λ particle with the Isle potential. Fig. 2

The values of η and R calculated with $\bar{q}/q_{max}$=0.9, where q_{max} is the maximum pion momentum in each decay mode, are presented in Table I. The value of η_-(=0.32) with the SG potential corresponds to the result of Dalitz and Liu (η_-=0.34).[4] With the Isle potential the Pauli blocking effect is reduced by 20% and the pionic decay rate is enhanced by 40% in comparison with those of the SG potential. This large enhancement is due to the hard core and large intrinsic range of the elementary Λ-N potential for the Isle potential. The intrinsic range of the Dalitz-Downs single Gaussian potential is 1.48fm, which is rather shorter than that of the Dalitz hard-core potential(2.0fm). In order to extract the net effect of the Λ-N hard core, we evaluate η and R based on the single Gaussian Λ-N potential with the intrinsic range of 2.0fm. As presented in Table I, the difference of the intrinsic ranges in the single Gaussian Λ-N potential affects the pionic decay rate by only 10%. Therefore the pionic decay rate of ${}^{5}_{\Lambda}He$ is enhanced by about 30% as the effect of the Λ-N repulsive core. Table I

As discussed in Ref. 1, the central rise of the Λ-α potential is very sensitive to the intrinsic range of the hard-core Λ-N potential. As shown in Fig.1, Maeda and Schmid[6] have obtained the Λ-α potential with a small central rise from the Herndon hard-core Λ-N potential,[7] of which intrinsic range is 1.5fm. The Maeda and Schmid (MS) Λ-α potential is parameterized into a sum of two Woods-Saxson forms, and is not similar to the Isle potential but to the SG potential with respect to the overall range. With the MS potential we get small enhancement of the pionic decay rate as presented in Table I. So we should examine which Λ-α potentials are more favorable experimentally in order to confirm the importance of the Λ-N repulsive core on the pionic decay of ${}^{5}_{\Lambda}He$. To do this we evaluate the lifetime of ${}^{5}_{\Lambda}He$ below.

The lifetime τ is given with the sum of the pionic decay rate and nonmesic decay rate R_{nm};

$$\tau = \frac{\hbar}{c} \frac{1}{R^{-}+R^{0}+R_{nm}}. \qquad (5)$$

The ratio of R_{nm}/R^{-} is experimentally given to be 1.31 ± 0.09 by Coremans et al.[8] There are several experimental estimates of the lifetime of ${}^{5}_{\Lambda}He$[9] and the newest one is $(2.74^{+0.60}_{-0.50}) \times 10^{-10}$ sec. which is estimated with 1640 events by Bohm et al.[10] Fig 3 Table II

The lifetime calculated for $\bar{q}/q_{max}$=0.9 are shown in Fig.3 with the errorbars coming from that of R_{nm}/R^{-} and we also present the values for $\bar{q}/q_{max}$=0.9 and 0.95 in Table II. As seen in Fig.3, the lifetime evaluated with the Isle potential, $(3.02^{+0.10}_{-0.09}) \times 10^{-10}$ sec., is in good agreement with the experimental one. On the other hand τ's with the MS and SG potentials are too long, even if we take somewhat large value of $\bar{q}/q_{max}$(=0.95). This discrepancy between the experimental and theoretical estimates with the MS potential does not seem to be resolved. Neglect of the real pion absorption in the experimental analysis and use of the closure approximation in the theoretical calculation may lead to the over-estimates of the nonmesic and pionic decay rates, respectively. Furthermore the N-N correlations in the α particle make the lifetime of ${}^{5}_{\Lambda}He$ longer since the overlapping between the Λ and nucleon wave functions becomes large for the effect of the N-N correlations. Therefore the present analysis supports that the effective Λ-α potential has a central repulsion like the Isle potential and the Λ-N potential has a large intrinsic range. This result is consistent with that the Dalitz hard-core Λ-N potential is more favorable meson-theoretically than the Herndon's.[1]

Finally we notice that the present result is independent of the peculiarity of the hard-core potential. We construct the Λ-α potential with the soft-core Λ-N potential whose core height is about 1.4GeV and whose effective range and scattering length are equal to those of the Dalitz hard-core potential. The resultant Λ-α potential is very similar to the Isle potential and is also represented with the two-range Gaussian form whose parameters are V_R=228.1MeV, V_A=204.4MeV, b_R=1.21fm and b_A=1.52fm. The lifetime of ${}^{5}_{\Lambda}$He calculated with this potential for $\bar{q}/q_{max}$=0.9 is $(3.07\pm0.10)\times10^{-10}$ sec., which is the almost same as that with the Isle potential.

In conclusion, the central repulsion of the effective Λ-α potential which is obtained from the hard-core Λ-N potential with the intrinsic range of 2.0fm strongly affects the pionic decay of ${}^{5}_{\Lambda}$He and is very favorable to reproduce the lifetime of ${}^{5}_{\Lambda}$He.

In order to confirm quantitatively the central repulsion of the effective Λ-α potential we need more accurate measurement of the lifetime of ${}^{5}_{\Lambda}$He and detailed theoretical calculation. We also should investigate the effect of the central repulsion of the effective Λ-α potential on such light hypernuclei as ${}^{5}_{\Lambda\Lambda}$He and ${}^{9}_{\Lambda}$Be.

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Table I. The Pauli blocking correction and the π^- and π^0 decay rates of ${}^{5}_{\Lambda}He$. The values are obtained for $\bar{q}/q_{max}=0.9$ and those in parentheses are calculated for $\bar{q}/q_{max}=0.95$.

Λ-α pot. type	η_-	η_0	R^- (10^{-13}MeV/c)	R^0 (10^{-13}MeV/c)
Isle	.557	.544	7.64	4.15
	(.538)	(.524)	(8.51)	(4.62)
SG	.681	.669	5.50	3.01
	(.662)	(.649)	(6.22)	(3.41)
SG(2.0)[a]	.652	.640	6.00	3.28
	(.633)	(.620)	(6.75)	(3.69)
MS[b]	.661	.656	5.86	3.20
	(.641)	(.628)	(6.60)	(3.61)

a) SG(2.0) denotes the Λ-α potential based on the single Gaussian Λ-N potential with the intrinsic range of 2.0fm.

b) Maeda-Schmid Λ-α potential is obtained from the Herndon hard-core Λ-N potential with the intrinsic range of 1.5fm.

Table II. Lifetime of ${}^{5}_{\Lambda}He$ calculated with the Isle-type, MS and SG Λ-α potentials. The values are obtained for $\bar{q}/q_{max}=0.9$ and those in parentheses for $\bar{q}/q_{max}=0.95$. All values are given in unit of 10^{-10} sec.

Isle	MS	SG	exp.[a]
$3.02^{+0.10}_{-0.09}$	$3.93^{+0.13}_{-0.12}$	$4.18^{+0.14}_{-0.12}$	$2.74^{+0.60}_{-0.50}$
(2.71 ± 0.09)	(3.49 ± 0.11)	$(3.70^{+0.12}_{-0.11})$	

a) See ref.9.

Figure captions

Fig.1 $\Lambda - \alpha$ potentials. The solid, dashed and dashed-dotted lines denote the Isle, SG and MS potentials, respectively.

Fig.2 Λ-density distributions in ${}^{5}_{\Lambda}$He. The solid and dashed lines denote the density distributions calculated with the Isle and SG potentials, respectively.

Fig.3 Lifetime of ${}^{5}_{\Lambda}$He. The solid circles and triangles are the experimental and theoretical estimates, respectively.

Fig. 1

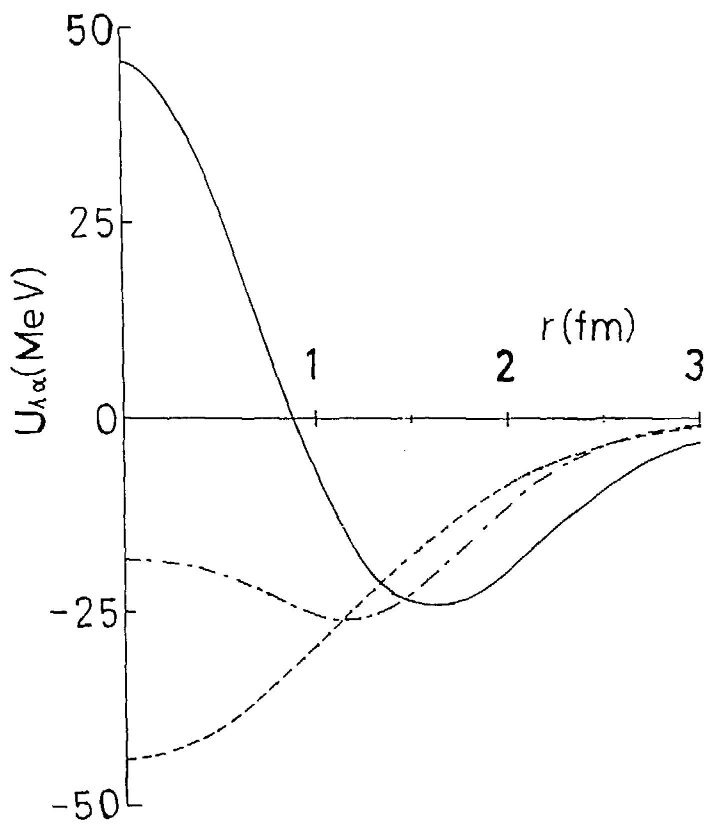
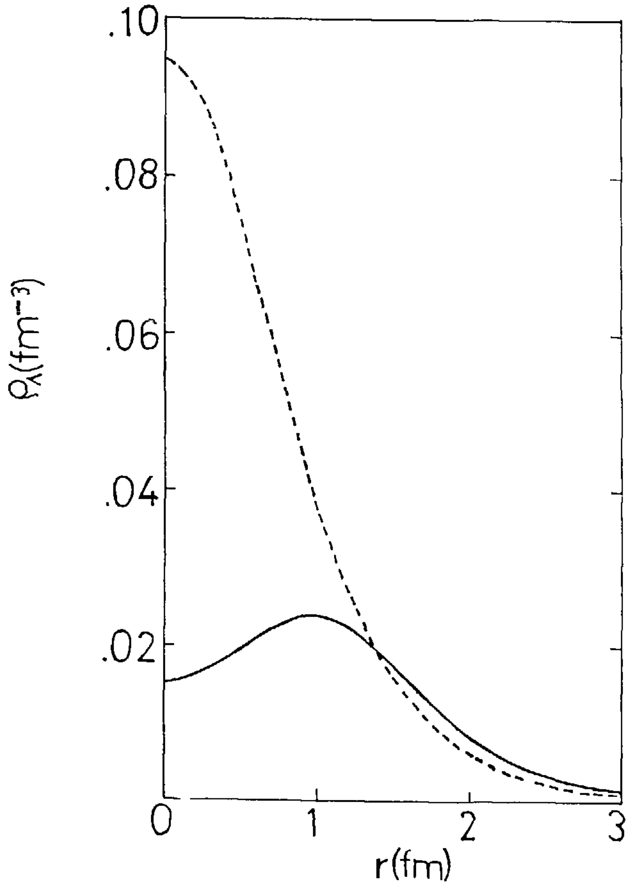
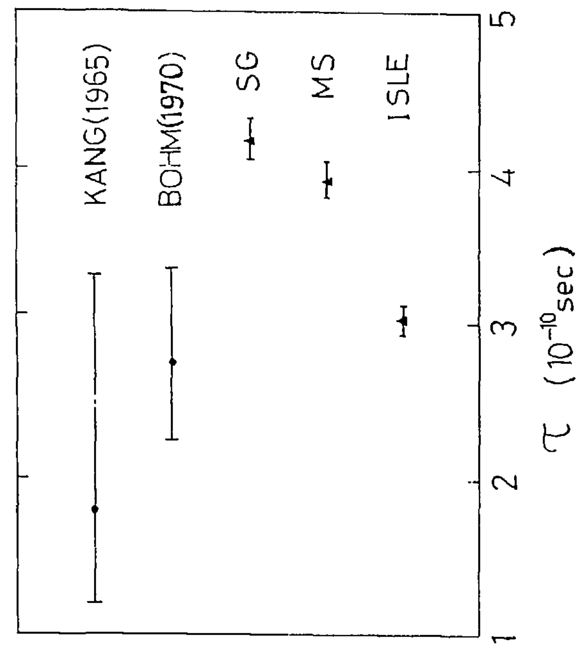


Fig 2



.10
.08
.06
.04
.02
$\rho_\Lambda(fm^{-3})$
0
1
2
3
r(fm)

Fig 3



KANG(1965)
BOHM(1970)
SG
MS
ISLE
1
2
3
4
5
τ (10^{-10}sec)