第29卷第8期
2005年8月

高能物理与核物理
HIGH ENERGY PHYSICS AND NUCLEAR PHYSICS

Vol.29, No.8
Aug., 2005

Phenomenological Analysis of Energy Shifts and Widths of Kaonic Atoms

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Abstract We analyze kaonic atoms in terms of the phenomenological optical potential of Woods-Saxon form. By fitting data of kaonic atoms, we obtain an optimal set of optical potential parameters. Comparing this optical potential near surface of nucleus with other optical potentials obtained in some successful research works, we find that they are in rather good agreement with each other. On the other hand, the imaginary part of our potential between kaon and nucleus is similar to that between nucleon and nucleus, but the real part of the potential between kaon and nucleus is much deeper and narrower in radial distribution.

Key words phenomenological analysis, Woods-Saxon optical potential, kaonic atom, energy shift, width

1 Introduction

An "exotic atom" is formed when a negatively charged particle except electron is captured by a target atom and enters an outer orbit of the atom. It will then, by emitting Auger electrons and characteristic X-rays, cascades down its own sequence of atomic levels and transit into some state with the minimal radial quantum number. The particle is eventually absorbed by the nucleus through its interaction with the nucleus. If the negatively charged particle in the exotic atom is a hadron, such as π^-, K^-, $\bar{p}$, Σ^-, Ξ^-, Ω^- etc., it is called "hadronic atom". By measuring the spectra of the characteristic X-rays of the hadronic atom, one can obtain the information about the strong interaction between hadron and nucleus. Thus, hadronic atoms provide a special physical environment for studying strong interaction. Some details about the hadronic atoms have already been introduced in Ref.[1].

"Mesonic atom" refers to the hadronic atom consisting of a nucleus and a meson, it is called "kaonic atom" if the meson is a kaon. The interactions between nucleus and meson include both electromagnetic and strong interactions. The study on kaonic atoms was firstly used to analyze the physics concerning the low-density limit[2,3]. Then fits to the experimental data were improved and some new results were obtained, which indicate that they can be applied to the study of astrophysics[4]. Up to now, altogether sixty-six kaonic atom data covering states from $2p$ of $_{K^-}$He to $8j$ of $_{K^-}$U have been collected. Considering that the data base for kaonic atoms is quite extensive and generally of good accuracy[3], kaonic atoms become a natural choice for studying the K^--nucleus strong interaction.

Recently, a remarkable progress on the study of K^--atoms has been made. The main works include the phenomenological research of Friedman[1—3,5—9] and the microscopical study of Oset[10—16].

The phenomenological optical potential of the Woods-Saxon(W-S) type has widely been applied to study nucleon-nucleus interactions and achieved obvious successes. On other side, it has also been successfully applied to analyze on the ground state binding energy of the hyper-nucleus of Λ, Λ_c^+[17] and Ξ^-[18]. As another phenomenological approach, in this work we are trying to apply such optical potential to describe the strong interaction between K^- and nucleus. We calculate the energy shifts and widths of these kaonic atoms and obtaind

Received 14 October 2004, Revised 16 February 2005
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satisfactory results.

This paper is arranged as follows. In Sec.2, we present the theoretical framework and the input parameters for later numerical computations. In Sec.3, we give numerical results and make some discussion, moreover, we compare our results with that obtained in terms of the density-dependent(DD) potential and microscopical potential. The last section is devoted to a summary.

2 Method

The interesting observable quantities are the energy shifts (ε) and widths (Γ) of the atomic levels caused by strong interaction of kaon with nucleus. Energy shifts and widths can be calculated by adding an optical potential to the Coulomb potential. Thus the study of the strong interaction in hadronic atoms is transferred to the study of this additional optical potential.

We define the energy shift and width by means of

$$\varepsilon = B_c - \mathrm{Re}B_n, \tag{1}$$

$$\Gamma = 2\mathrm{Im}B_n, \tag{2}$$

where B_n and B_c are the total and the purely electromagnetic binding energies, respectively. The interaction of K^- with nucleus is described by the Klein-Gordon equation (KGE)[19]

$$[-\hbar^2c^2\nabla^2+\mu^2c^4+2\mu c^2V_{opt}(r)]\Psi(\boldsymbol{r}) = [E-V_c(r)]^2\Psi(\boldsymbol{r}), \tag{3}$$

where V_c is the Coulomb potential, V_{opt} is the strong interaction optical potential, μ is the K^--nucleus reduced mass, E is meson energy. Let $E = \mu c^2 + E_n = \mu c^2 - B_n$, and the above equation is reduced to

$$\left[-\frac{\hbar^2}{2\mu}\nabla^2+B_n+V_{opt}(r)+\frac{\mu c^2-B_n}{\mu c^2}V_c(r)-\frac{V_c^2(r)+B_n^2}{2\mu c^2}\right]\Psi(\boldsymbol{r})=0. \tag{4}$$

To derive the K^--nucleus bound states, we solve the KGE(4).

Letting $\Psi(\boldsymbol{r})=\frac{u_l(r)}{r}Y_{lm}(\theta,\varphi)$, and substituting it in to Eq.(4), we obtain the radial equation in a standard form

$$\frac{\mathrm{d}^2u_l(r)}{\mathrm{d}r^2} = F_l(r)u_l(r). \tag{5}$$

The coefficient $F_l(r)$ is

$$F_l(r) = \frac{l(l+1)}{r^2}+\frac{2\mu}{\hbar^2}\left(B_n+V_{opt}(r)+\frac{\mu c^2-B_n}{\mu c^2}V_c(r)-\frac{V_c^2(r)+B_n^2}{2\mu c^2}\right). \tag{6}$$

It can be solved with a typical numerical method[18]. Here, $V_c(r)$ is given by

$$V_c(r)(\mathrm{MeV}) = \begin{cases} 1.440975Z_KZ/r & r > R_c(\mathrm{fm}) \\ \frac{0.720488}{R_c}Z_KZ\left(3-\frac{r^2}{R_c^2}\right) & r \leqslant R_c(\mathrm{fm}) \end{cases}, \tag{7}$$

$Z_K = -1$, $R_c = r_cA^{1/3}$. We fix the parameter $r_c = 1.3$fm.

The phenomenological optical potential is taken as the Woods-Saxon form

$$V_{opt}^{(WS)}(r) = V(r) + iW(r). \tag{8}$$

The real part

$$V(r) = -V/[1+\exp((r-r_vA^{1/3})/a_v)], \tag{9}$$

and the depth V of real part $V(r)$ is divided into three parts,

$$V = V_0 + V_1\frac{N-Z}{A} + V_2\frac{Z}{A^{1/3}}, \tag{10}$$

where V_0 represents the constant term, V_1 and V_2 represent the coefficients of isospin relevant term and the term in proportional to charge number while inversely proportional to nucleus radius, respectively. r_v and a_v are the radius and the diffusion parameter of the real part potential, respectively.

The imaginary part of the optical potential represents the absorption effect. For nucleon-nucleus Woods-Saxon potential, it is usually divided into two parts: surface absorption and volume absorption. Here we only take the volume absorption potential and suppose the surface absorption to be negligible. It reads as

$$W(r) = -W/[1+\exp((r-r_wA^{1/3})/a_w)], \tag{11}$$

where

$$W = W_0 + W_1\frac{N-Z}{A}, \tag{12}$$

W_0, W_1, r_w, a_w have similar physical significance to the corresponding parameters V_0, V_1, r_v, a_v in the real part. The only difference is that the term proportional to charge number and inversely proportional to nucleus radius does not appear in W, namely $W_2 = 0$. In this work there are altogether nine adjustable parameters: $V_0, V_1, V_2, r_v, a_v, W_0, W_1, r_w$ and a_w. They are automatically adjusted with a code written by one of the authors, Chonghai CAI, to minimize χ^2 so that the calculated energy shifts and widths of kaonic atoms in optimal accordance with the experiment values[3], and then we obtain an optimal set of optical potential parameters shown in Table 1, with the corresponding minimum χ^2. The χ^2 is defined as

$$\chi^2 = \left[\sum_{i=1}^{N_{es}}\left(\frac{\varepsilon_i^{cal}-\varepsilon_i^{exp}}{\Delta\varepsilon_i^{exp}}\right)^2W_{es}/N_{es} + \sum_{j=1}^{N_w}\left(\frac{W_j^{cal}-W_j^{exp}}{\Delta W_j^{exp}}\right)^2W_w/N_w\right]/(W_{es}+W_w), \tag{13}$$

Table 1. Parameters used in W-S optical potential.

V_0/MeV	V_1/MeV	V_2/MeV	r_v/fm	a_v/fm	W_0/MeV	W_1/MeV	r_w/fm	a_w/fm
250.0	0.05078	-9.0	0.98252	0.30	28.343	0.11166	1.275	0.50297

the χ^2 defined in Eq.(13) means the χ^2 per degree of freedom; N_{es} and N_w are the numbers of kaonic atoms in χ^2 calculations corresponding to the energy shifts and widths; ε_i^{cal}, ε_i^{exp} and $\Delta\varepsilon_i^{exp}$ are the calculated, experimental energy shift and its error corresponding to the ith kaonic atom; W_j^{cal}, W_j^{exp} and ΔW_j^{exp} are the calculated, experimental width and its error corresponding to the jth kaonic atom; W_{es} and W_w are the weights given to energy shifts and widths, respectively, in this work we suppose $W_{es} = W_w = 1$ (i.e. with equal weight). There is another kind of phenomenological optical potential[19] which is called as $V_{opt}^{(DD)}(r)$

$$2\mu V_{opt}^{(DD)}(r) = -4\pi\left(1+\frac{\mu}{m}\right)\rho(r)\left[b_0^{exp} + B_0\left(\frac{\rho(r)}{\rho_0}\right)^{\alpha}\right], \tag{14}$$

where m is the nucleon mass and $\rho(r)$ is the nuclear density distribution. In Ref.[19], ρ_0 is set to 0.16fm^{-3}, and the complex parameter b_0^{exp} is fixed as empirical scattering lengths

$$b_0^{exp} = (-0.15 + 0.62\text{i})\text{fm}, \tag{15}$$

there are three adjustable real parameters: α, the real and the imaginary part of B_0; the nuclear density is taken as harmonic oscillator (for light nuclei) or two parameters fermi (for heavier nuclei) distribution, respectively, and with experimental charge distribution parameters for every nucleus.

In order to find how much the density distribution effects are, instead we use a common Woods-Saxon form density for all these nuclei,

$$\rho(r) = \rho_0/[1+\exp(r-(r_\rho A^{1/3} - r_0)/a_\rho)], \tag{16}$$

then we have six adjustable real parameters: the real and imaginary parts of the complex parameter B_0, and the real parameters α, r_ρ, r_0 and a_ρ. An optimal set of parameters we obtained for $V_{opt}^{(DD)}(r)$ are given in Table 2.

Table 2. Parameters used in DD optical potential.

ReB_0/fm	ImB_0/fm	α	r_ρ/fm	r_0/fm	a_ρ/fm
1.5573	0.10	0.13	1.096	0.05	0.39219

3 Results and discussion

The principal quantum number is $n = n_r + l + 1$. For deeply bound kaonic atom, there is no radial excitation, $n_r = 0$, i.e. $n = l + 1$. Given a right value to l, and we calculate the corresponding "lower" levels and "upper" levels which are interpreted in Refs.[1,4].

The starting value B_0 of binding energy is given by the formula for the hydrogen-like atom

$$B_0 = -E_0 = \frac{\mu Z^2 e^4}{2n^2\hbar^2}. \tag{17}$$

We show the numerical results for kaonic atoms with W-S optical potential and DD optical potential in Tables 3 to 5, respectively. Table 3 is for the "lower" level energy shifts, Table 4 for the "lower" level widths, and Table 5 for the "upper" level widths. The last column corresponds to the experimental data, collected in Refs.[1,3].

In Tables 3 – 5, B_c is obtained by solving KGE(4) with $V_{opt} = 0$. We find that usually the difference of B_c and B_0 is very small except for the lightest ^{4}He, which indicates that in comparison with "point charge" nucleus, the nucleus charge distribution is of large effect on binding energy only for very light kaonic atom. The reason of the large difference of B_c and B_0 for ^{4}He is, perhaps, that $r_c = 1.3$ is too large, or the assumption of a uniform spherical charge distribution is not suitable for ^{4}He. The fact that B_c is very close to B_0 for most kaonic atoms also indicates that our method in numerically solving KGE(4)[18] is correct.

For comparison, the results of χ^2 in Ref.[19] are shown in Table 6.(1), (1m), and (2DD) indicate the results obtained from different optical potentials. (1) refers to the purely microscopical $V_{opt}^{(1)}(r) = (1/2\mu)\Pi_K - (\rho(r))$, where $\Pi_K - (\rho(r))$ is the K^--self-energy evaluated at threshold and nuclear density $\rho(r)$. (1m) denotes $V_{opt}^{(1m)}$ by adding a fitting phenomenological part to $V_{opt}^{(1)}$. (2DD) indicates the optical potential given in Ref.[19] with the same form of $V_{opt}^{(DD)}$ as we mentioned in Sec.2, with the best fitting parameters: $\alpha = 0.273$, $B_0 = 1.62 - 0.028\text{i}$ fm. Firstly, we compare (DD) with (2DD). χ^2 is 2.3325 for (DD) and 1.83 for (2DD). This is reasonable because the density parameters for (2DD) are different for different nucleus, while for (DD) the same set of parameters is used for all nuclei. The magnitude of density effect can be calculated by

$$\frac{2.3325 - 1.83}{1.83} = 27.46\%. \tag{18}$$

Table 3. Energy shifts of "lower" kaonic atom level.

nucleus	nl	B_0/keV	B_c/keV	(WS)/keV	(DD)/keV	exp/keV
$^{4}He^{*}$	$2p$	1.1625×10	6.752	-5.7378×10^{-3}	-4.2124×10^{-3}	-0.036 ± 0.032
^{7}Li	$2p$	2.754×10	2.6336×10	-1.3861×10^{-2}	-1.8074×10^{-2}	0.002 ± 0.026
^{9}Be	$2p$	4.9733×10	4.9523×10	-4.2839×10^{-2}	-6.4785×10^{-2}	-0.079 ± 0.021
^{10}B	$2p$	7.8142×10	7.8119×10	-1.2897×10^{-1}	-1.9772×10^{-1}	-0.208 ± 0.035
^{11}B	$2p$	7.8499×10	7.8477×10	-1.3947×10^{-1}	-2.1783×10^{-1}	-0.167 ± 0.035
^{12}C	$2p$	1.1347×10^{2}	1.1348×10^{2}	-4.0976×10^{-1}	-5.9187×10^{-1}	-0.590 ± 0.080
^{16}O	$3d$	9.0612×10	9.052×10	-1.3428×10^{-3}	-1.1749×10^{-3}	-0.025 ± 0.018
^{24}Mg	$3d$	2.0608×10^{2}	2.0613×10^{2}	-2.7817×10^{-2}	-3.1357×10^{-2}	-0.027 ± 0.015
^{27}Al	$3d$	2.4244×10^{2}	2.4251×10^{2}	-7.2388×10^{-2}	-8.1024×10^{-2}	-0.080 ± 0.013
^{28}Si	$3d$	2.8136×10^{2}	2.8147×10^{2}	-1.3708×10^{-1}	-1.5286×10^{-1}	-0.139 ± 0.014
^{31}P	$3d$	3.2358×10^{2}	3.2372×10^{2}	-3.4021×10^{-1}	-3.3807×10^{-1}	-0.330 ± 0.080
^{32}S	$3d$	3.6835×10^{2}	3.6855×10^{2}	-5.7690×10^{-1}	-5.6641×10^{-1}	-0.494 ± 0.038
^{35}Cl	$3d$	4.1641×10^{2}	4.1667×10^{2}	-1.1832	-1.0405	-1.000 ± 0.170
^{59}Co	$4f$	5.9446×10^{2}	5.9495×10^{2}	-1.6046×10^{-1}	-1.3800×10^{-1}	-0.099 ± 0.106
^{58}Ni	$4f$	6.3921×10^{2}	6.3978×10^{2}	-1.9421×10^{-1}	-1.7719×10^{-1}	-0.223 ± 0.042
^{63}Cu	$4f$	6.8618×10^{2}	6.8684×10^{2}	-3.5986×10^{-1}	-2.9761×10^{-1}	-0.370 ± 0.047
^{108}Ag	$5g$	1.1575×10^{3}	1.1593×10^{3}	-3.2361×10^{-1}	-2.2205×10^{-1}	-0.180 ± 0.120
^{112}Cd	$5g$	1.2075×10^{3}	1.2095×10^{3}	-4.4519×10^{-1}	-2.9626×10^{-1}	-0.400 ± 0.100
^{115}In	$5g$	1.2585×10^{3}	1.2607×10^{3}	-5.8374×10^{-1}	-3.8281×10^{-1}	-0.530 ± 0.150
^{118}Sn	$5g$	1.3106×10^{3}	1.3129×10^{3}	-7.5659×10^{-1}	-4.9097×10^{-1}	-0.410 ± 0.180
^{165}Ho	$6h$	1.6363×10^{3}	1.6398×10^{3}	-2.2925×10^{-1}	-1.2646×10^{-1}	-0.300 ± 0.130
$^{173}Yb^{*}$	$6h$	1.7864×10^{3}	1.7906×10^{3}	-4.2700×10^{-1}	-2.3999×10^{-1}	-0.120 ± 0.100
^{181}Ta	$6h$	1.9430×10^{3}	1.9480×10^{3}	-7.6172×10^{-1}	-4.3896×10^{-1}	-0.270 ± 0.500
^{208}Pb	$7i$	1.8019×10^{3}	1.8060×10^{3}	-3.7109×10^{-2}	-1.3794×10^{-2}	-0.020 ± 0.012
^{238}U	$7i$	2.2689×10^{3}	2.2755×10^{3}	-2.4829×10^{-1}	-1.1426×10^{-1}	-0.260 ± 0.400
χ^{2}				1.8702	2.3325	

Table 4. Widths of "lower" kaonic atom level.

nucleus	nl	(WS)/keV	(DD)/keV	exp/keV
$^{4}He^{*}$	$2p$	6.9378×10^{-3}	1.2216×10^{-2}	0.030 ± 0.030
^{7}Li	$2p$	3.0259×10^{-2}	4.5490×10^{-2}	0.055 ± 0.029
^{9}Be	$2p$	1.5957×10^{-1}	1.9505×10^{-1}	0.172 ± 0.580
^{10}B	$2p$	5.3936×10^{-1}	6.1364×10^{-1}	0.810 ± 0.100
^{11}B	$2p$	6.7994×10^{-1}	7.0443×10^{-1}	0.700 ± 0.080
^{12}C	$2p$	1.84	1.7934	1.730 ± 0.150
^{16}O	$3d$	6.6322×10^{-3}	8.4991×10^{-1}	0.017 ± 0.014
^{24}Mg	$3d$	2.1174×10^{-1}	2.2839×10^{-1}	0.214 ± 0.015

(Table 4 continued)

nucleus	nl	(WS)/keV	(DD)/keV	exp/keV
^{27}Al	$3d$	4.5790×10^{-1}	4.6024×10^{-1}	0.443 ± 0.022
^{28}Si	$3d$	7.7008×10^{-1}	7.6585×10^{-1}	0.801 ± 0.032
^{31}P	$3d$	1.402	1.3092	1.440 ± 0.120
^{32}S	$3d$	2.1248	1.9677	2.187 ± 0.103
^{35}Cl	$3d$	3.2243	2.9473	2.910 ± 0.240
^{59}Co	$4f$	6.8545×10^{-1}	6.1348×10^{-1}	0.640 ± 0.250
^{58}Ni	$4f$	8.6481×10^{-1}	7.879×10^{-1}	1.030 ± 0.120
^{63}Cu	$4f$	1.2716	1.1105	1.370 ± 0.170
^{108}Ag	$5g$	1.2143	9.6046×10^{-1}	1.540 ± 0.580
^{112}Cd	$5g$	1.5432	1.2205	2.010 ± 0.440
^{115}In	$5g$	1.9108	1.5184	2.380 ± 0.570
^{118}Sn	$5g$	2.3453	1.8782	3.180 ± 0.640
^{165}Ho	$6h$	9.4987×10^{-1}	6.849×10^{-1}	2.140 ± 0.310
^{173}Yb	$6h$	1.606	1.1706	2.390 ± 0.300
^{181}Ta	$6h$	2.6139	1.9341	3.760 ± 1.150
^{208}Pb	$7i$	2.0061×10^{-1}	1.2808×10^{-1}	0.370 ± 0.150
^{238}U	$7i$	1.044	6.8808×10^{-1}	1.500 ± 0.750
χ^2		1.8702	2.3325	

Table 5.　Widths of "upper" kaonic atom level.

nucleus	nl	B_0/keV	B_c/keV	(WS)/eV	(DD)/eV	exp/eV
^{9}Be	$3d$	2.2104×10	1.6818×10	1.1747×10^{-1}	1.3118×10^{-1}	0.04 ± 0.02
^{12}C	$3d$	5.0431×10	4.9427×10	7.5816×10^{-1}	1.1109×10^{-1}	0.99 ± 0.20
^{24}Mg	$4f$	1.1592×10^{2}	1.1578×10^{2}	1.4773×10^{-1}	1.5813×10^{-1}	0.08 ± 0.03
^{27}Al	$4f$	1.3637×10^{2}	1.3633×10^{2}	3.4537×10^{-1}	3.6705×10^{-1}	0.30 ± 0.04
^{28}Si	$4f$	1.5827×10^{2}	1.5827×10^{2}	6.8534×10^{-1}	7.2533×10^{-1}	0.53 ± 0.06
^{31}P	$4f$	1.8201×10^{2}	1.8203×10^{2}	1.4966	1.5589	1.89 ± 0.30
^{32}S	$4f$	2.0720×10^{2}	2.0724×10^{2}	2.726	2.8469	3.03 ± 0.29
^{35}Cl	$4f$	2.3423×10^{2}	2.3429×10^{2}	5.4976	5.7031	5.80 ± 1.70
^{58}Ni	$5g$	4.091×10^{2}	4.0929×10^{2}	2.2551	1.9874	5.90 ± 2.30
^{63}Cu	$5g$	4.3915×10^{2}	4.3938×10^{2}	3.9443	3.5366	5.25 ± 1.06
^{108}Ag	$6h$	8.0384×10^{2}	8.0463×10^{2}	7.5414	5.8501	7.30 ± 4.70
^{112}Cd	$6h$	8.3856×10^{2}	8.3942×10^{2}	1.0572×10	8.1863	6.20 ± 2.80
^{115}In	$6h$	8.7397×10^{2}	8.7491×10^{2}	1.4293×10	1.1045×10	11.4 ± 3.70
^{118}Sn	$6h$	9.1011×10^{2}	9.1114×10^{2}	1.917×10	1.4753×10	15.1 ± 4.40
^{208}Pb	$8j$	1.3796×10^{3}	1.3819×10^{3}	1.942	9.7646×10^{-1}	4.10 ± 2.00
^{238}U	$8j$	1.7371×10^{3}	1.7408×10^{3}	1.4887×10	7.8071	45.0 ± 24.0
χ^2				1.8702	2.3325	

Table 6. χ^2 results of Ref.[19].

	(1)	(1m)	(2DD)
χ^2	3.76	1.57	1.83

Then we compare (W-S) with (1), (1m), and (2DD). Noting that in Table 3 and Table 4 some nuclei are marked with star, which means that they are not included in our calculation of χ^2, in order to keep consistency with the other three kinds of optical potential. χ^2 for (W-S) is 1.8702, which is a little larger than that of (1m) and (2DD). However, we have obtained a common set of parameters (only nine altogether) suiting for all these nuclei.

For ^{208}Pb, the real and imaginary parts of the W-S potential, $V_{\rm opt}^{(1m)}$ and $V_{\rm opt}^{(2DD)}$, as a function of r are given in Figs.1 and 2, respectively, from which we can see that the results of kaonic atoms are not sensitive to the values of the optical potentials at the center of nucleus, but rather sensitive to their behavior near nuclear surface, just as indicated in Ref.[19]. We also find that the imaginary part of $V_{\rm opt}^{(WS)}$ is similar to $V_{\rm opt}^{(1m)}$ and $V_{\rm opt}^{(2DD)}$ when $r>7$ fm. In order to clearly see the panorama of the optical potential, both the real and imaginary parts of the W-S potential vs. $0\leqslant r\leqslant 12.0$ fm are plotted in Fig.3. Near nuclear surface ($r>7$ fm for ^{208}Pb), the imaginary part dominates the optical potential (the absolute value of the real part is less than a tenth of that of the imaginary part), and plays a more important role than the real part in determining the energy shift and width of kaonic atom.

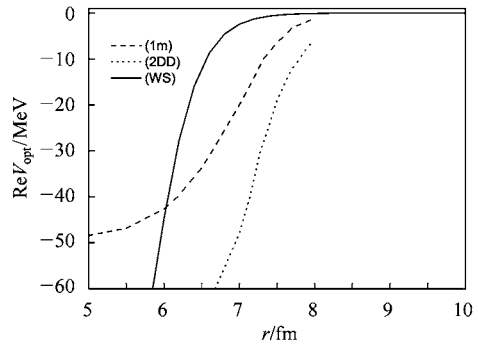

Fig.1. Real part of optical potential in ^{208}Pb.

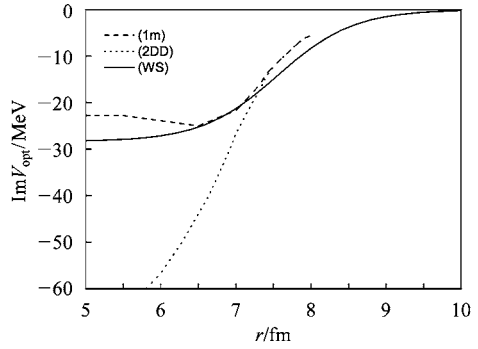

Fig.2. Imaginary part of optical potential in ^{208}Pb.

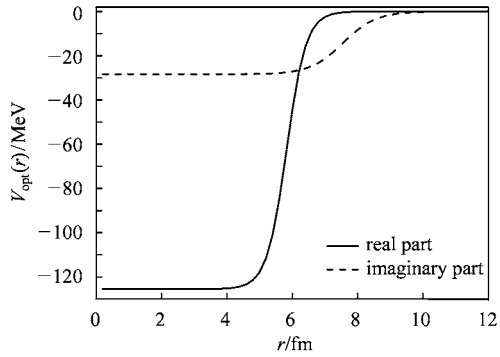

Fig.3. Woods-Saxon optical potential in ^{238}Pb.

4 Summary

We introduce a set of phenomenological Woods-Saxon optical potential for the interaction between kaon and nucleus. This kind of optical potential is usually used to describe the interaction of nucleon-nucleus. In this work we use it to analyze kaonic atoms. Through fitting the experimental data of energy shifts and widths of all those kaonic atoms, we find an optimal set of parameters for the kaon-nucleus W-S optical potential, there are only nine free parameters for all nuclei shown in Tables 3,4 and 5. Also, it is found that nuclear density distribution plays an important role in the hadron-nucleus optical potential. We do not take different density distribution forms for light and heavy nuclei, but use a universal form for all nuclei. Our calculated results are satisfactory in comparison with the experimental data, as well as those obtained from (1m) and (2DD) optical potentials[19]. The shape of Im$V_{\rm opt}^{(WS)}$ agrees with those of (1m) and (2DD) when $r>7$ fm. If there are more experimental data in the future, we will use them to verify this kind of optical potential.

We also find that the imaginary part of our W-S potential for kaonic-nucleus is similar to that for nucleon-nucleus. But for the real part, our W-S potential for kaon-nucleus is much deeper and thinner than that for nucleon-nucleus (V_0 is about 50 – 60 MeV, $a_{\rm v}$ is about 0.5 – 0.7 fm, and $r_{\rm v}$ is about 1.1 –

1.3fm). V_1 and W_1 for kaon-nucleus potential are very small in comparison with the nucleon-nucleus potential (usually, $V_1 = \pm 24$, $W_1 = \pm 12$). Perhaps, the reason is that kaon is a completely different particle from proton and neutron, so it is much less dependent on $(N - Z)/A$ of nucleus than nucleon.

At last, we find that with any kinds of optical potential, including the phenomenological $V_{\rm opt}^{\rm (WS)}$, $V_{\rm opt}^{\rm (2DD)}$ and the microscopical $V_{\rm opt}^{\rm (1m)}$, the calculated results for nucleus ^{16}O are always not good. Perhaps for the nucleus on closure shell, we need to do further special study in the future.

The authors would like to thank Prof. Xueqian Li for his help to improve the English writing of this paper.

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K 原子能移和宽度的唯象分析

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摘要　尝试用 Woods-Saxon 形式的光学势来分析 K 原子,通过拟合一系列 K 原子数据,得到了一套最佳光学势参数.把得到的这套光学势和前人的其他几种光学势在接近核表面处作了比较,发现它们彼此符合得很好.另外,与核子 - 核势相比较,对于虚部势,K-核的 Woods-Saxon 势与核子 - 核的很相似,但是对于实部,K-核势要更深更窄一些.

关键词　唯象分析　Woods-Saxon 光学势　K 原子　能移　宽度

2004 - 10 - 14 收稿,2005 - 02 - 16 收修改稿

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