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EFFECTIVE PION MASS IN THE NUCLEAR MEDIUM DEDUCED FROM DEEPLY BOUND PIONIC STATES IN ^{207}Pb

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Deeply bound $1s$ states of π^- as well as the $2p$ states in ^{207}Pb were identified in the $^{208}\text{Pb}(d, ^3\text{He})$ reaction at 600 MeV. The binding energies of π^- in ^{207}Pb have been determined as $B_\pi(2p) = 5.31 \pm 0.09$ MeV and $B_\pi(1s) = 7.1 \pm 0.2$ MeV by comparing the observed Q -value spectrum with theory. These values indicate that the effective π^- mass increases by 20 ± 3 MeV at the center of the ^{207}Pb nucleus.

The question as to how hadrons behave and their properties change in the nuclear medium is interesting and important from the viewpoint of QCD. The masses of light hadrons are largely of dynamical origin [1] and reflect the symmetry breaking pattern of QCD. Their changes in a nuclear environment may offer insights about changes of vacuum properties such as the quark condensate [2]. The pion is special in this context because of its role as Goldstone boson of spontaneously broken chiral symmetry. Efforts are being made to explore hadron masses in nuclei, but so far, no clear-cut quantitative experimental information has been obtained. This situation is mainly due to the lack of suitable experimental methods. Very recently, deeply bound π^- states in ^{207}Pb have been discovered as a narrow peak at 135 MeV nuclear excitation energy in the $^{208}\text{Pb}(d, ^3\text{He})$ reaction at 600 MeV incident energy [3]. The dominant peak was assigned to the $(2p)\pi(3p_{1/2,3/2})_n^{-1}$ configurations predicted by Toki *et al.* [4–8], and the binding energy of the pionic $2p$ orbital was

obtained as $B_\pi(2p) = 5.4 \pm 0.2$ MeV. This new type of nuclear spectroscopy initiates "hadron mass spectroscopy in the nuclear systems". In the present paper we report an improved analysis of the experiment, showing that the narrow peak is composed of not only the $2p$ π^- states but also the $1s$ states. The π^- binding energies determined are then analyzed to deduce the effective pion mass in the nuclear medium.

Toki *et al.* [4,5] calculated the energy levels of π^- in ^{208}Pb using one typical set (SMA-1) of the Seki-Masutani [9] parameters of the Ericson-Ericson potential [10,11], and showed that even the lowest $1s$ state has a small nuclear absorption width. This quasi-stability was explained in terms of a repulsive nuclear potential together with an attractive Coulomb interaction which jointly accommodate halo-type bound states, as first pointed out by Friedman and Soff [12]. The probability of the π^- being in the nucleus is around 5 % and the absorption width is reduced accordingly.

The repulsive central potential which is responsible for the narrow structure is already indicative of an increased effective mass of π^- in the nucleus. Whereas the known strong interaction shifts of pionic atoms of higher orbits studied by x-ray spectroscopy (see, for instance, Konijn *et al.* [13]) are sensitive primarily to the non-local p-wave part of the pion optical potential and thus reflect "surface" effects, the deeply bound pionic states provide rather direct information on the "bulk effect" arising from the local s-wave part. Since the deeply bound states are halo like states, we need a careful analysis of the potential parameter dependence of their binding energies to elucidate the mass-shift problem. Our proce-

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ture is i) to decompose the peak region into the 1s and 2p components, ii) to determine the π^- binding energies $B_\pi(1s)$ and $B_\pi(2p)$ by comparing the experimental spectrum with the theoretical one, iii) to relate the experimental B_π values to the central potential strength, and iv) finally to deduce the pion effective mass $m_\pi^{\text{eff}}(r)$ from the strength of the best fit potential.

The experimental Q -value spectrum of the $^{208}\text{Pb}(d, ^3\text{He})$ reaction at $T_d = 600$ MeV reported previously [3] is in excellent overall agreement with the theoretical one by Hirenzaki *et al.* [7,8]. Fig.1 shows a portion of the observed spectrum obtained from an improved analysis of the same experimental data. In this analysis all the energy shift/spread effects due to the kinematics, ion optics and energy losses have been carefully taken into account. The present spectrum is consistent with the previous one. Comprehensive reports of the experimental method, results and analyses will be published in forthcoming papers [14–16].

FIG. 1. Portion of the experimental Q -value spectrum of the $^{208}\text{Pb}(d, ^3\text{He})$ reaction at 600 MeV [3] in comparison with the theoretical spectrum calculated by Hirenzaki *et al.* [7,8]. The 1s component (dotted curve) and the 2p component (dashed curve) are simultaneously fitted to the experimental spectrum so as to determine the binding energies of the 1s and 2p orbitals. In this fitting the 1s/2p intensity ratio was assumed to be 2.5 times the theoretical ratio. The $B_\pi = 0$ in the ground state of ^{207}Pb corresponds to $Q = -140.147$ MeV.

The dominant 2p peak has a skewed shape due to the coupling to the two neutron hole states, $3p_{1/2}$ and $3p_{3/2}$, which are produced with an intensity ratio 1:2 (statistical weight) and are separated in energy by their difference of 0.898 MeV. These states are of “quasi-substitutional” configurations, of which the production cross sections are enhanced at a small momentum transfer. The

monoenergetic peak from the $p(d, ^3\text{He})\pi^0$ reaction proved to be symmetric and was used for the energy calibration. With a close comparison between the experimental and the original predicted spectrum [7] we recognize a slight difference of the peak position. Furthermore, we observe not only the dominant 2p peak but also a bump on the right-hand shoulder, which is very close to the one predicted to be the 1s component. Although the presence of the 1s component in the spectrum is very clear, it is not well separated from the dominant 2p component.

Thus, to obtain the binding energies, $B_\pi(1s)$ and $B_\pi(2p)$, we attempted a chi-squares fitting of the experimental spectrum to the theoretical spectra only by adjusting the intensities, binding energies and widths of the 1s and 2p π^- components. This procedure is justified because the shape of the theoretical spectral profile has no substantial change, as we move the potential parameters in a limited range. The neutron hole states taken into account are $3p_{1/2}$ (ground state), $2f_{5/2}$ (0.570 MeV), $3p_{3/2}$ (0.898 MeV), $1i_{13/2}$ (1.633 MeV), $2f_{7/2}$ (2.340 MeV) and so on. We obtained the following best-fit result on the binding energy of the 2p π^- orbital:

$$B_\pi(2p) = 5.31 \pm 0.09 \text{ MeV}. \quad (1)$$

The error assigned involves a statistical error (0.02 MeV) as well as a systematic error. This binding energy is slightly larger than the original theoretical value of Toki *et al.* [5], 5.16 MeV.

The 1s peak consists of the $3p_{3/2}$, $2f_{5/2}$ and $3p_{1/2}$ neutron hole configurations, which contribute to the cross sections more or less equally, as shown by the dotted curve in Fig.1. If we fix the 1s intensity relative to the 2p intensity to the theoretical value, the best-fit $B_\pi(1s)$ is obtained as 7.3 MeV, but the overall fitting is rather poor. On the other hand, if we allow the relative 1s/2p intensity ratio to be unconstrained by theory, the chi-squares value decreases and the best-fit $B_\pi(1s)$ decreases with an increase of the 1s/2p intensity ratio; typically, for $(1s/2p)_{\text{fit}}/(1s/2p)_{\text{theor}} = 2, 2.5$ and 3 , $B_\pi(1s) = 7.08, 7.00$ and 6.93 MeV, respectively. The binding energies are also correlated with the widths in a complicated way. Thus, at the present stage we have to assign a large systematic uncertainty as

$$B_\pi(1s) = 7.1 \pm 0.2 \text{ MeV}. \quad (2)$$

The dotted curve in Fig.1 is for the case of $(1s/2p)_{\text{fit}}/(1s/2p)_{\text{theor}} = 2.5$. The experimental value of $B_\pi(1s)$ is close to the predicted one 6.96 MeV [5].

The dependence of the 1s and 2p binding energies of π^- on the optical potential parameters was studied by solving the Klein-Gordon equation

$$[-\nabla^2 + m_\pi^2 + \Pi(\vec{r})]\phi(\vec{r}) = (E - V_C)^2\phi(\vec{r}), \quad (3)$$

where m_π is the pion mass and V_C is the Coulomb potential. The self energy term $\Pi(\vec{r})$ is related to the optical potential $U_{\text{opt}}(\vec{r})$ [10,11] as

$$\begin{aligned}\Pi(\vec{r}) &= 2E \cdot U_{opt}(\vec{r}) \\ &= -4\pi[b(r) + (1 + m_\pi/2M)B_0\rho^2(r)] \\ &\quad + [\text{Non local term}],\end{aligned}\quad (4)$$

where

$$b(r) = (1 + m_\pi/M)\{b_0\rho(r) + b_1[\rho_n(r) - \rho_p(r)]\}. \quad (5)$$

We calculate the binding energies using realistic proton and neutron densities of ^{207}Pb as given by Skyrme-Hartree-Fock calculations [17] and parameterized as follows:

$$\rho(r) = \rho_p(r) + \rho_n(r) \quad (6)$$

with

$$\rho_{p/n}(r) = \rho(0) \frac{1 - B(\frac{r}{R})^2}{1 + \exp(\frac{r^2 - R^2}{A^2})} \quad (7)$$

where the parameters for proton are $\rho_p(0) = 0.065 \text{ fm}^{-3}$, $R_p = 7.039 \text{ fm}$, $A_p = 1.973 \text{ fm}$ and $B_p = 0.228$, and those for neutron are $\rho_n(0) = 0.103 \text{ fm}^{-3}$, $R_n = 7.127 \text{ fm}$, $A_n = 2.223 \text{ fm}$ and $B_n = 0.312$.

For further discussions the real part of the s-wave (local) optical potential is collectively expressed in the form

$$V_{\text{LOCAL}}(r) = V_0 \frac{\rho(r)}{\rho(0)}, \quad (8)$$

The local part of the potential is poorly known and is the subject of the present study, whereas the non-local part and the imaginary part are relatively well known. In order to see the influence of the local potential we calculate the binding energies using different V_0 values from 0 to 30 MeV. This was done by changing artificially the magnitude of b_0 and b_1 , while keeping the non-local part as well as the imaginary part to be the SMA-1 set of the Seki-Masutani parameters [9].

In this region of the optical potential parameters the contribution of the imaginary part to the binding energies is very small: $\Delta B_\pi(1s) = -0.033 \text{ MeV}$ and $\Delta B_\pi(2p) = -0.066 \text{ MeV}$. This is understood because the π^- density is localized around the nuclear surface and thus the nuclear absorption gives only little effect on the π^- density distributions. The non-local part of the optical potential contributes to sizable increases of the binding energies: $\Delta B_\pi(1s) = +0.262 \text{ MeV}$ and $\Delta B_\pi(2p) = +0.358 \text{ MeV}$, which are, however, small parts of the strong interaction shifts (-5.28 and -0.78 MeV, respectively).

The calculated binding energies for various values of V_0 are shown in Fig.2 (upper). Both $B_\pi(1s)$ and $B_\pi(2p)$ decrease with V_0 as long as $V_0 > 10 \text{ MeV}$. Their pure-Coulomb values are 12.24 and 5.94 MeV, respectively. The calculated level widths are shown in Fig.2 (lower).

The widths increase with the decrease of V_0 , as expected, because the halo character of the states is diminished as the repulsive barrier decreases. The fact that the experimental width of the 2p orbital is less than 0.8 MeV sets a constraint: $V_0 > 17 \text{ MeV}$. A detailed analysis of the spectrum to deduce the widths of the 1s and 2p π^- orbitals will be given in [16].

FIG. 2. (Upper) Calculated binding energies of the 1s and 2p π^- orbitals in ^{207}Pb as functions of the local potential height V_0 , with the non-local and imaginary parts fixed to the SMA-1 set of the Seki-Masutani parameters. The experimental binding energies yield V_0 values, as shown. (Lower) Calculated level widths of the 1s and 2p π^- orbitals in ^{207}Pb as functions of the potential height V_0 .

The experimental binding energies we have obtained, eqs. (1),(2), are now compared with the theoretical ones in Fig.2 (upper) to deduce V_0 . The $B_\pi(2p)$ value has a small uncertainty and gives a stringent constraint:

$$V_0 = 20 \pm 3 \text{ MeV}. \quad (9)$$

Although $B_\pi(1s)$ is most sensitive to V_0 , its experimental value has a larger error, and the corresponding constraint on V_0 ($20.5 \pm 4 \text{ MeV}$) is weaker. Nevertheless, it is remarkable that the above two independent values are mutually consistent. In the past analyses of pionic atom

data various values were obtained for the local potential strength: for instances, 17 MeV (Ericson and Tauscher [18]), 19 MeV (Batty *et al.* [19]), 26 MeV (Seki and Masutani [9]) and 40 MeV (Konijn *et al.* [13]).

The local potential thus determined can be translated into an effective mass of the π^- in ^{207}Pb . For an infinite system of nuclear density ρ , the effective pion mass is defined as the real part of the self energy for a pion at rest ($\vec{q}=0$) in matter:

$$[m_\pi^{\text{eff}}(\rho)]^2 = [m_\pi^2 + \vec{q}^2 + \text{Re}\Pi(E, \vec{q}; \rho)]_{q \rightarrow 0} \sim m_\pi^2 + 2m_\pi \text{Re}U_{\text{opt}}^{s-\text{wave}}, \quad (10)$$

since the non-local (p-wave) part vanishes as $\vec{q} \rightarrow 0$. Using a local density distribution $\rho(r)$ this yields

$$m_\pi^{\text{eff}}(r) \sim m_\pi + \Delta m_\pi^{\text{eff}}(r), \quad (11)$$

where

$$\Delta m_\pi^{\text{eff}}(r) = V_{\text{LOCAL}}(r) = V_0 \frac{\rho(r)}{\rho(0)} \quad (12)$$

Namely, the pion mass shift $\Delta m_\pi^{\text{eff}}(r)$ is proportional to the nuclear density $\rho(r)$ and is equal to the local s-wave potential $V_{\text{LOCAL}}(r)$. So, we conclude that the π^- mass at the center of the ^{207}Pb nucleus increases by 20 ± 3 MeV. The obtained radial distribution of $\Delta m_\pi^{\text{eff}}(r)$ is shown in Fig.3.

In the present procedure we have fixed the non-local part and the imaginary part of the optical potential to the Seki-Masutani values. If we can achieve more systematic studies of deeply bound pionic states in the future, we may be able to determine those parameters independently. Further experiments are planned to elucidate the issue, such as to produce $\pi^- \otimes ^{205}\text{Pb}$ which has no contribution of the $p_{1/2}$ neutron hole [20] and will thus provide a simpler peak structure so as to obtain the binding energies and the widths more precisely.

The present results confirm and sharpen considerably our previous knowledge about the s-wave pion-nucleus optical potential [10,11]. From a low energy theorem based on chiral symmetry it is well known that the isospin-even πN scattering length b_0 is small (in fact, zero to leading order), whereas the isospin-odd scattering length b_1 is sizable, in accordance with their empirical values. The b_0 that enters in eq.(5) is in fact an effective scattering length which includes rescattering effects proportional to b_1^2 . Of the repulsive pion mass shift deduced from the present data, roughly a half comes from the $b_1(\rho_n - \rho_p)$ term, the other half from the $b_0\rho$ term in eq.(5). In Ref. [21] it is shown that an s-wave optical potential derived from chiral symmetry alone is remarkably consistent with this information. An additional dispersive term proportional to $\text{Re}B_0\rho^2$, related to s-wave absorption on a pair of nucleons, does not seem to play any significant role.

FIG. 3. a) The local part of the optical potential $V_{\text{LOCAL}}(r)$, which is equivalent to the pion mass shift $\Delta m_\pi^{\text{eff}}(r)$, and the total potential including the Coulomb interaction V_C , as obtained from the analysis of the measured 1s and 2p π^- binding energies. b,c) Radial distributions of the 1s and 2p π^- densities (dashed curves for the pure Coulomb case and solid curves for the total optical potential).

Finally, we point out that the deeply bound pionic states are one kind of Coulomb-assisted hybrid bound states of negatively charged hadrons [22]. In the future one may be able to find and study deeply bound states of other hadrons such as K^- , Σ^- , Ξ^- and $\bar{p}$, and to extract constraints on their effective masses in the nuclear medium.

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