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DISCOVERY OF DEEPLY BOUND π^- STATES IN THE ^{208}Pb(d,^{3}He) REACTION* **

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In the ^{208}Pb$\,(d,^3$He) reaction at 600 MeV the population of deeply bound pionic states was observed for the first time. The states were identified as the pionic $2p$ and $1s$ states, respectively. The π^- binding energies have been determined to be $B_\pi(2p) = 5.28 \pm 0.11$ MeV and $B_\pi(1s) = 7.04 \pm 0.32$ MeV. Using these binding energies a π^- mass shift of $+20\pm4$MeV in nuclear matter at saturation density with the neutron excess of ^{207}Pb was deduced.

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Deeply bound states in pionic atoms were recently observed for the first time in a ^{208}Pb$\,(d,^3$He) reaction [1]. While the conventional method of forming atomic states of negative pions with nuclei using capture and electromagnetic deexcitation of stopped π^- populates only states with small overlap of the pionic and the nuclear density distribution, the contrary is the case in a direct pionic transfer reaction such as (d,^{3}He) on a heavy nucleus [2]. The experiment is described in more detail in Ref. [1]. A 50 mg/cm^2 ^{208}Pb target was bombarded with a 600 MeV d beam ($I_d \sim 10^{10} - 10^{11}$/s) from the heavy-ion synchrotron SIS at GSI Darmstadt, and the ^{3}He ions emitted at 0^0 were momentum analysed by the Fragment Separator (FRS) using a set of drift chambers, and identified with a time of flight measurement using scintillation detectors. The incident energy was chosen such that the momentum

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transfer was small in order to favor the population of states with low angular momentum. In a systematic theoretical study it was predicted [3] that at $T_d = 600$ MeV predominantly the $\left[(2p)_\pi (p_{3/2,1/2})_n^{-1}\right]_{L=0}$ configuration which has a 'quasisubstitutional' character should be populated.

The first analysis of the ^{208}Pb$\,(d,^3$He) experiment [1] showed a striking similarity of the experimental Q value spectrum with the theoretical prediction [3]. In a more involved analysis of the data various corrections, such as for the time dependence of the beam momentum, the ion-optical aberrations of the FRS, and the long term shifts of the FRS magnetic field, were taken into account. Thus the instrumental resolution could be considerably improved ($\delta Q \approx 0.4$ MeV) so that the $(p_{1/2})_n^{-1}$ ground state and the 897 keV $(p_{3/2})_n^{-1}$ excited state in ^{207}Pb, to which the $(2p)_\pi$ state couples, are clearly separated (see figure 1).

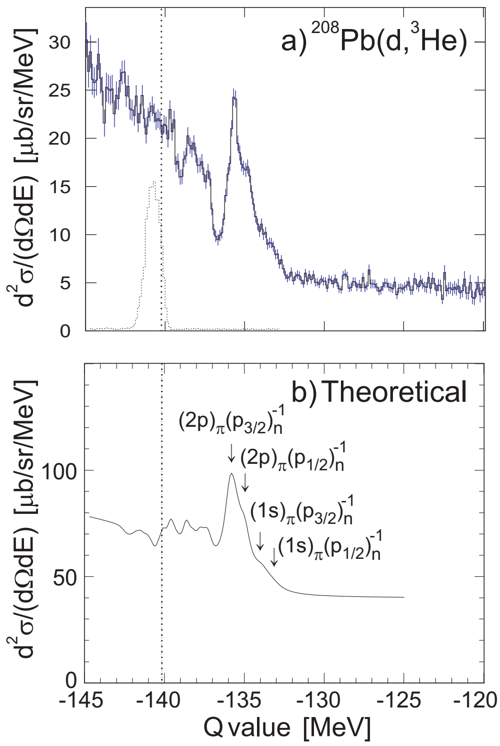

Fig. 1. The experimental Q value spectrum obtained in the ^{208}Pb$\,(d,^3$He) reaction at the present stage of analysis (a) in comparison to the theoretical prediction by Hirenzaki *et al.* [3]. The dotted line at $Q = -140.15$ MeV indicates the π^- binding threshold. The $p\,(d,^3$He$)\pi^0$ peak used for the Q value calibration is also shown.

In the more strongly bound region a shoulder of the $(2p)_\pi$ peak is seen at the expected position of the $(1s)_\pi(p_{3/2,1/2})_n^{-1}$ duplett. The $(2p)_\pi$ and the $(1s)_\pi$ components together with a constant background were fitted simultaneously to the peak region, using a fixed distance (ΔE = 897 keV) and intensity ratio (2:1) of the $(p_{3/2})_n^{-1}$ and $(p_{1/2})_n^{-1}$ neutron hole contributions, as shown in Fig. 2. From the peak positions the π^- binding energies were deduced to be $B_\pi(2p) = 5.28 \pm 0.11$ MeV and $B_\pi(1s) = 7.04 \pm 0.32$ MeV [4], based on a Q value calibration with the $p(d,^3\mathrm{He})\pi^0$ reaction. The given errors include an overall systematic error of 0.09 MeV of the energy calibration.

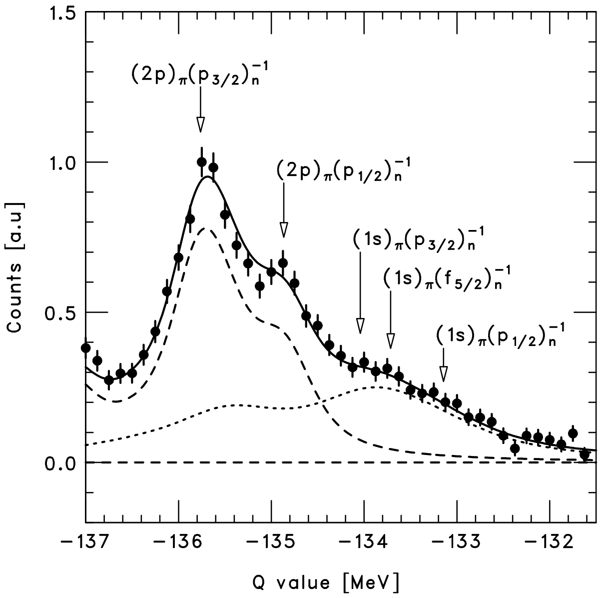

Fig. 2. Decomposition of the peak region of the experimental Q value spectrum of the ^{208}Pb$(d,^3\mathrm{He})$ reaction into the $2p$ component (dashed curve) and the $1s$ component (dotted curve), using the shape of the theoretical calculation [3]. The best fit is obtained if the $1s/2p$ intensity ratio is 2.5 times the theoretical ratio.

The measured binding energies are close to the values of 5.16 MeV and 6.96 MeV, respectively, predicted by Toki *et al.* [5]. For comparison, Konijn *et al.* [6] obtain $B_\pi(2p) = 5.13 - 5.14$ MeV and $B_\pi(1s) = 6.90 - 6.93$ MeV with extended phenomenological parametrizations of the π^--nucleus optical potential, while Nieves *et al.* [7] predict $B_\pi(2p) = 5.10$ MeV and $B_\pi(1s) = 6.78$ MeV with a semiphenomenological model, clearly lower than the measured values. The predictions are much more uncertain for the widths than for the binding energies, extending from $\Gamma(2p) = 154$ keV [6] to $\Gamma(2p) = 410$ keV [5] and $\Gamma(1s) = 63$ keV [6] to $\Gamma(1s) = 632$ keV [5]. At the present stage of the data analysis only upper limits of the width can be given, which are too high to test these predictions. A more involved analysis is currently under way, and more precise measurements of the widths both of the pionic $2p$ and $1s$ states are subject of a further experimental study.

Although a large body of data on level shifts and widths of more shallow states in pionic atoms has become available up to now the local (s-wave) part of the potential has still been poorly known. This is due to the small overlap of the pionic wave function and the nuclear density distribution of the previously known states populated in electromagnetic cascades, resulting in a weak sensitivity to the local part of the potential.

The measured binding energies of the deeply bound states may be used to put constraints on the local (s-wave) part of the π^--nucleus optical potential. The details of this study are discussed in Ref. [4]. In order to see the mutual relation of the pionic binding energies and the local potential, the non-local p-wave part and the imaginary part were kept constant at the SMa-1 parameter values [8]. This procedure is justified since the p-wave parameters are well defined by the more shallow pionic states. Since the non-local part contributes only a small part of the strong level shifts of the $1s$ and $2p$ states a variation of the p-wave parameters within a limited range causes only a small change of the binding energies. The contribution of the imaginary part to the $1s$ and $2p$ binding energies is even smaller. For the present study, the local potential is assumed to be proportional to the nuclear density, neglecting different shapes of the proton and neutron density distributions and effects quadratic in the density:

$$V_{\rm local}(r) = -\frac{4\pi}{2E}\left(1+\frac{m_\pi}{M}\right)\left[b_0\rho(r) + b_1(\rho_n(r) - \rho_p(r))\right] = V_0\frac{\rho(r)}{\rho(0)} \ .$$

Solving the Klein–Gordon equation with artificially varied values of V_0 and comparing the calculated pionic binding energies to the measured ones, we obtain the constraint $V_0 = 20 \pm 4$ MeV from the $(2p)_\pi$ state and, independently, $V_0 = 20.5 \pm 5.5$ MeV from the $(1s)_\pi$ state, as illustrated in figure 3. This range of the V_0 parameter is also consistent with the experimental limits on the widths of both states.

The local potential obtained in this way may be translated to an effective mass of the π^- in the ^{207}Pb nucleus [4, 9]:

$$m_\pi^{\rm eff}(r) = m_\pi + V_{\rm local}(r) = m_\pi + V_0\frac{\rho(r)}{\rho(0)} \ .$$

We can therefore deduce an effective mass of $m_\pi^{\rm eff} = 159.6 \pm 4$ MeV for the π^- at the center of the ^{207}Pb nucleus. The π^- mass shift and the π^- density distributions as calculated for the measured binding energies are shown as function of the radius in figure 4.

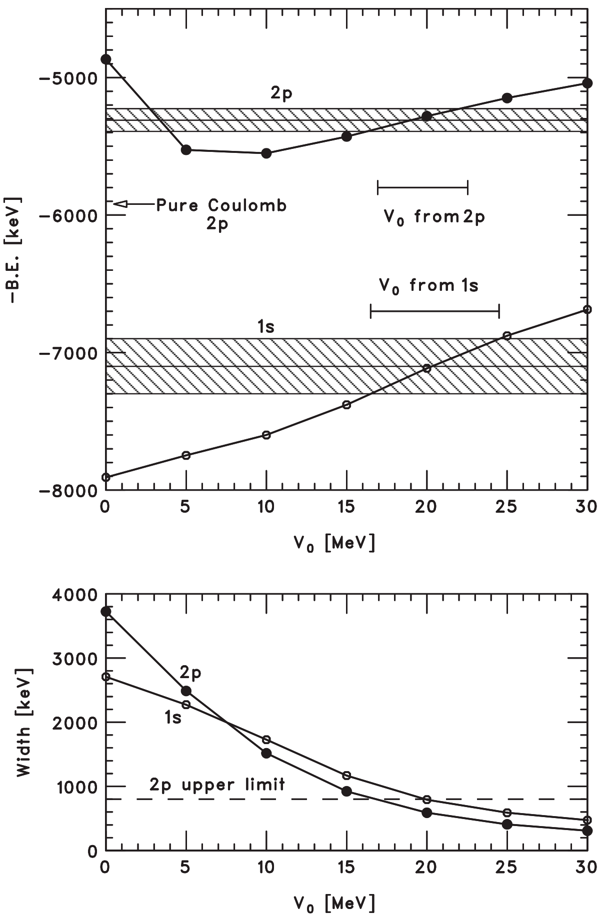

Fig. 3. Relation of the local potential V_0 and the binding energies of the pionic $2p$ and $1s$ states (upper part) and of the width of both states (lower part).

Very similar values of the real part of the central potential V_0 and the effective π^- mass in nuclear matter at $\rho = \rho_0$ with $\rho_n/\rho_p = 1.5$ have been obtained using a chiral s-wave potential derived from constraints based on chiral symmetry [9]. In a very recent analysis by Friedman and Gal [10] of all data available on pionic atoms, the authors obtain slightly higher values for the real part of the central potential of 28 ± 3 MeV and a correspondingly higher π^- effective mass.

In order to determine the potential parameters in a more independent way, including the non-local and the imaginary part, a more precise measurement of the $(1s)_\pi$ state and of the widths of both $(2p)_\pi$ and $(1s)_\pi$ states will be essential. To achieve this, further experiments are planned, such as

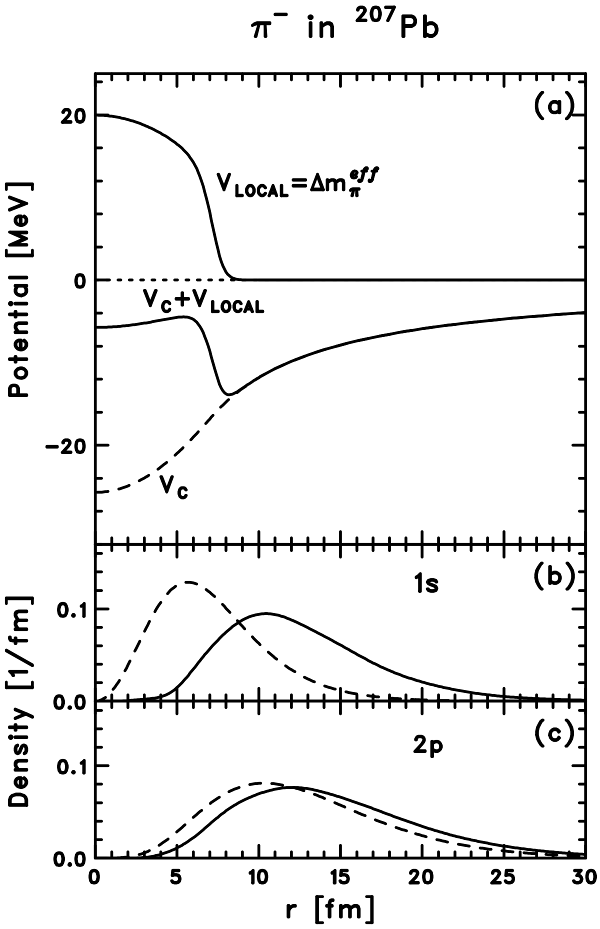

Fig. 4. The π^- mass shift and local potential (top) and the π^- densities in the $1s$ and $2p$ state (bottom) as a function of the radius. The dashed curves are obtained for a pure Coulomb potential.

a ^{206}Pb(d,^{3}He) experiment with a cooled d beam from SIS at GSI. Besides a better instrumental Q value resolution due to the smaller momentum spread of the beam and thinner targets, we expect a simpler peak structure of the Q value spectrum since there are no $p_{1/2}$ neutron hole contributions in ^{205}Pb.

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