DEEPLY BOUND PIONIC STATES IN Pb * **

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At the GSI Fragment Separator the formation of deeply bound pionic states in Pb has been studied in ^{208}Pb(d,^{3}He) and recently also in ^{206}Pb(d,^{3}He) reactions. The ^{208}Pb(d,^{3}He) experiment is now fully analysed and its result is compared to model predictions. In the ^{206}Pb(d,^{3}He) reaction the pionic $1s$ state was observed as a well-separated peak in the excitation energy spectrum.

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1. Introduction

The investigation of deeply bound pionic states in heavy nuclei allows to study "real" pions in nuclear matter and to deduce the local (s-wave) part of the pion-nucleus potential, whereas level shifts of shallow states in pionic atoms are dominated by the non-local (p-wave) part of the interaction [1,2]. Since deeply bound states are not populated in the conventional technique of forming pionic atoms, namely in the capture of stopped π^-, new methods such as pionic transfer reactions of (n,d) and (d,^{3}He) [3] were proposed. A strong relation between the angular momentum of the preferentially populated states and the momentum transfer of the reaction is expected, hence the cleanest conditions for the population of the pionic $2p$ or $1s$ states are obtained near the recoil free kinematics.

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2. Experimental method

The $(d,^3\mathrm{He})$ spectra on Pb targets were measured using the GSI Fragment Separator (FRS) as high-resolution spectrometer. At incident energy $T_d = 300$ MeV$/u$ the momentum transfer is very small ($q \simeq 50$ MeV$/c$) for excitation energies near the pion mass. The ^{3}He nuclei are momentum analysed at the dispersive FRS central focal plane using drift chambers with high-rate capability, and identified by time-of-flight and energy loss measurement using scintillation detectors at the central and final focal planes. This technique allows both high resolution for the ^{3}He detection and complete suppression of scattered deuteron projectiles and of protons from deuteron breakup. By measuring the momentum vector of the ^{3}He nuclei the missing mass and hence the excitation energy of the $(A_{\mathrm{target}} - 1)$ residual system is fully determined. Frequent energy calibrations were done using the $p\,(d,^3\mathrm{He})\pi^0$ reaction on $(\mathrm{CH}_2)_n$ targets which yields monoenergetic ^{3}He within the angular acceptance of the FRS. The experimental method is described in more detail in Refs. [4, 5].

3. The ^{208}Pb $(d,^3$He$)$ experiment

The study of the $^{208}\mathrm{Pb}\,(d,^3\mathrm{He})$ reaction at the FRS lead to the first observation of deeply bound pionic states [4]. The data obtained in this experiment have been fully analysed. figure 1 shows the measured excitation en-

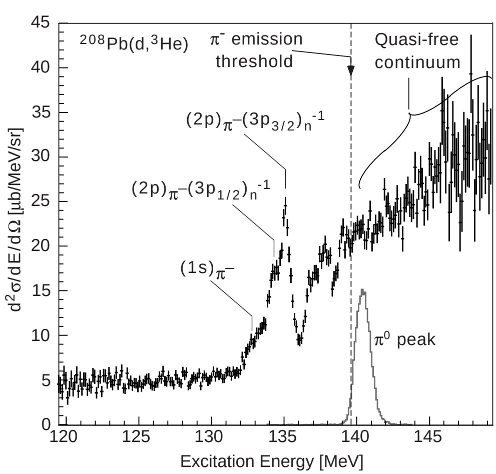

Fig. 1. Measured excitation energy spectrum in the $^{208}\mathrm{Pb}\,(\mathrm{d},^3\mathrm{He})$ reaction. The excitation energy is defined with respect to the ground state of ^{207}Pb such that the π^- emission threshold (dashed line) is located at $E_x = m_\pi$. The calibration peak from the $p\,(d,^3\,\mathrm{He})\pi^0$ reaction is also shown converted to the corresponding excitation energy.

ergy spectrum with respect to the ground state of ^{207}Pb.The prominent peak in the spectrum was assigned to the $(2p)_\pi \otimes (p_{1/2,3/2})_n^{-1}$ configuration which was expected to be dominantly populated in theoretical investigations [6]. The pionic $1s$ state is also populated but not well-separated from the $(2p)_\pi$ component. In order to determine the pionic binding energies the excitation energy spectrum within the bound region ($120\,\mathrm{MeV} < E_x < 136\,\mathrm{MeV}$) was decomposed into the $(2p)_\pi$ and the $(1s)_\pi$ components, both coupled to the relevant neutron hole states, and a continuum background. The relative strength of the neutron hole states was taken from theory [6] whereas binding energies, widths and intensities of the pionic $2p$ and $1s$ states as well as slope and offset of the continuum background were determined in a fit (8 fit parameters) [7]. In the fit function the spectral shape of the pionic state was folded with the instrumental resolution which was determined to be 0.48 ± 0.06 MeV (fwhm) [5]. For the $2p$ state binding energy and width were determined [7] to be $B_{2p} = 5.13 \pm 0.02 \pm 0.12$ MeV and $\Gamma_{2p} = 0.43 \pm 0.06 \pm 0.06$ MeV, respectively, the first error being statistical, the second one systematic. Since the $1s$ peak is not clearly resolved we have to allow a large uncertainty both in the binding energy, $6.6\ \mathrm{MeV} < B_{1s} < 6.9\,\mathrm{MeV}$, and in the width, $0.4\ \mathrm{MeV} < \Gamma_{1s} < 1.2\ \mathrm{MeV}$. There is a strong correlation of the $1s$ binding energy and width with the $1s/2p$ intensity ratio. If the $1s/2p$ ratio is as predicted by the DWIA calculation [6] we obtain $B_{1s} = 6.79 \pm 0.06 \pm 0.12$ MeV and $\Gamma_{1s} = 0.67 \pm 0.11 \pm 0.06$ MeV for the $1s$ binding energy and width, respectively [7].

4. The ^{206}Pb $(d,{}^3$He$)$ experiment

Due to its larger overlap with the nucleus the pionic $1s$ state is more sensitive to the local potential than the $2p$ state. Unfortunately in the ^{208}Pb $(d,{}^3$He) reaction the $1s$ component was poorly separated from the $2p$ component, which is in parts due to the $p_{3/2} - p_{1/2}$ doublet structure of the neutron hole spectrum in ^{207}Pb. From shell model systematics, the $p_{1/2}$ neutrons are not expected to be present in ^{206}Pb which should hence be a better suited target for the observation of the pionic $1s$ state. This expectation was supported in theoretical investigations [8]. In a recent experiment the ^{208}Pb target was replaced by a ^{206}Pb target in order to study deeply bound pionic states in ^{205}Pb. The instrumental resolution was further improved to ~ 0.3 MeV. As visible in figure 2 (left) the $1s$ state is now clearly separated from the $2p$ state, allowing for a reliable determination of its binding energy and width. The spectrum is decomposed into pionic $1s$ and $2p$ components and non-pionic background as described in the previous section, and as illustrated in figure 2 (right). At the present stage the analysis is still preliminary. However, we may already conclude that the binding energies

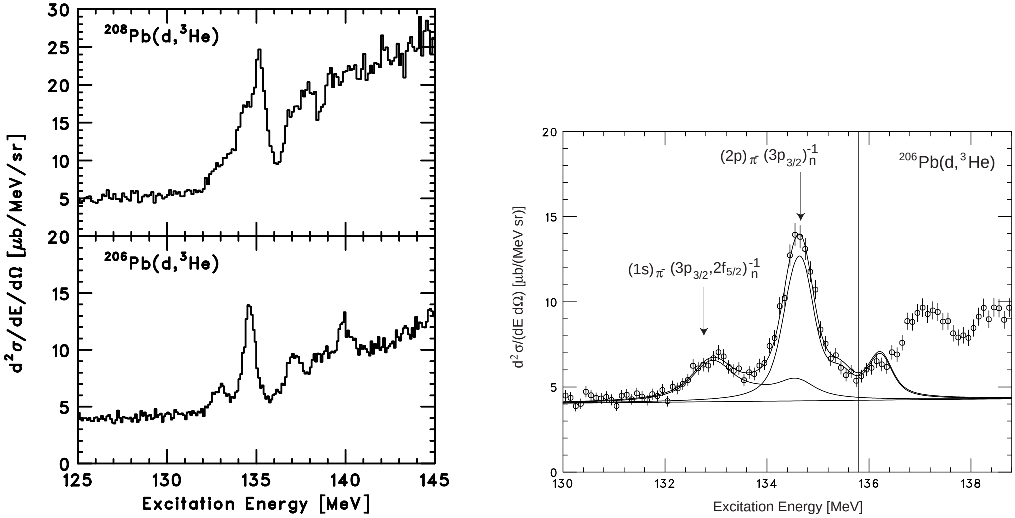

Fig. 2. Measured excitation energy spectrum in the ^{206}Pb $(d,^3$He) reaction (left, lower panel), compared to the ^{208}Pb $(d,^3$He) reaction (left, upper panel), and its decomposition into $1s$ and $2p$ components (right). The excitation energy is defined with respect to the ground states of ^{207}Pb and ^{205}Pb, respectively.

and widths for the pionic $2p$ and $1s$ states in ^{205}Pb are in agreement with the values obtained for ^{207}Pb within the errors as given in the previous section, and that the $1s$ state is populated by about 50% more strongly relative to the $2p$ state than theoretically predicted. A finite isotope shift, which is larger for the $1s$ state than for the $2p$ state, is expected, however, due to the large uncertainty for the $1s$ state in ^{208}Pb the precision will not be sufficient to observe it.

5. Constraints on the pion-nucleus potential

The measured binding energies and widths are compared to model predictions (see references in [7]) in figure 3 both for the $2p$ state (left) and for the $1s$ state (right). As seen in the figure, the present result is precise enough to test the theoretical predictions. Only few predictions are consistent with both the result for the $2p$ state and the $1s$ state whereas others are clearly disfavoured. The constraints on the potential parameters (b_0 and ImB_0) deduced from the $2p$ state and from the $1s$ state are mutually consistent.

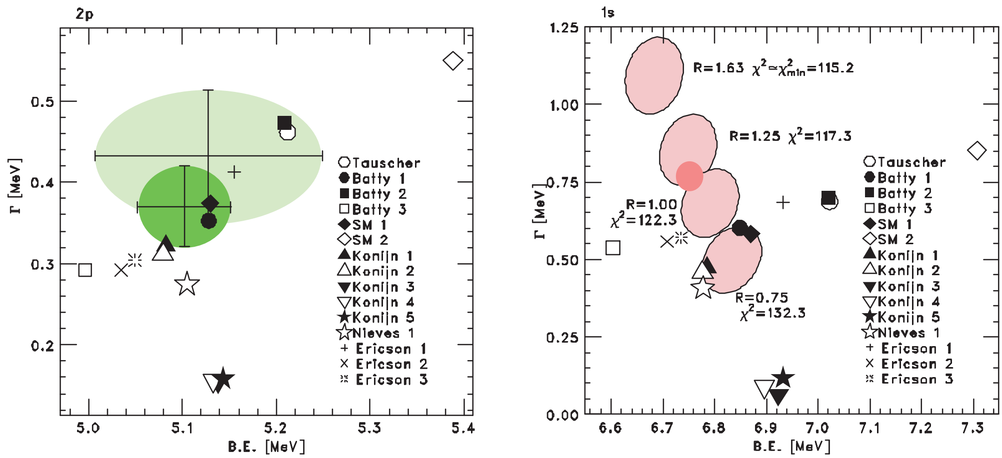

Fig. 3. Comparison of measured binding energy and width of the pionic $2p$ (left) and $1s$ (right) states in ^{207}Pb (light shaded areas) and in ^{205}Pb (dark shaded areas) to various model predictions. The values for ^{205}Pb are preliminary. In the left panel for the $2p$ state the ellipses include both the statistical and the systematic error, in the right panel for the $1s$ state only the 1σ contour of the statistical error is shown.

6. Future studies

In the near future we plan to study pionic $1s$ states in Sn isotopes [9]. Sn and Xe isotopes have low-lying $s_{1/2}$ neutron hole states allowing to populate the pionic $1s$ state in quasi-substitutional configurations at vanishing momentum transfer. As contributions from other neutron hole states in the nuclear excitation spectrum are expected to be very small [10] the pionic $1s$ binding energy and width can be determined in a model independent way. Due to the existence of a long chain of stable isotopes the isotopic shift of deeply bound pionic states may be measured for the first time, allowing to impose separate constraints on the isoscalar and the isovector part of the pion-nucleus potential. Similar studies at the Big Karl spectrometer at COSY on Xe isotopes are being discussed. Their feasibility is based on the development of an external deuteron beam at COSY with sufficient intensity.

7. Summary

After the discovery of deeply bound pionic states in ^{207}Pb using the ^{208}Pb$(d,^3$He$)$ reaction, the deeply bound pionic $1s$ state in ^{205}Pb was observed as isolated peak in the excitation energy spectrum measured in the ^{206}Pb$(d,^3$He$)$ reaction. The good separation of $1s$ and $2p$ state allows to determine the $1s$ binding energy and width to much higher precision than in the previous experiment. The coupling of the pionic states to neutron hole spectrum in ^{205}Pb still induces some model dependence since the relative contribution of the neutron hole states cannot be determined from the experiment. In this respect promising candidates for future studies are Sn and Xe isotopes where the pionic $1s$ state can be populated dominantly in quasi-substitutional configurations.

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