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Heavy Ξ^- hyperatoms at $\overline{\text{P}}$ANDA

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Over the course of its full lifetime, $\overline{\text{P}}$ANDA at FAIR will address the physics of strange baryons with $S = -2$ in nuclei by several novel and unique measurements. This series of experiments will start with the exclusive production of hyperon–antihyperon pairs close to their production threshold in antiproton–nucleus collisions. This day-one experiment offers a hitherto unexplored opportunity to elucidate the behaviour of antihyperons in nuclei. In its intermediate stage, $\overline{\text{P}}$ANDA will offer the unique possibility to search for X-ray transitions from very heavy hyperatoms, e.g. Ξ^--^{208}Pb which will complement experiments at J-PARC measuring X-rays in medium-sized nuclei. Finally, $\overline{\text{P}}$ANDA will extend the studies on double Λ hypernuclei by performing high resolution γ-spectroscopy of these nuclei for the first time.

This contribution focuses on the hyperatom experiment. Calculations for several possible target materials with respect to the experimental observables show the high feasibility of a ^{208}Pb hyperatom experiment. Further simulation studies were performed to estimate the expected event and background rates and their effect on the achievable precision for the observables and hence the Ξ^--nuclear potential. Since the results are strongly correlated with the shape of the periphery of the ^{208}Pb nucleus, the systematic uncertainty related to the neutron skin thickness of ^{208}Pb is also discussed. We predict an uncertainty in the estimation of the real part as well as the imaginary part of the Ξ^- nuclear potential of approximately 1 MeV.

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1. Experimental situation of the Ξ^- nuclear potential

Our knowledge of the Ξ^- nuclear interaction is very limited. Its short lifetime prevents a direct access via scattering experiments. The ALICE experiment at the LHC observed an attractive interaction of Ξ^- and free protons in femtoscopic studies of p–Pb collisions [1]. Information on the Ξ^- interaction within nuclear matter originates from the spectroscopy of bound systems. Several individual Ξ^- hypernuclear events decaying into twin Λ hypernuclei within nuclear emulsions could be observed in the past (see Ref [2] and references therein). In addition to that, J-PARC E05 was conducted to observe the missing-mass spectra in the $^{12}\text{C}(K^-,K^+)^{12}_{\Xi}\text{Be}$ reaction. Its follow-up experiments E70 and E75 are planned with increased mass resolution.

Further insight of the strength of the Ξ^- potential at nuclear densities will arise from the high resolution X-ray spectroscopy of Ξ^- hyperatoms at J-PARC (E03 and E07) and at $\overline{\text{P}}$ANDA.

2. Production and spectroscopy of Ξ^- hyperatoms at $\overline{\text{P}}$ANDA

The production of hyperatoms at $\overline{\text{P}}$ANDA is a two-staged process with a split-up target design [3]. This separation allows to optimize the primary target solely for the production of slow Ξ^-. Then the secondary target, can be optimized for the stopping of Ξ^- to produce hyperatoms while keeping the absorption of produced X-ray transitions as low as possible [4]. Finally, the PANGEA germanium detector will be used to detect these transitions and to study the small deviations from pure QED calculations with high precision.

3. Choice of the secondary target of the $\overline{\text{P}}$ANDA hyperatom experiment

The experiments at J-PARC employ only few target nuclei and hence can study only few hyperatoms. In E07, hyperatoms are a byproduct of the search for double Λ hypernuclei using emulsion detectors. This limits the possible hyperatoms to Br and Ag. E03 is situated at the same K^- beam line as E07 and designed to use a single, thick target to produce, stop and capture Ξ^-. This reduces the range of possible targets to medium mass nuclei such as Fe.

The separated targets of $\overline{\text{P}}$ANDA increase the flexibility in the choice of the target material. Several target material for the secondary target have been studied and compared. The most important observables in this study are the energy shift and the width of the energy levels due to the strong interaction between the Ξ^- and the nucleus. Since the width is smeared by the resolution of the the germanium detectors, it will be difficult to disentangle both. The relative yield $Y_{(n,l)}$ of the nuclear-effected transition offers a way to study the width indirectly via the relation

$$Y_{(n,l)} = \frac{N_{(n,l)\to(n-1,l-1)}}{N_{(n+1,l+1)\to(n,l)}} = \frac{\Gamma^{em}_{n,l}}{\Gamma^{em}_{n,l} + \Gamma^{abs}_{n,l}}. \tag{1}$$

This correlation combines the experimentally measured yield of transitions (N_x) to the calculated radiative width Γ^{em}_x and the strong absorptive width due to the nuclear interaction Γ^{abs}_x.

These widths as well as the energy shift and the plain QED transition energy were calculated using a tρ potential with a software based on the formalism presented in Ref. [5]. This potential is sufficient for an estimation of the experimental feasibility of a given target material. The interaction

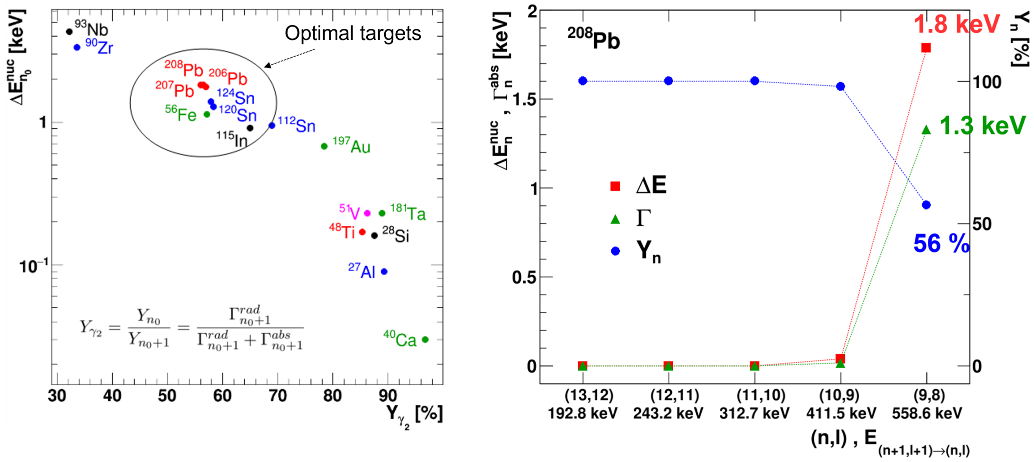

Fig. 1: Left: Calculated observables for several possible Ξ^- hyperatom target materials. Suitable choices are marked by the circle. **Right**: Calculated observables for Ξ^--^{208}Pb hyperatom X-ray transitions. Only the last visible transition is affected by the strong interaction of the Ξ^- and the nucleus.

strength of the Ξ^- and the nucleus in the calculations is characterized by the complex parameter b_0. This parameter can be related to the hadron–nucleon scattering length. Ref. [5] proposed a *typical* value of $b_0 = 0.25\,\text{fm} + i\,0.04\,\text{fm}$ which yields a potential depth of about 20 MeV for the real part and about 3 MeV for the imaginary part.

The left panel of Fig. 1 shows an overview of possible hyperatoms. Suitable targets offer a high energy shift and still moderate yield to reach sufficient statistics. These requirements are best fulfilled by the island of nuclei marked by the circle. The ^{56}Fe target used by E03 is part of these nuclei. Unfortunately, the use of such an iron target is hardly possible within the strong magnetic field of $\overline{\text{P}}$ANDA. Lead, however, offers a very similar performance in both observables. Details for Pb are shown in the right panel of Fig. 1. Here the energy shift ΔE, the width Γ as well as the relative yield Y are plotted for various states of ^{208}Pb hyperatoms. These calculations demonstrate that the effect of the strong nuclear interaction only occurs in the last visible transition $(n = 10, l = 9) \longrightarrow (n = 9, l = 8)$. No significant energy shift, widening or reduced yield due to the strong nuclear interaction can be seen for higher transitions.

4. Statistical and systematic uncertainties at $\overline{\text{P}}$ANDA

On a closer look, the calculations of the observables are not only affected by the nuclear interaction strength of the Ξ^-. Two additional factors have to be considered: the wave function of the atomically bound Ξ^- and the shape of the nucleus. While the wave function of the Ξ^- can be precisely calculated via QED, the nuclear density distribution requires experimental input. In this respect, ^{208}Pb is well known [6]. Nevertheless, the remaining uncertainties will result in a systematic error of the deduced Ξ^- potential. This was estimated by calculating the observables while varying the thickness of the neutron skin of the ^{208}Pb nucleus Δ_{np}. As shown in the left panel of Fig. 2 the observables exhibit a linear dependence on Δ_{np}. Experimental results for Δ_{np} of ^{208}Pb are summarized in the same figure. These were used to estimate the systematic uncertainties of the

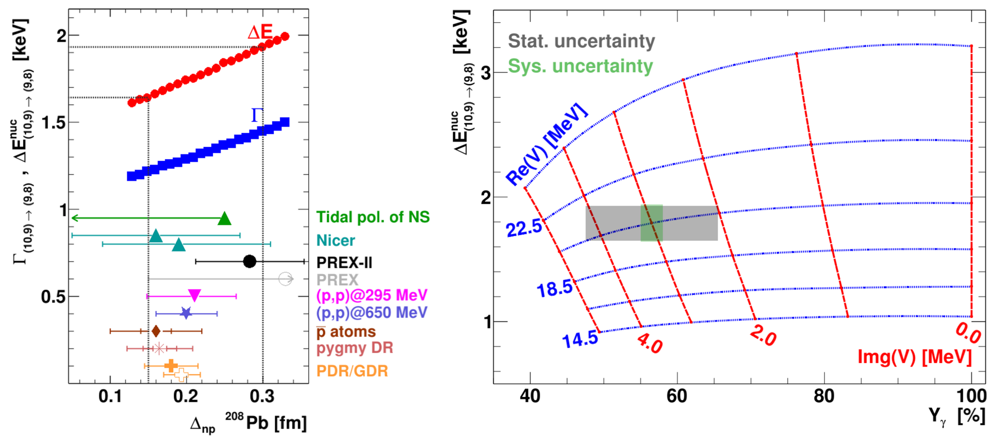

Fig. 2: Left: Experimental observables show a linear dependence on the neutron skin thickness Δ_{np} of ^{208}Pb. The induced systematic uncertainties were calculated using the data points taken from Refs. [8–17]. **Right**: Translation of these uncertainties into an accuracy for the estimation of the complex Ξ^- potential.

observables. We chose a conservative range of 0.15 fm to 0.3 fm which contains all present data points. This range translates to a systematic uncertainty of ±150 eV for the strong energy shift of the $(n = 10, l = 9) \rightarrow (n = 9, l = 8)$ transition.

Full simulations of the experiment within the PandaRoot [7] framework have been performed to estimate the achievable statistical uncertainty. A series of cuts on the event topology allow to distinguish the signal from its background. Approximately 1200 signal events remain after the application of all cuts and assuming a beam time of 180 days [4]. These event and background rates were fed into an extended unbinned maximum-likelihood study to estimate the statistical uncertainty of the experiment.

These statistical and systematic uncertainties for the energy shift and the relative yield were used to predict the uncertainty of the estimation of the Ξ^- potential V. This was achieved by varying the real part and the imaginary part of the potential independently within the calculations. The results of these variations are shown in the right panel of Fig. 2. The blue and red curves illustrate equipotential lines for the real part of the potential Re(V) and the imaginary part Im(V), respectively. They are embedded in a coordinate system spanned by the energy shift and yield resulting from the varied potential. The experimental uncertainties were added to this by simple rectangles around the potential suggested by Ref. [5]. The predicted small statistical uncertainty of the energy shift will allow a precise estimation of Re(V) at $\overline{\text{P}}$ANDA. The systematic uncertainty for this observable will be of similar size. The uncertainties of the imaginary part, however, will be dominated by the statistical uncertainty, which follows from the uncertainties in the estimation of the counting rates of detected hyperatom transitions caused by the low statistics and high background. More sophisticated cuts and analysis techniques might reduce these uncertainties in the future.

To conclude, the expected uncertainties will allow to determine Re(V) as well as Im(V) at $\overline{\text{P}}$ANDA with a statistical as well as systematical uncertainty of approximately ±1 MeV.

5. Summary

$\overline{\text{P}}$ANDA will offer the unique possibility to perform X-ray spectroscopy of heavy Ξ^- hyperatoms such as Ξ^--^{208}Pb. This experiment will measure the Ξ^- nuclear potential in the neutron skin of ^{208}Pb, which resembles neutron-rich matter. The well-known size of this neutron skin decreases the expected systematic uncertainties of the experiment to approximately ± 1 MeV for the real part as well as the imaginary part of the potential. The predicted statistical uncertainties are similar in size.

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