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QED precision studies in kaonic atoms with SIDDHARTA-2

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Summary. — Kaonic atoms, where a negatively charged kaon replaces an electron, provide a unique system for precision studies of bound-state and strong-field quantum electrodynamics (QED). The SIDDHARTA-2 experiment at the DAΦNE at INFN-LNF collider performs high-resolution X-ray spectroscopy of these systems using Silicon Drift Detectors. The recent measurement on kaonic neon enables stringent bound-state QED tests and a pathway towards a refined determination of the charged kaon mass, while preliminary kaonic fluorine data demonstrate the potential to probe strong-field QED effects. These results highlight the role of SIDDHARTA-2 in advancing high precision QED studies with hadronic atoms.

1. – Introduction

Kaonic atoms, in which a negatively charged kaon replaces an electron, provide a distinctive environment for precision studies of fundamental interactions. While traditionally employed to probe Quantum Chromodynamics (QCD) in the non-perturbative regime [1-4], they also serve as a powerful testbed for bound-state Quantum Electrodynamics (BSQED) and searches for Beyond-Standard-Model (BSM) physics. BSQED effects have mostly been investigated in highly charged ions [5], where finite nuclear size uncertainties limit experimental precision. This has motivated measurements in exotic atoms, where the compactness of the system enhances BSQED effects and offers complementary experimental conditions [6]. In this framework, hadronic atoms, owing to their larger reduced mass, are particularly sensitive to higher-order QED effects such as vacuum polarization and radiative corrections. Kaonic atoms are especially suitable, as the spinless nature of the kaon removes fine-structure splitting and simplifies theoretical interpretation. By selecting appropriate transitions, effects from nuclear size and electron screening can be minimized, providing a clean probe of BSQED [6]. These transitions also fall within the energy range accessible to modern high-resolution X-ray detectors [7-11]. Furthermore, the compactness of kaonic atoms allows exploration of BSQED in the presence of strong electromagnetic background fields. In this regime, known as Strong-Field QED (SFQED), the perturbative expansion of QED begins to break down [12-14], opening novel possibilities to experimentally search for BSM physics. The SIDDHARTA-2 experiment at the DAΦNE e^+e^- collider of INFN-LNF [3,4,15,16] provides an ideal platform for pioneering these studies. Kaons produced via $\phi \to K^+K^-$ decays are slowed and stopped in a gaseous target, forming kaonic atoms whose X-ray transitions are detected with Silicon Drift Detectors (SDDs) [7, 8, 15]. Through this approach, SIDDHARTA-2 extends BSQED tests to hadronic systems, enabling precision spectroscopy and improved determinations of fundamental quantities such as the charged kaon mass.

2. – Probing BSQED and SFQED with kaonic atoms

The SIDDHARTA-2 experiment has recently conducted precision spectroscopy of kaonic neon [17,18], providing a new avenue for stringent tests of BSQED and for searching possible BSM contributions. From the fit to the collected kaonic neon data it was possible to extract the energy of the measured X-ray transitions of kaonic neon and

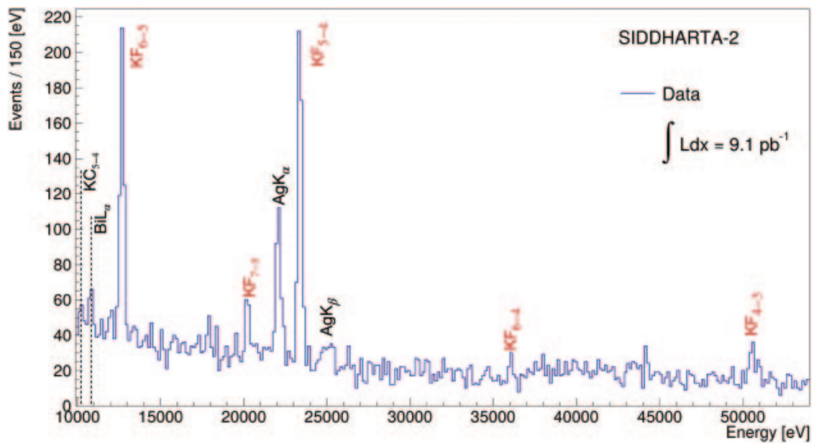

Fig. 1. – Preliminary X-ray spectrum of kaonic fluorine obtained by SIDDHARTA-2, corresponding to an integrated luminosity of 9.1 pb^{-1}. Several characteristic transitions can be identified demonstrating the experiment's capability to detect lines in the strong-field QED regime.

compare them with QED predictions. In addition to enabling fundamental QED tests, the measurement of purely electromagnetic transitions in kaonic neon offers the possibility to address the long-standing discrepancy in the charged kaon mass [18, 19]. The energies of kaonic atom X-ray transitions depend directly on the reduced mass of the system, and therefore on m_{K^-}, allowing for a model-independent determination of the kaon mass. Kaonic neon is particularly well suited for resolving this issue: the use of a gaseous target eliminates systematic uncertainties associated with solid targets, such as electron refilling and screening effects, while its cascade produces intense and well-isolated transitions in the 4–12 keV region, ideally matching the efficiency, calibration and resolution capabilities of the SIDDHARTA-2 SDDs [7, 8]. A new dedicated kaonic neon data taking campaign, one of the objectives of the EXKALIBUR project [19], will thus enable a refined determination of the charged kaon mass and contribute to resolving the current experimental discrepancy. Furthermore, some transitions in kaonic atoms occur in regions of extremely strong electromagnetic fields, providing experimental access to the strong-field regime of QED. To explore this regime, SIDDHARTA-2 has performed a measurement of kaonic fluorine. Figure 1 presents the preliminary X-ray spectrum of kaonic fluorine, obtained from a partial data sample corresponding to an integrated luminosity of 9.1 pb^{-1}. Despite the limited data sample, several characteristic lines can be identified, demonstrating both the capability of SIDDHARTA-2 to detect transitions in the SFQED domain and the suitability of kaonic atoms as novel systems to study QED under extreme field conditions. A refined data analysis is ongoing for a dedicated publication. Such measurements will not only strengthen the role of kaonic atoms in precision QED studies but also establish them as platform for exploring the interface between atomic, nuclear, and particle physics in systems with strangeness.

3. – Conclusions

Kaonic atoms offer a unique platform for precision tests of bound-state and strong-field QED, extending the reach of quantum electrodynamics of bound systems into regimes dominated by strong electromagnetic fields. The recent measurement performed by SIDDHARTA-2 on kaonic neon [17,18] demonstrates the experiment's ability to perform high-resolution spectroscopy of exotic systems, enabling stringent BSQED tests and an improved determination of the charged kaon mass. Preliminary results on kaonic fluorine further show the feasibility of accessing transitions sensitive to SFQED effects. These studies mark an important step toward exploring QED in extreme conditions and pave the way for future high-precision measurements within the EXKALIBUR program [19].

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