SIDDHARTA-2 veto system design and performance for kaonic atoms studies at DAΦNE

F. Sgaramella[1*], M. Bazzi[1], D. Bosnar[2], M. Bragadireanu[3], M. Cargnelli[4], M. Carminati[5,6], A. Clozza[1], G. Deda[5,6], R. Del Grande[7,1], K. Dulski[1,9,10], L. De Paolis[1], L. Fabbietti[7], C. Fiorini[5,6], I. Friščić[2], C. Guaraldo[1], M. Iliescu[1], M. Iwasaki[8], A. Khreptak[1,9], S. Manti[1], J. Marton[4], M. Miliucci[1,**], P. Moskal[9,10], F. Napolitano[1], S. Niedźwiecki[9,10], H. Ohnishi[11], K. Piscicchia[12,1], Y. Sada[11], A. Scordo[1], M. Silarski[9], D. Sirghi[1,3,12], F. Sirghi[1,3], M. Skurzok[9,10], A. Spallone[1], K. Toho[11], M. Tüchler[4,13], C. Yoshida[11], J. Zmeskal[4], and C. Curceanu[1]

[1]INFN-LNF, Istituto Nazionale di Fisica Nucleare-Laboratori Nazionali di Frascati, Frascati, 00044 Roma, Italy
[2]Department of Physics, Faculty of Science, University of Zagreb, 10000 Zagreb, Croatia
[3]Horia Hulubei National Institute of Physics and Nuclear Engineering IFIN-HH Măgurele, Romania
[4]Stefan-Meyer-Institut für Subatomare Physik, Vienna, 1030, Austria
[5]Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria, Milano, 20133, Italy
[6]INFN Sezione di Milano, 20133, Italy
[7]Physik Department E62, Technische Universität München, Garching, 85748, Germany
[8]RIKEN, Tokyo 351-0198, Japan
[9]Faculty of Physics, Astronomy, and Applied Computer Science, Jagiellonian University, Krakow, 30-348, Poland
[10]Center for Theranostics, Jagiellonian University, Krakow, Poland
[11]Research Center for Electron Photon Science (ELPH), Tohoku University, Sendai, 982-0826, Japan
[12]Centro Ricerche Enrico Fermi – Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Roma, 00184, Italy
[13]University of Vienna, Vienna Doctoral School in Physics, Vienna, 1090, Austria

Abstract. Light kaonic atoms spectroscopy provides a unique approach to study the low-energy strong interaction in the strangeness sector. Precise measurements of X-ray emission from light kaonic atoms provide valuable information on kaon-nucleus interaction at threshold without the need for extrapolation as required in scattering experiments. The SIDDHARTA-2 experiment at the DAΦNE collider of INFN-LNF is now poised to perform the challenging measurements of the K^-- d 2p→1s transition to extract the isospin-dependent antikaon-nucleon scattering lengths. To achieve this goal, the background reduction is a crucial factor. This paper provides an overview of the SIDDHARTA-2 Veto-1 system, which uses scintillators outside the vacuum chamber to detect charged particles produced by K^- absorption by the nucleus. The arrival time of these particles is correlated with the position where the kaonic atom has been created inside the setup, allowing for the rejection of kaons stopped outside the target cell, which is a critical component for reducing the background and improve the accuracy of the measurement.

1 Introduction

SIDDHARTA-2 is a cutting-edge experiment that aims to measure the properties of kaonic atoms, which are exotic atomic systems consisting of a negatively charged kaon and a nucleus. The study of kaonic atoms is a unique tool to understand the strong interaction between particles in the non perturbative regime with strangeness, with implications from nuclear and particle physics to astrophysics [1–4]. In 2009, the SIDDHARTA experiment performed precise measurements of atomic transitions in kaonic hydrogen. However, to determine the isospin dependent antikaon-nucleon scattering lengths, the crucial measurement of kaonic deuterium is still missing due to the expected low yield of the kaonic deuterium transition to the fundamental level. To perform this challenging measurement, the SIDDHARTA-2 collaboration developed a completely new apparatus. The SIDDHARTA-2 setup (Fig. 1) is currently installed at the interaction region of the DAΦNE [5] collider of Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali di Frascati (INFN-LNF). DAΦNE delivers low momentum (127 MeV/c) charged K^+K^- pairs coming from the ϕ meson decay. The trigger of the experiment consists of two plastic scintillators placed in the vertical plane above and below the beam pipe to detect the two charged kaons. Once the kaons are triggered, they pass through a thin degrader made of few hundred microns of mylar sheets and then enter in a cylindrical target cell filled with gas. The degrader is tuned to maximize the kaons stopped in the gas target [6]. Upon stopping, a K^- is captured into a kaonic atom that emits X-rays in the range of several keV before being absorbed by the nucleus. The gaseous cryogenic target is surrounded by 384 state-of-the-art Silicon Drift Detectors (SDDs) devel-

*e-mail: francesco.sgaramella@lnf.infn.it
**current address: ASI, Agenzia Spaziale Italiana, Roma, Italy

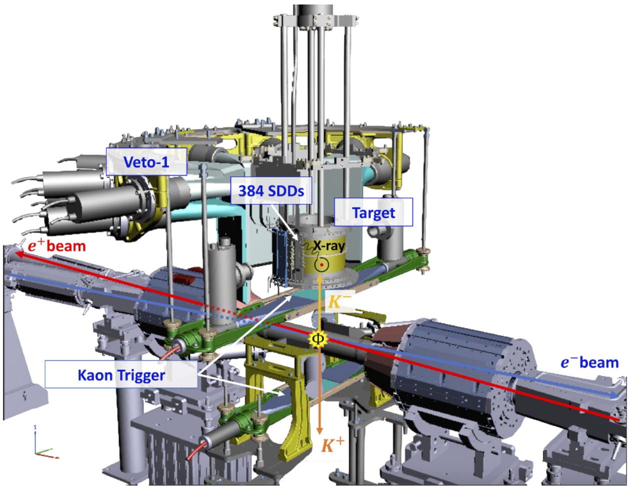

Figure 1. Schematic layout of the SIDDHARTA-2 experimental apparatus

oped specifically for high precision X-ray spectroscopy. The good energy and time resolution ($\Delta E/E < 10^{-3}$) as well as the excellent linear response of the SDD system are key features for performing the kaonic deuterium measurement with high precision [7–9]. In addition, the setup is equipped with several veto systems crucial to increase the signal to background ratio. In this work we present the Veto-1 system of the SIDDHARTA-2 experiment, based on the detection of the charged pions produced by kaons absorption on various materials, including the gas target.

2 The Veto-1 system

2.1 Working principle

To successfully measure kaonic deuterium transitions while dealing with low signal and significant background, it is crucial to select events that occur solely within the gas target and eliminate the hadronic background due to kaons stopped elsewhere. The Veto-1 working principle involves identifying events within the gas, based on their characteristic timing, related to kaon moderation. The Veto-1 system for the SIDDHARTA-2 experiment aims to provide a signal from particles, mainly pions, as result of K^- nuclear absorption in the gas target. The signal is easily distinguishable from events related to K^- stopped in the solid elements of the setup, due to their longer moderation time. The slowing-down time elapsed between the K^- entrance in high density gas and its subsequent capture by an atom has a typical range from 3 to 7 ns and is correlated to the number of collisions needed to transfer the majority of its kinetic energy to the gas atoms.
The system takes advantage of the high probability (around 90%) for the production of charged pions following the final kaon absorption by the atomic nucleus [10–13], making the Veto-1 an efficient tool to provide information on where the kaonic atom has been created.

2.2 Design

Considering that pions coming from hadronic interaction easily pass through SDDs and vacuum chamber, the design for the Veto-1 system consists of a barrel-shape scintillator, surrounding the cylindrical vacuum chamber. A dedicated Monte Carlo Geant4 based simulation has been performed, to determine the optimal set of geometric parameters that result in a high count of the detected photons, while minimizing the spread of signal time.
The barrel is made of 12 distinct (260×110×10) mm^3 plastic scintillator (ELJEN TECHNOLOGY, EJ-200) segmented into 3 equal strips, read by two Hamamatsu R10533 photomultipliers (PMT) through a complex multireflection light guides, in order to fit the available space around the vacuum chamber, limited by the external lead shielding (Fig. 2). To increase the covered solid angle, two additional scintillators have been placed under the vacuum chamber at the sides of the kaon trigger.

2.3 Performance

A Veto-1 prototype was tested at the PSI using a 170 MeV/c momentum pion beam. The measured mean time resolution was (746±53) ps FWHM, while the efficiency was (96±2)% [14], in agreement with the requirements for the optimal operation of the system. In 2022 the full Veto-1 system was installed around the SIDDHARTA-2 vacuum chamber and was tested for the first time with the rest of the apparatus during the commissioning run of the experiment. The target cell was filled with Helium at a temperature of 27 K and pressure of 1 bar, which corresponds to 1.0% LHeD (Liquid Helium Density). The high yield of the kaonic helium allowed to verify the operation of the full SIDDHARTA-2 setup with an integrated luminosity of 5 pb^{-1}.
The timing information given by the difference between the between a pion-induced signal in the Veto-1 scintillators and the kaon trigger signal is related to the moderation time of kaons in the gaseous target, allowing for the separation of the events corresponding to kaons stopped in the gas from background events caused by the decay of K^+ or K^- stopped in the setup materials. This discrimination can be clearly seen in Fig. 3. The plot shows the time distribution, given in arbitrary units of the Time to Digital Converter (TDC), obtained during the kaonic helium run. The first peak corresponds to particles produced by the K^- absorption in the setup materials, such as the target entrance window, the degrader or the several mechanical support frames. Instead, the second peak corresponds to the K^- stopped inside the gas target, since the kaon moderation time in the gas is longer with respect to the moderation time in solid elements. Finally, the right tail is related to the K^+ decay and no peak is seen because there is no nuclear absorption.
The sensitivity of the Veto-1 to the kaon moderation time can be used also to optimize the degrader, since the amplitude and the position of the peaks shown in Fig. 3 change depending on the thickness and density of the materials through which the kaon passes. The degrader is a fundamental element of the apparatus and the optimization of its

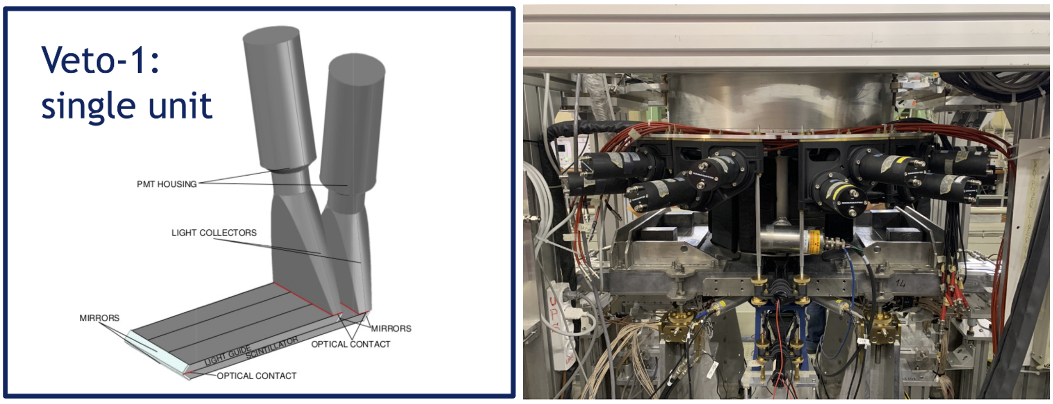

Figure 2. Left: Veto-1 single unit layout. Right: Photo of the Veto-1 system installed around the SIDDHARTA-2 vacuum chamber.

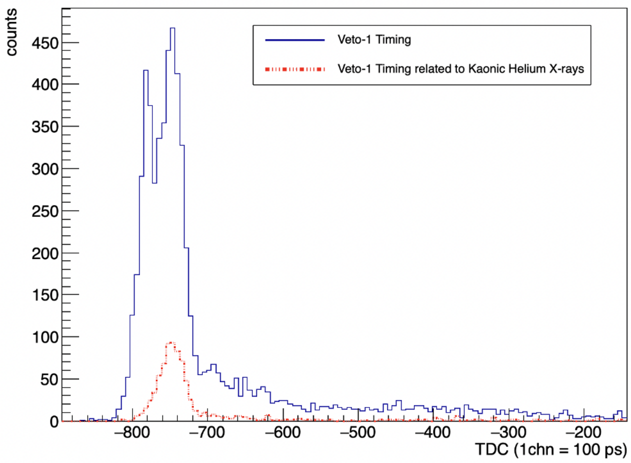

Figure 3. Veto-1 time distribution, in arbitrary unit of the Time to Digital Converter (TDC), measured during the SIDDHARTA-2 Kaonic Helium run. The red dotted line represents the time distribution of events related to kaonic Helium atoms.

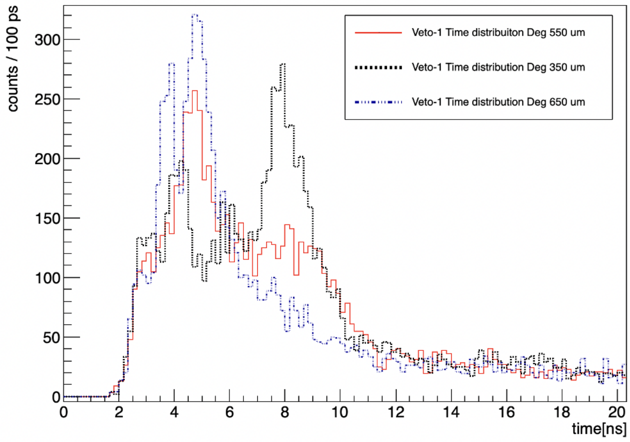

Figure 4. Veto-1 timing simulations for different degraders and the target filled with helium at 1.4% LHeD.

thickness is essential to maximize the kaons stopped inside the gas [6]. As an examples Fig. 4 shows the simulated time distributions for different degrader thicknesses and a target cell filled with helium at 1.4% LHeD. The difference between the plots is clearly visible and comparing the simulations with the real data will help to cross-check the Monte Carlo simulation and optimize the degrader thickness.

Moreover, the time distribution also changes if there is a variation in gas pressure or temperature, since the kaon stopping distribution strongly depends on the gas density. Therefore, the Veto-1 can be used to monitor the experiment's parameters and helps to ensure the stability of the data taking conditions.

3 Conclusions

In conclusion, the Veto-1 system is a critical component of the SIDDHARTA-2 experiment. The system's design and performance were carefully evaluated, and the results showed that the Veto-1 system can identify the pions produced by kaons absorption with high efficiency and good time resolution. The Veto-1 system's ability to provide timing information is essential for the success of the experiment improving the signal to background ratio, by rejecting the events related to K^+ decay or K^- stopped outside the gas target. Furthermore, the Monte Carlo simulations demonstrate that the Veto-1 system also provides valuable information for monitoring the experiment's condition and ensuring its stability.

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