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SAILING WITH NEEDLE BEYOND THE HORIZON[*]

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The NEEDLE setup is designed and built to study exotic neutron-deficient nuclei. It allows for increased sensitivity to explore the nuclear structure close to the proton drip line. This detector setup combines the EAGLE γ-ray spectrometer and the capabilities of the NEDA array to identify the events in which a number of neutrons were emitted from the compound nucleus. Within this contribution, the first NEEDLE campaign and future plans are discussed.

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1. Introduction

The general scientific objective of the NEEDLE [1] project is to extend knowledge of the strong nuclear force by studying the internal structure of nuclei as a function of their proton and neutron numbers (isospin), angular momentum, and excitation energy. We focus our research on excited states of nuclei located in the Segré chart close to the proton drip line, far off of the valley of β-stability, along the $N = Z$ line, including regions of the self-conjugate doubly-magic nuclei ^{56}Ni and ^{100}Sn. These investigations are in the front line of contemporary low-energy nuclear physics research [2–4].

Within this project, information on excited states is acquired in experiments in which beams of heavy ions from the Warsaw cyclotron [5, 6] are used to induce fusion–evaporation reactions, and γ-ray radiation emitted from excited states of products of the reactions is analysed. Nuclei of interest are produced with very small reaction cross sections, and consequently, ancillary detectors are needed to allow for sufficient channel selection. The setups usually consist of a γ-ray spectrometer, neutron detectors, and charged particle detectors. The role of neutron detectors is particularly essential as they allow for distinguishing weak neutron evaporation channels from stronger charged-particle evaporation channels in experiments close to the proton drip line. An efficient neutron multiplicity filter, such as NEDA, also allows us to tag the number of neutrons in cases in which neutron emission is not rare. This feature has been exploited in the first experimental campaign of NEEDLE.

2. The first NEEDLE campaign

The fundamental tool for the γ-spectroscopy studies at HIL is the EAGLE (central European Array for Gamma Levels Evaluation) setup [7]. For the campaigns aiming at spectroscopic studies of exotic neutron-deficient nuclei, EAGLE was augmented by the NEDA array [8, 9]. The new setup was named NEEDLE. It has a γ-ray photopeak efficiency of 1.4% at 1.3 MeV, and about 30% and 3% efficiency to detect and identify one and two neutrons, respectively. The general description of the setup and its readout was given in Ref. [1], and the details of the performance will be described in a dedicated publication. The bird's eye view of the setup is shown in Fig. 1. The experiments performed within the first two NEEDLE campaigns are listed in Table 1. During the first physics campaign of NEEDLE, the Köln plunger [10] was employed for studying the lifetimes of the excited states of nuclei selected with a neutron multiplicity condition.

The properties of excited states of neutron-deficient $A \approx 118$–134 nuclei were studied. In the first experiment (HIL099), lifetimes of excited states up to 10^+ in the yrast band of ^{134}Sm were investigated. The evolution of $B(\mathrm{EL})/B(\mathrm{E2})$ ratio will shed light on the character of symmetry of

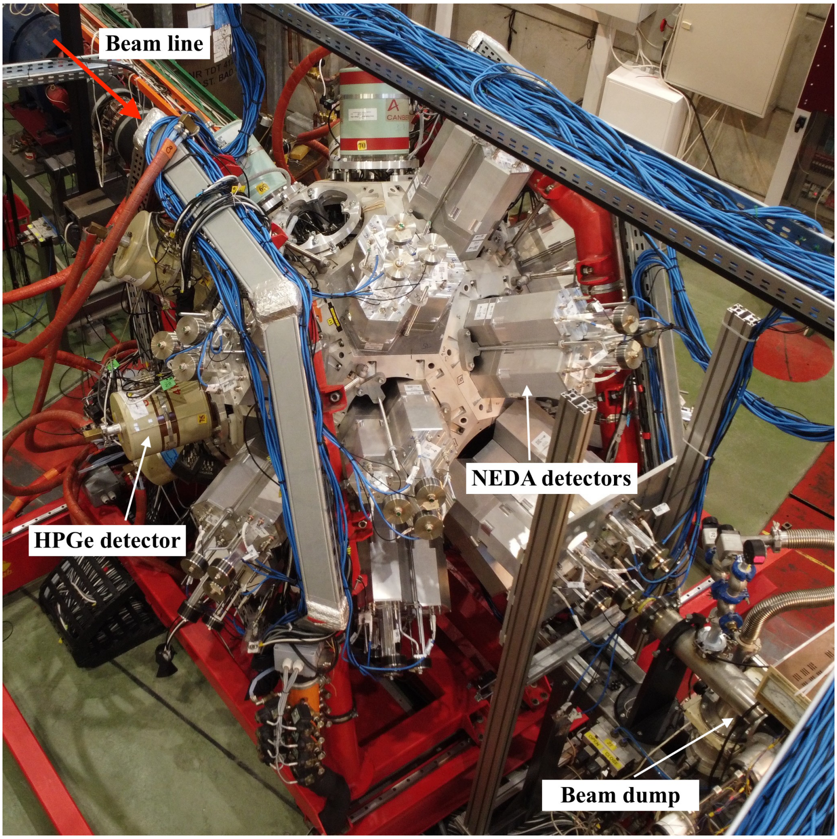

Fig. 1. The NEEDLE setup. From top left to bottom right (the beam direction): the HPGe detectors (dewars visible), NEDA detectors installed in the EAGLE frame, and the NEDA's forward wall.

Table 1. Experiments performed with NEEDLE in the first half of 2023. The beam-time is given in UT = 8 h.

Exp.	Reaction	Setup	Beam-time [UT]
HIL-101	$^{32}\mathrm{S} + {}^{27}\mathrm{Al}$	EAGLE + NEDA	15
HIL-099	$^{32}\mathrm{S} + {}^{106}\mathrm{Cd}$	EAGLE + NEDA + Plunger	42
HIL-097	$^{16}\mathrm{O} + {}^{106}\mathrm{Pd}$	EAGLE + NEDA + Plunger	42
HIL-106	$^{32}\mathrm{S} + {}^{92}\mathrm{Mo}$	EAGLE + NEDA + Plunger	42
HIL-101	$^{32}\mathrm{S} + {}^{28}\mathrm{Si}$	EAGLE + NEDA + DIAMANT	15

^{134}Sm and the neighbouring nuclei, which are predicted to be well described with the algebraic $X(5)$ symmetry [11]. Two further experiments (HIL097 and HIL106) concentrated on the shape co-existence and octupole correlations in the light Xe–Cs–Ba region. In this perspective, ^{119}Cs, ^{118}Xe, and ^{120}Ba were of special interest. The new data will assess the prolate–oblate shape coexistence and chiral bands recently discovered in these nuclei. In July 2023, the setup of EAGLE–NEDA–DIAMANT, *i.e.*, NEEDLE coupled to the DIAMANT charged-particle detector array [12] was commissioned (HIL101). This setup aims at a further enhancement of the selectivity using gate conditions both on neutrons and light-charged particles. DIAMANT can consist of up to 96 CsI(Tl) detectors (depending on the configuration) and effectively register and distinguish proton and α particles, also at high rates. See Ref. [13] for more details.

Figures 2 and 3 show the effect of gating on the number of neutrons detected in NEDA, emitted from the ^{32}S + ^{92}Mo and ^{32}S + ^{27}Al reactions (HIL106 and HIL101 experiments), respectively. The conditions on the number of detected neutrons and α particles enable to enhance γ-ray transitions assigned to the nucleus of interest.

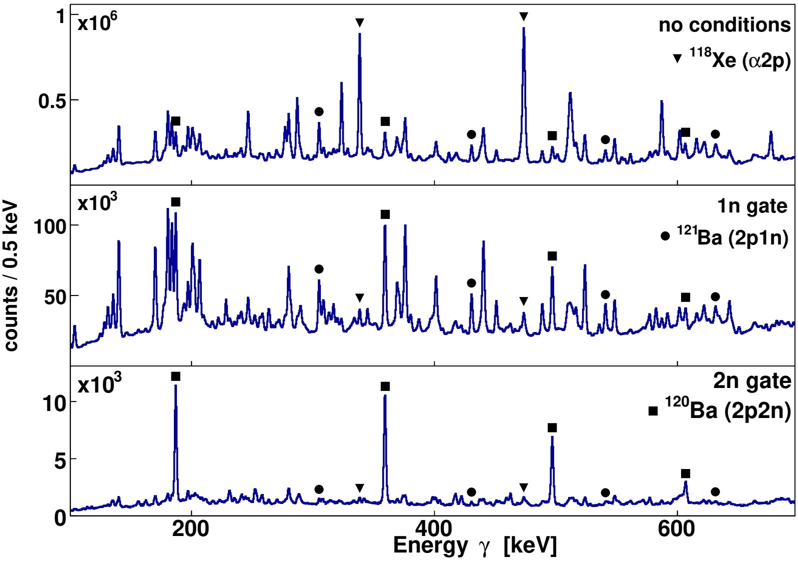

Fig. 2. Gamma-ray energy spectra obtained in the reaction of the 152 MeV ^{32}S beam on the 1.2 mg/cm^2 ^{92}Mo target (HIL106 experiment) with various conditions on the number of detected neutrons. From top to bottom: no condition applied, at least one neutron detected in coincidence, at least two neutrons detected in coincidence. The $2n$ condition clears the spectrum significantly, making the yrast-band E2 transitions up to the 8^+ state in ^{120}Ba the dominant peaks in the spectrum.

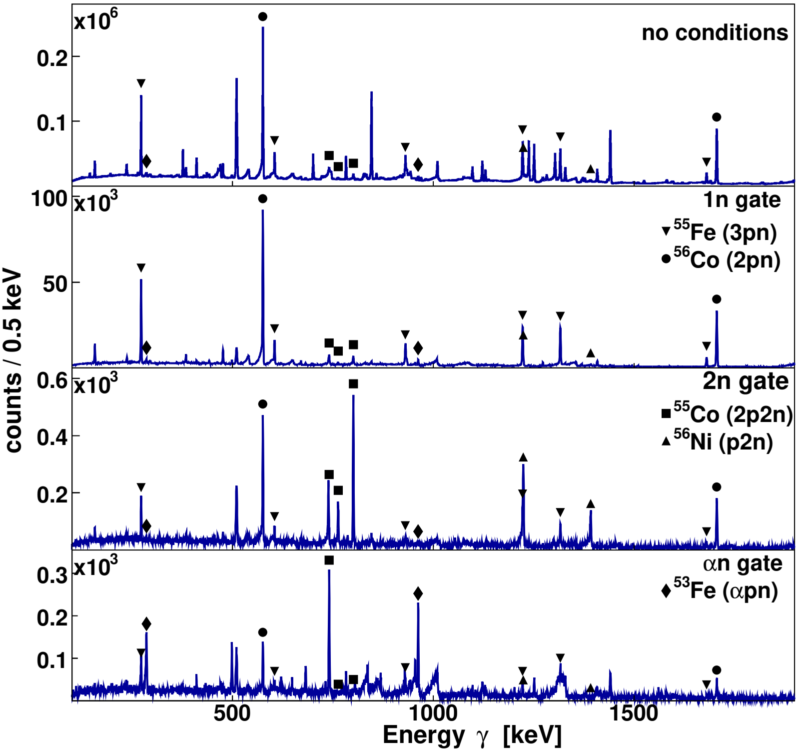

Fig. 3. Gamma-ray energy spectra obtained in the reaction of the 88 MeV ^{32}S beam on the ^{27}Al target (HIL101 experiment) with various conditions on NEDA and DIAMANT. From top to bottom: no condition applied, at least one neutron detected in coincidence, at least two neutrons detected in coincidence, α particle, and at least one neutron detected in coincidence. These conditions allow to observe transitions from ^{55}Fe, ^{56}Co, ^{55}Co, ^{56}Ni, and ^{53}Fe nuclei.

3. Summary

The EAGLE array was augmented with NEDA detectors, forming the new setup named NEEDLE. The first physics campaign, concentrated on plunger measurements, was conducted successfully and rich data sets were collected, whose analysis is in progress. Successively, the NEEDLE setup was enriched with the DIAMANT light-charged particle detector, further enhancing the selectivity [13].

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