DIAMANT — ON BOARD WITH NEEDLE*

I. Kuti[a], J. Molnár[a], G. Jaworski[b], M. Palacz[b], A. Goasduff[c]
T. Abraham[b], M. Antczak[b], M. Ciemała[d], G. Colucci[b]
A. Fijałkowska[e], J. Grębosz[d], M. Kisieliński[b]
K. Hadyńska-Klęk[b], M. Komorowska[b], M. Kopeć[e], R. Kopik[b]
M. Kowalczyk[b], J. Kowalska[b], A. Krakó[a], B. Kruzsicz[a]
A. Malinowski[e], M. Matuszewski[b], B.M. Nyakó[a], I. Piętka[b]
P. Sekrecka[b], D. Sohler[a], A. Stolarz[b], J. Timár[a]

on behalf of the EAGLE, NEDA, and DIAMANT collaborations

[a]HUN-REN Institute for Nuclear Research (ATOMKI), Debrecen, Hungary
[b]Heavy Ion Laboratory, University of Warsaw, Warszawa, Poland
[c]Legnaro National Laboratories, INFN, Legnaro, Italy
[d]Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
[e]Faculty of Physics, University of Warsaw, Warszawa, Poland

Received 5 December 2023, accepted 10 February 2024, published online 24 April 2024

The DIAMANT 4π light-charged-particle detector array has been recently commissioned at the Heavy Ion Laboratory, University of Warsaw, and began a physics campaign there, for the first time coupled to NEEDLE: EAGLE (central European Array for Gamma Levels Evaluations) and NEDA (NEutron Detector Array) detector systems. Properties of this experimental setup and its performance during commissioning are discussed.

DOI:10.5506/APhysPolBSupp.17.3-A13

1. Introduction

Studies of pattern and properties of excited states in nuclei can reveal exotic, previously not known, nuclear features and phenomena. These excited states are, in most of the cases, studied experimentally with γ-ray spectroscopic methods using nuclear reactions, in which the interaction of the beam and the target could lead to several different reaction channels, producing different final nuclei and emitted light particles. Cross sections for the reaction channels leading to nuclei of interest are often very small, and respective events have to be selected out of the background formed

* Presented at the XXXVII Mazurian Lakes Conference on Physics, Piaski, Poland, 3–9 September, 2023.

by other reaction products. This can be done by requiring coincidences with the particles emitted from the reaction channel of interest. Hence in such experiments, not only sophisticated gamma-detector arrays with high efficiency and granularity are required, but for the best discrimination of various reaction channels, it is crucial that high-efficiency ancillary neutron- and charged-particle detectors are also employed.

2. The DIAMANT detector array

The DIAMANT [1, 2] light-charged-particle detector system has been developed with the major contribution of the HUN-REN Institute for Nuclear Research (ATOMKI, Debrecen, Hungary). DIAMANT has already been coupled successfully to several large γ-detector arrays such as EUROBALL IV [3], EXOGAM [4], and AGATA [5], for many years, in various physics cases, with significant results [6–9]. Recently, the mechanical structure of DIAMANT underwent a major redesign. It has become possible to combine the device with a plunger, in a configuration with only part of the detectors installed, or to use its full geometry version with a pass-through target loader. The front-end electronics were also refurbished and optimised for the digital signal read-out. A general overview of DIAMANT is given below, details of the design, arrangement, and performance will be provided in a forthcoming publication [10].

The array consists of 64 to 96 CsI(Tl) scintillators, depending on the configuration. Each 3 mm thick CsI(Tl) scintillator crystal is coupled to a PIN photodiode via a 5 mm thick optical light guide made of plexiglass, having $> 70\%$ light-collection efficiency. All the detectors are equipped with charge-sensitive preamplifiers working in vacuum. The preamplifiers are mounted on a flexible PCB (FlexiBoard), which provides also a self-supporting structure for the array. The main unit of DIAMANT has a rhombicuboctahedronal shape, where two of the square faces facing each other are empty to let the beam pass through. The FlexiBoard can be unfolded from this quasi-spherical geometry, providing convenient access to the detectors themselves. A separate set of 8 or 24 detectors, called ForwardWall or ChessBoard, respectively, is situated downstream of the main structure, to increase the granularity of the array in the forward direction.

The CsI(Tl) detectors of DIAMANT have an intrinsic particle discrimination capability, based on the different decay time constants of the scintillation lights of the crystals for different particles. The former analogue VXI system of DIAMANT used the ballistic deficit method for discrimination. In the currently used NUMEXO2 digitizers [11], the bipolar and unipolar shapers of the analogue system are replaced by two trapezoidal filters with short and long peaking times, having output values (average amplitude) of

P_s and P_l respectively. The representation of the particle type (particle identification, PID) is defined as 1-P_s/P_l, whereas the energy of the particle is represented by P_l itself. The signal processing is carried out in the FPGA units of NUMEXO2, while the division is taking place offline. In the final data stream, three output parameters are provided: PID, Energy, and Time.

The reaction channels of interest can be unequivocally identified by setting gates on the PID values, or on 2-dimensional distributions of either PID *vs.* energy or PID *vs.* time. Conditions on time also lead to rejection of random events. A typical PID *vs.* energy spectrum is shown in Fig. 1.

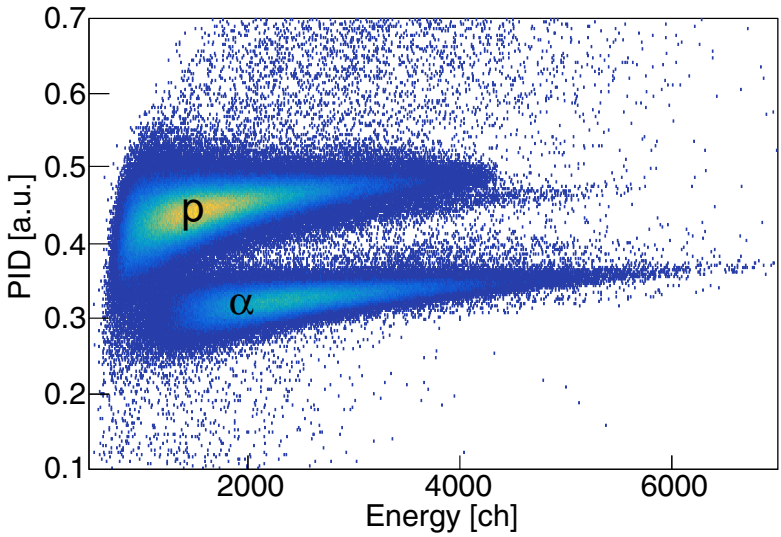


Fig. 1. A typical PID *vs.* energy spectrum of DIAMANT, peaks representing particle types (protons and α particles) are indicated.

3. Physics campaign with DIAMANT

NEDA (NEutron Detector Array), the state-of-the-art aggregate of neutron detectors [12, 13] has recently been installed at the Heavy Ion Laboratory (HIL), University of Warsaw, in connection to the EAGLE (central European Array for Gamma Levels Evaluations) γ-detector array [14]. A first successful experimental campaign with this setup has recently been completed [15]. The device has already proved to be very capable. Nonetheless, due to the nature of the reactions which are used in the proposed experiments, its selectivity can be further enhanced by adding a light-charged particle detector array. Installation of DIAMANT in particular enables a precise selection of the reaction channels in studies of proton-rich nuclei.

The structure of an atomic nucleus, being a complex many-body system, carries a wealth of information on the interplay between collective and single-particle motions. Such an interplay should be manifested in the excited states of ^{57}Cu — an important waiting point in the rp-process — due to its one valence proton outside the relatively soft $N = Z = 28$ core. The gamma-ray spectroscopy study of the excited states of this nucleus is a flagship example of an experiment possible only with a setup like EAGLE–NEDA–DIAMANT. Relatively limited experimental data for ^{57}Cu are available in the literature so far. The ground-state spin of ^{57}Cu has been determined in a β-decay work [16], while the lowest excited states were identified in γ-ray spectroscopy measurements [17, 18]. The study is aiming at the identification of the single-proton shell-model states as well as $N = Z = 28$ core excitations in this one-valence-proton neighbour of the doubly-magic ^{56}Ni. An unambiguous assignment of newly observed γ rays to ^{57}Cu will be possible based on the analysis of spectra created with various combined DIAMANT–NEDA gates.

Physics case of ^{57}Cu was chosen as the first experiment of the campaign. The same reaction was also used in part of the commissioning of the new EAGLE–NEDA–DIAMANT setup.

3.1. Commissioning

The 82 MeV ^{32}S beam provided by the U-200P cyclotron at the Heavy Ion Laboratory, University of Warsaw was used to bombard two targets. Besides a ^{28}Si target with a thickness of 3.2 mg/cm^2 on Au backing, a ^{27}Al target with a thickness of 4 mg/cm^2 was also used. Gamma rays were detected with the 15 anti-Compton shielded (ACS) Ge detectors of the EAGLE detector system. Light-charged particles were detected by the 8-segment Forward-Wall detector set of DIAMANT. The ancillary setup was completed with 52 detectors of the state-of-the-art NEDA neutron multiplicity filter. The experimental setup is shown in Fig. 2. In the forthcoming physics campaign, the 64-segment FlexiBoard of DIAMANT will also be used.

The reaction channels were identified by setting conditions on the two-dimensional PID *vs.* energy distributions of DIAMANT. Examples of gated γ-ray spectra from the reaction ^{32}S+^{27}Al are presented in Fig. 3.

Comparing the ungated spectrum and the gated spectra in Fig. 3, it can be clearly seen that using the particle gates of DIAMANT considerably reduces the contaminating peaks of other reaction channels.

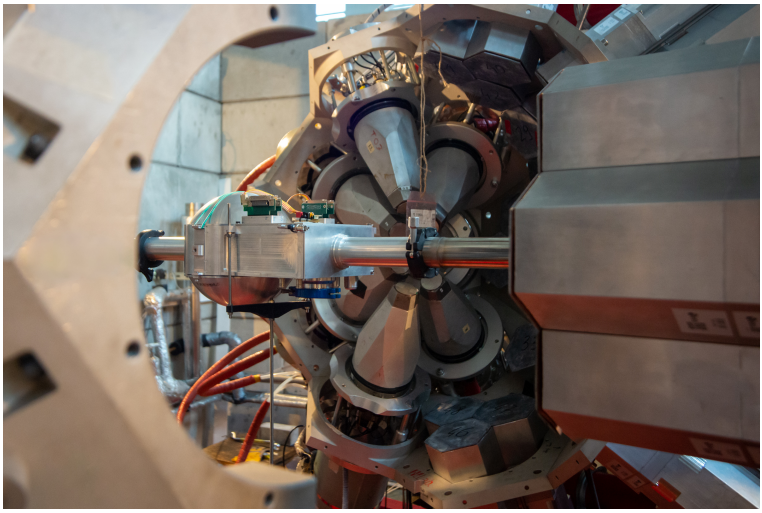


Fig. 2. The EAGLE–NEDA–DIAMANT setup, installed at the beamline of the cyclotron at HIL. From left to right: the reaction chamber with the DIAMANT detector array inside, EAGLE detectors, NEDA array.

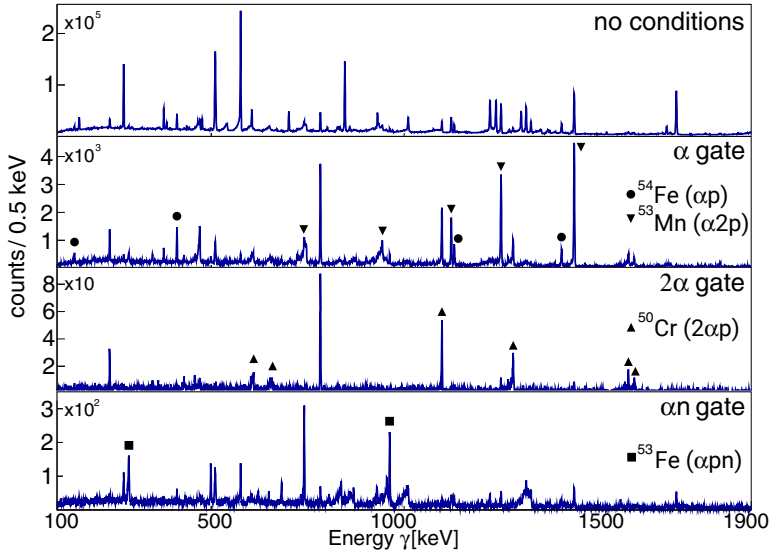


Fig. 3. Effects of conditions on charged particles and neutrons. From top to bottom: no condition; requirement of one and two α particle detected in DIAMANT; requirement of one α particle detected in DIAMANT and at least one neutron detected in NEDA.

4. Summary

The DIAMANT light-charged-particle detector was coupled to the EAGLE and NEDA detector systems for the first time. For the commissioning as well as the first experiment, the physics case of ^{57}Cu had been chosen, aiming to study the delicate balance between the individual and collective motions in the atomic nucleus.

This work was supported by the National Research, Development and Innovation Fund of Hungary (NKFIH), financed by the project with contract No. TKP2021-NKTA-42 and under the K18 funding scheme with project No. K128947. The installation and use of NEDA at HIL are supported by the National Science Centre (NCN), Poland (grant No. 2020/39/D/ST2/00466). Authors acknowledge the support of the International Visegrad Fund under project No. 62320200. The project has received funding from the European Union's Horizon Europe Research and Innovation programme under grant agreement No. 101057511 (EURO-LABS). The use of germanium detectors from GAMMAPOOL is acknowledged.

REFERENCES

[1] J. Sheurer *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **385**, 501 (1997).
[2] J. Gál *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **516**, 502 (2004).
[3] J. Simpson, *Z. Phys. A* **358**, 139 (1997).
[4] J. Simpson *et al.*, *Acta Phys. Hung. A* **11**, 159 (2000).
[5] E. Clément *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **855**, 1 (2017).
[6] J. Timár *et al.*, *Phys. Rev. Lett.* **122**, 062501 (2019).
[7] B. Cederwall *et al.*, *Nature* **469**, 68 (2011).
[8] A. Ertoprak *et al.*, *Eur. Phys. J. A* **56**, 291 (2020).
[9] B. Cederwall *et al.*, *Phys. Rev. Lett.* **124**, 062501 (2020).
[10] I. Kuti *et al.*, in preparation.
[11] F.J. Egea-Canet *et al.*, *IEEE Trans. Nucl. Sci.* **62**, 1056 (2015).
[12] J.J. Valiente-Dobon *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **927**, 81 (2019).
[13] G. Jaworski *et al.*, *Acta Phys. Pol. B* **50**, 585 (2019).
[14] J. Mierzejewski *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **659**, 84 (2011).
[15] G. Jaworski, *Acta Phys. Pol. B Proc. Suppl.* **17**, 3-A12 (2024), this issue.
[16] D.J. Vieira *et al.*, *Phys. Lett. B* **60**, 261 (1976).
[17] D. Kahl *et al.*, *Phys. Lett. B* **797**, 134803 (2019).
[18] X.G. Zhou *et al.*, *Phys. Rev. C* **53**, 982 (1996).