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Review Article **Open Access**

ARIEL & SANDA nuclear data activities

Carola Franzen[1], Arnd R. Junghans[1]*, Enrique M. Gonzalez[2], and Arjan J. M. Plompen[3]

[1] Helmholtz-Zentrum Dresden – Rossendorf, Bautzner Landstrasse 400, 01328 Dresden, Germany
[2] Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Avda. Complutense, 40, 28040 Madrid, Spain
[3] European Commission, Joint Research Centre – JRC, Retieseweg 111, 2440 Geel, Belgium

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Abstract. Nuclear data are fundamental quantities for developing nuclear energy concepts and research. They are essential for the simulation of nuclear systems, safety and performance calculations, and reactor instrumentation. Nuclear data improvement requires a combination of many different know-hows that are distributed over many institutions along Europe. In the EURATOM call for Nuclear Fission and Radiation Protection NFRP-2018, two nuclear data projects were started in September 2019: the Coordination and Support Action ARIEL (Accelerator and Research reactor Infrastructures for Education and Learning) and the Research and Innovation Action SANDA (Solving Challenges in Nuclear Data for the Safety of European Nuclear facilities). The ARIEL project integrates education and training of young scientists and technicians with access to neutron beam research infrastructures and supports scientific visits to conduct short-term research projects relevant to thesis works. The SANDA project is focuses on research innovation actions, including detector and nuclear target development, important nuclear data measurements, nuclear data evaluation, and validation. A description of these ongoing projects, including the first results, is the subject of this article.

1 Introduction

Nuclear data are the fundamental base for developing all nuclear technologies, whether for nuclear energy, nuclear waste management, or other applications, e.g., in the medical sector. For the safety assessment of current and future advanced nuclear systems, particle transport calculations that simulate realistically the ongoing nuclear and atomic processes play a crucial role. Building prototype reactors and performing test experiments is extremely costly and time-consuming. Detailed and accurate simulations are the most relevant methodology for the cost-effective design of new concepts. They are relevant for designing, optimizing, and interpreting critical experimental tests and validations and thereby pave the way to efficient deployment. They are used for determining system behavior in various possible configurations and running conditions and allow selecting progressively between different technological options using only a limited number of experimental validations and prototypes. High-quality nuclear data, in particular complete and accurate information about the nuclear reactions taking place in nuclear systems, are an essential component of such modeling capabilities. The quality of a simulation depends on many aspects, but a significant uncertainty component is associated with the quality of nuclear data. No simulation or interpretation of measurements can be better than the limit imposed by the nuclear data. Several parameters, particularly safety parameters of reactors and other nuclear facilities, need to be known with a precision well below 0.1% resulting in nuclear data precisions better than a few percent, sometimes below 2%. In other cases, the precision needed can range from ca. 5–20%, but the isotope or material under investigation is radioactive or scarce. The advent of multi-physics simulations is also a challenge for the basic nuclear data required [1]. Nuclear data research has still not reached these levels of precision in all cases. The quality and completeness of the nuclear databases are continuously improving thanks to EURATOM-supported research projects in many framework programs (FP5, FP6, FP7, Horizon 2020, and Horizon Europe). The nuclear databases consist of numerous nuclear reaction data like cross sections of neutron-induced nuclear reactions, particle emission probabilities, as well as nuclear structure properties of the ground and excited states, e.g., masses, decay half-lives, level energies, and branching ratios, to name a few. Producing these nuclear data is a complex and lengthy process that relies on access to modern neutron beam facilities and highly-trained nuclear physicists. The nuclear data path to an

* e-mail: a.junghans@hzdr.de

evaluated complete nuclear data library requires work from many experts: measurements with neutron beams, production of radioactive actinide samples, data evaluations to create a consistent and complete nuclear data library, validation of the library with benchmarks, and integral experiments, finally inclusion of the nuclear data into the simulation codes.

Present-day nuclear data measurement activities follow the demands of the nuclear industry and research laboratories for complete and evaluated data files on neutron-induced nuclear reactions. On the European level, these data files are maintained by the OECD/NEA databank, which manages the Joint Evaluated Fission and Fusion File (JEFF). The experimental needs are prioritized on an international level by the Working Party for Evaluation Co-operation (WPEC) of the OECD/NEA Nuclear Science Committee. To prioritize research needs for improving the database to match the requirements for the development of advanced nuclear energy systems, a subgroup of the WPEC performed a comprehensive sensitivity study assessing the impact of uncertainties in the nuclear database on the modeling of a series of selected innovative systems which are presently under development. The most important requests for improvements in the nuclear data files are being collected in the High-Priority Request List (HPRL) of the NEA.

The best experimental data are collected internationally in the EXFOR database maintained as an open source of reliable information by the IAEA. Once the data are analyzed and evaluated, they are stored as ENDF libraries, also maintained by IAEA, NEA, and some worldwide laboratories, ready to be used for research and commercial applications from open repositories. The corresponding database for decay and structure data is ENSDF, and it is also maintained in an open platform with support from the IAEA and national nuclear data centers. All the results from EURATOM projects are introduced into these three databases that provide an excellent storage and dissemination tool both at EC and worldwide nuclear data research and user communities.

1.1 ARIEL (Accelerator and Research reactor Infrastructures for Education and Learning)

Integration of access to neutron facilities with education and training

Transnational access to European research facilities for nuclear data measurements, nuclear technology development, and nuclear engineering has been a valuable and successful activity in applied nuclear research through many EURATOM-supported projects. In the Framework program FP6, the EFNUDAT project (2006−2010) started with a transnational access consortium of 9 partners; in the project ERINDA (2010−2013) of FP7, the consortium had grown to 13 partners, while in the TAA activity of CHANDA (2013−2018) 16 partners out of 35 participated. The JRC neutron facilities in Geel took part in these projects while maintaining their own successful access schemes of NUDAME and EUFRAT.

An active league of nuclear data facilities in Europe has been formed. It is the objective of ARIEL to support transnational access of scientists and technical staff to these facilities on the national and transnational levels for training, education, and competence building. Many young scientists found jobs in the energy industry, medical physics, or in the state or federal governing administration for nuclear power, waste management, radiation protection, and the environment.

The ARIEL project combines the most modern and state-of-the-art European neutron beam laboratories using the full range of neutron sources from high-energy proton synchrotrons to research reactors. Experiments in international teams at these facilities provide hands-on training for students at the master, graduate, and postgraduate levels leading to PhD and master theses, as well as postdoctoral competence building. Based on the experience from the earlier projects, now technical staff, e.g., accelerator operators or research engineers, are able to participate fully in the training activities planned in ARIEL facilities.

To make the transnational access to these facilities most attractive for early stage researchers, the spectrum of research activities offered has been widened and includes nuclear data measurements and evaluation, radiation detector development, integral experiments of reactor parameters, material irradiation & nuclear data for isotope production, fundamental nuclear physics, medical applications, neutron imaging, and radiochemical experiments.

Twenty-six partners from 15 European countries are working together for the education and training of a new generation of young scientists and technical staff. The ARIEL project provides:

- transnational access to state-of-the-art neutron facilities,
- training of early-stage researchers through scientific visits,
- four schools for students to increase attractivity at the university level,
- three scientific workshops and progress meetings.

The ARIEL consortium provides access to research infrastructures with neutron beams in a large parameter range from cold and thermal neutron beams with meV energy to multi-MeV fast neutron beams, see Figure 1. The neutron sources can be grouped into four categories:

- time-of-flight facilities for fast neutrons GELINA (JRC-Geel), nELBE (HZDR, Dresden), NFS (GANIL, Caen), n_TOF (CERN, Geneva),
- charged-particle accelerators producing quasi monoenergetic neutron beams at Bordeaux, Orsay, Grenoble, Bruyères-le-Châtel, Frascati, Sevilla, Uppsala, and Bucharest,
- neutron reference fields at PTB Braunschweig, NPL Teddington and IRSN Cadarache,
- research reactor facilities at Budapest, Mol, Mainz, Řež, and Grenoble.

The consortium has several new or upgraded facilities: the Neutrons for Science facility (NFS) at GANIL, Caen, is

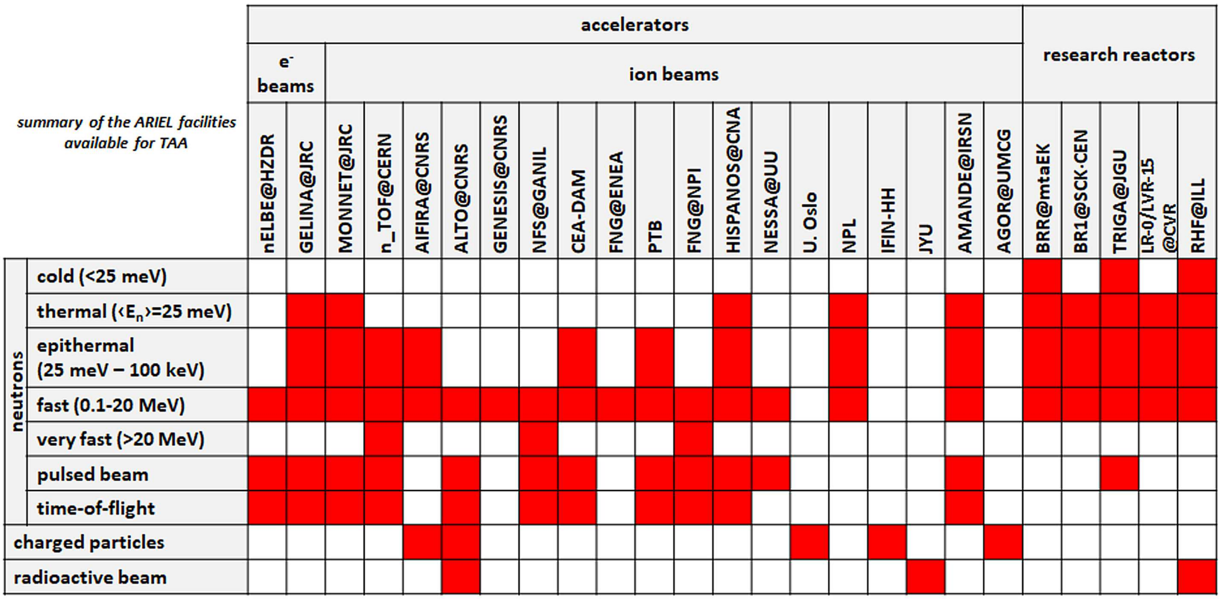

Fig. 1. Neutron and ion beams available at the ARIEL research facilities.

the first operational area at the SPIRAL-2 LINAC [2]. It provides high-intensity fast neutron beams up 40 MeV using a deuteron beam on a thick converter target with a maximum source strength of up to 1.8×10^{13} n/s using a 4−30 m flight path. Quasi mono-energetic neutron beams up to 31 MeV can be produced using protons on a thin lithium converter. In addition to time-of-flight measurements, irradiation stations for neutron beams and ion-induced reactions (protons 2−33 MeV, deuterons, helium 2−20 MeV/u) are available in the NFS converter room. The NFS facility has an excellent energy resolution due to the short pulse length of the SPIRAL-2 LINAC and compact converter target. The background due to the instantaneous gamma-flash from the neutron-producing reactions is less intense than at photoneutron or spallation sources. First experiments on neutron-induced light charged particle production, e.g., ^{16}O(n,α), fast neutron-induced fission and neutron emission (n,f), (n,xn) with radioactive samples and fission fragment spectroscopy with the FALSTAFF spectrometer are ongoing. The development of the SCONE detector for (n,xn) reactions is supported by SANDA.

After the long-shutdown LS2 of CERN, the n_TOF facility became operational again in April 2022. A new nitrogen gas-cooled spallation target with a water-moderated spectrum and optimized beam intensity and energy resolution for the two experimental areas has been built and performs as predicted. In addition, a near station (close to the spallation target) has been built for long-term irradiation up to 1 MGy/year and material research and activation measurements in mixed fields. The physics program at n_TOF for the year 2022 includes important nuclear data measurements that are supported by SANDA and ARIEL: The measurement of the ^{239}Pu(n,γ) cross section and capture to fission ratio in the resolved resonance range with high resolution using dedicated thin and thick ^{239}Pu targets produced at JRC-Geel is prepared for the autumn of this year. The setup consists of a fission chamber with 10 deposits inside the 4π BaF_2 total absorption calorimeter at the long flight path EAR1.

At the accelerator laboratory of the University of Jyväskylä, a new Multi-Reflection Time-of-Flight Mass Separator has been built to allow separating and identifying isobars from proton-induced fission at the IGISOL-4 facility for mass measurements and decay studies [3]. Fission fragment isomeric yields studies and the improvement of the IGISOL setup are supported by the SANDA project.

A total of 3000 h of additional beam time for external users will be provided by the ARIEL project. This corresponds to 30 typical experiments. Up to 4 users with a preference for early-stage researchers not more than 6 years after the PhD can be supported to work in these experiments.

The education and training of young scientists will be supported by scientific visits at the participating institutes, typically 8 weeks up to 12 weeks duration. In total, 30 visits will be organized. Early-stage researchers and short-term visitors will be able to work within the full spectrum of experimental capacities of the consortium resulting in a high potential for competence building. These activities are meant to support student graduate education, train engineers and technicians or share knowledge between facilities by visits of experienced researchers. IAEA, NEA has expressed interest in participating in this activity.

The transnational access and education and training activities are based on a semi-annual call for proposals that is peer-reviewed by a Project Advisory board consisting of 5 external experts. The selection will be based on scientific excellence and value to education and training through the participation of early-stage researchers.

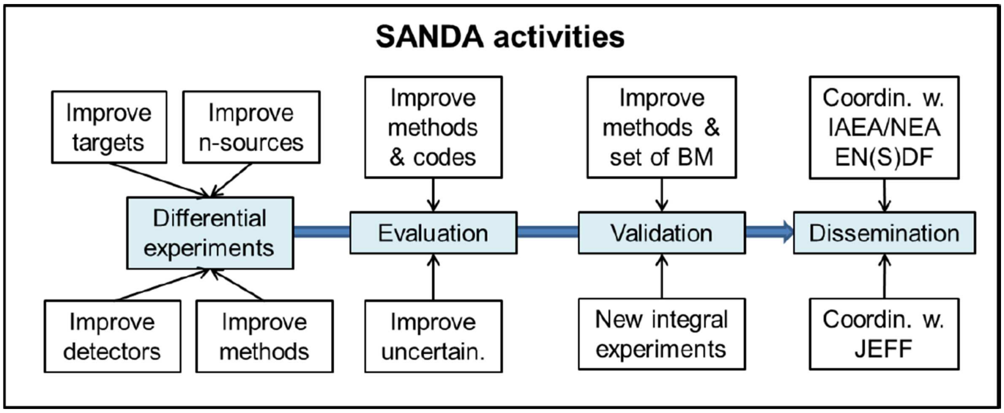

Fig. 2. SANDA activities and objectives on the full nuclear data cycle.

The strategic value shall be determined along the following list:

- focus on nuclear safety and support to modeling and evaluation (e.g., for advanced development for MYRRHA, molten salt reactors, spent fuel concepts, and decommissioning).
- Research experience for early-stage researchers with advanced techniques for radiation measurements, testing, and development of novel detector concepts. Transfer and exchange of knowledge and methodologies for senior scientists and technical staff.
- Coordination with research initiatives from ongoing EURATOM projects related to nuclear data (e.g., High precision nuclear data for the major actinides present in advanced reactor fuels).
- Coordination with OECD/NEA (High Priority Request list, JEFF, NEST), the IAEA International Nuclear Data Evaluation Network (INDEN), and European Technological Platforms.

Education and training activities will be complemented by four schools to attract students to the nuclear data field. The schools cover theoretical lectures and practical hands-on laboratory exercises on all aspects of the nuclear data path from experiment to the end-use in applications. They are held at consortium laboratories with an excellent background in providing these courses to early-stage researchers and graduate and postgraduate students. The course duration is one to two weeks. The target group here is any young European scientists or engineers. Cooperation with ENEN will allow advertising these courses to a wider research community.

Four schools are organized by the partners in Madrid, Seville, Uppsala, and Mainz:

- international online school on nuclear data: the path from the detector to the reactor calculation, CIEMAT, Madrid (24 participants) February 22 – March 4, 2022 [4].
- Hands-on school on the production, detection, and use of neutron beams, University of Seville (18−24 participants) September 2022.
- EXTEND'2023 summer school at Uppsala University (20−25 participants) June 2023.
- Lab course in Reactor Operation and Nuclear Chemistry, University of Mainz (10 participants) October 2023.

The scientific results are disseminated in four scientific meetings. The kick-off meeting was organized by HZDR, the first progress meeting and scientific workshop by JRC Geel, the second by NPL, and the final scientific workshop by IPN Orsay. The first ARIEL progress meeting [5] was part of the Joint ARIEL-SANDA meeting in March 2022 to maximize the networking between the two communities with a turnout of 89 registered participants.

1.2 SANDA

The SANDA project unites most of the European nuclear data community, infrastructures (35 partners from 19 countries), and resources. The main goals are to improve and develop experiments determining microscopic nuclear data (differential experiments), nuclear data evaluation, and validation to the very high level required to comply with the needs for safety standards mandatory for present and future European nuclear reactors and other installations using radioactive materials, see Figure 2. The selection of activities has been made considering the relevance, expected impact, and priorities of the resulting data according to the NEA/OECD and IAEA high priority lists. The impact has been evaluated from the perspective of safe, efficient, and competitive use of nuclear technologies.

Improving detectors. For nuclear data improvements, measurements and experiments need to be improved. To make progress beyond the state of the art, advanced detector and data acquisition systems need to be developed that will be used in new measurements for energy and non-energy applications. In particular, equipment is required which allows high precision measurements for the major actinides and the new nuclides present in advanced reactor fuels and fuel cycles (e.g., closed fuel cycles). In SANDA, new equipment and nuclear targets will be developed, and equipment and nuclear targets constructed during the previous CHANDA project will be used in new measurements.

The innovative detector developments address improving the experimental determination of:

- actinide fission cross sections to improve modeling of new fast reactor systems;
- fission yields and radioactive decay data to improve spent fuel heat, dose rate, and β-delayed neutron yield estimates;
- (n, xn) reaction cross sections to improve fast neutron flux distributions in new (fast) reactors. This includes the development of fast neutron spectrometers based on organic single crystals for neutron flux measurements with gamma-ray discrimination in complex environments and the development of a plastic detector array with a large solid angle for (n, xn) (e.g., ^{239}Pu(n, xn)) reaction studies at NFS;
- radiative neutron capture cross sections for actinides. This implies developing detectors that work well under high background conditions. (i-TED and Cs2LiYCl6:Ce (CLYC) inorganic scintillators);
- neutron-induced light charged particle emission cross sections and yields. A Si-detector-based $\Delta E{-}E$ telescope is under development at multi-MeV neutron energies where these reactions can cause secondary dose e.g., in proton therapy.

Nuclear data measurements. New nuclear data are determined by the measurement of the

- average neutron multiplicity of ^{235}U(n, f) and the fission cross sections of the ^{230}Th(n, f), ^{241}Am(n, f) and ^{239}Pu(n, f) reactions;
- neutron capture cross sections of the ^{239}Pu(n, γ) and ^{92,94,95}Mo(n, γ) reactions;
- neutron elastic and inelastic scattering and neutron multiplication cross sections for the nuclides ^{14}N,^{35,37}Cl, ^{209}Bi, ^{233}U, ^{238}U, and ^{239}Pu;
- decay data of ^{95}Rb, $^{100\mathrm{gs}}$Nb, $^{102\mathrm{m}}$Nb, ^{103}Tc, ^{140}Cs with Total Absorption Gamma-ray spectrometry and of ^{106}Ru, ^{153}Sm, ^{166}Ho, ^{186}Re, ^{212}Pb, ^{225}Ac, and ^{223}Ra half-lives and branching ratios for reactor and medical applications;
- fission yields and related distributions from neutron-induced fission of ^{235}U at LOHENGRIN (ILL) and PI-ICR at IGISOL and $(p, 2p)$ inverse kinematics fission reactions for ^{238}U and ^{237}Pa;
- spectrum-averaged cross sections for the ^{117}Sn(n,inl)$^{117\mathrm{m}}$Sn and ^{60}Ni(n, p) reactions in a ^{252}Cf spectrum for dosimetry, ^{12}C double differential cross sections relevant for hadron therapy and the production cross sections of $\beta+$ emitters ^{11}C, ^{13}N, ^{15}O, ^{30}P for proton-induced reactions up to 250 MeV energy (non-energy applications);

Nuclear targets. The demand for high-quality targets, specially designed for the envisaged experiments and targets manufactured for nuclear reaction studies in a wide variety of application fields is constantly increasing, with the production of radioactive samples comprising particular challenges due to the special requirements arising from the emitted radiation. Only a handful of laboratories in Europe are capable and equipped to address these special requirements. In SANDA, the target production for the nuclear data community is structured so that resources and knowledge are shared, and requested targets can be produced and used efficiently for the project. A special feature is the development of an isotope separator allowing the production of rare, isotopically enriched targets for which stock material is not available otherwise.

Evaluation of nuclear data. Nuclear data evaluation aims to obtain a complete and consistent set of nuclear data files, such as those of the JEFF library, which can be used for modeling applications. Such files are delivered in a format readily processed into the data files used by a broad set of simulation tools. The SANDA project aims at contributing to nuclear data evaluation for international data libraries, such as JEFF, by

- developing open-source evaluation codes with improved phenomenological and microscopic models (those of the TALYS and EMPIRE codes for reaction nuclear data, dedicated codes for decay and structure data, as well as codes modeling the fission process to determine yields and spectra);
- performing evaluations of neutron-induced reaction data of actinides and fission products;
- providing processed data ready for use by simulation codes;
- providing sensitivity vectors for uncertainty quantification and sensitivity analysis;
- recommending benchmarks for the validation of the new evaluations against a wider suite of integral parameters, thereby aiming at a true general-purpose library;

Validation of nuclear data. The evaluated nuclear data are subject to a validation process, where experimental data, e.g., from benchmarks and integral experiments, are compared with realistic simulations using different evaluated nuclear data sets. Impact studies of data and uncertainties aim at relating nuclear data improvements to the needs dictated by their end-use in selected applications. SANDA includes the performance of new validation experiments in existing experimental facilities. The validation work comprises

- sensitivity analyses, impact studies, and uncertainty estimates for the following selected systems: ESFR/ASTRID, MYRRHA, JHR, LWR; MSR and waste management;
- validation studies for the above applications using the relevant experiments from the IRPhE, ICSBEP, SINBAD, and SFCOMPO databases of the OECD-NEA;
- new validation experiments at GELINA, LR-0, and TAPIRO and determining the needs for new integral data;

2 Impact and outlook for the nuclear data field

The two projects SANDA and ARIEL focus on the improvement and availability of precise nuclear data, including all required activities from the experiment to the final nuclear data library. In addition, ARIEL has an important focus on competence development, in particular of young researchers. As ARIEL and SANDA are still ongoing projects, delayed significantly by COVID, only a fraction of all planned activities have been completed. A short discussion is presented below.

Experiments at the consortium facilities will lead to a better knowledge of nuclear reaction cross-sections in the full energy interval of relevance to existing and future nuclear facilities, as well as for certain aspects of non-energy applications. The safety assessment of innovative nuclear technologies, e.g., accelerator-driven systems or reactors using a fast neutron spectrum, also depends on accurate nuclear data to be used in the respective numerical simulations. Data measured at the ARIEL facilities can be relevant for several activities in the current EURATOM work program, e.g., the GEN IV safety validation and radiation protection research and the current intensive research into small modular reactors.

Young scientists will develop multi-disciplinary and nuclear competencies through the research projects of ARIEL and SANDA, leading to PhD and master theses. Access to high-quality neutron beam facilities through experiments and education and training visits will lead to increased availability of experts and researchers for nuclear safety, radiation protection, and radioactive waste management.

The EURATOM-supported research is of special value as it forms a scientific community distributed over many countries with a strong exchange of people and knowledge to help develop science-based solutions in the different local energy sectors and the national energy policies.

2.1 Impact of ARIEL

The transnational access to neutron beam facilities in ARIEL has received 21 proposals in the first four calls, out of which 15 were endorsed by the PAC, and 6 experiments were already completed. This implies that 1265 beam time hours are committed (of 3000), and 596 h have been delivered up to now.

The completed experiments are:

- the response matrix of stilbene and p-terphenyl, including pulse shape discrimination, was investigated at PTB Braunschweig by M. Kostal et al., Rez.
- The light yield and energy resolution for fast neutrons of the scintillator CLYC-7 with 99% enriched ^{7}Li were measured at HISPANOS, CAN Seville, in a remotely controlled experiment by M. Nocente et al., ISTP-CNR Milano with dd − neutrons and ^{9}Be(d, n) neutron spectra.
- The response function and absolute calibration of a stilbene compact fast neutron spectrometer have been determined at PTB Braunschweig by A. Sardet et al., Cadarache with 2.5 MeV neutrons (ISO neutron energy, pT reaction) and with a time of flight spectra from the cyclotron d+^{9}Be continuous energy neutron source reaction. The data acquisition was remotely controlled by the users during the experiment.
- The Medley setup was used to measure double differential cross sections for light ion production on carbon at the new Neutrons for Science facility at GANIL by A. Prokofiev et al., Uppsala.
- A fiber -mounted scintillation neutron detector for measuring scalar flux and gradient was calibrated in the BR1 reactor in Mol by Imre Pazsit et al., Göteborg.
- The plasma delay effect on the timing of PIPS silicon detectors was measured at the ILL Lohengrin fission fragment spectrometer by A. Al-Adili et al., Uppsala.

For education and training activities, 16 proposals were submitted and endorsed in the first four calls amounting to 119 weeks of stay. Eight visits already took place even during pandemic conditions. The completed E & T activities are:

- the OPEN-CL framework was used to optimize data acquisition algorithms for fast Digitizer FPGA signal processing to be faster than external CPU processing by M. Astrain from Universidad Politecnica de Madrid visiting HZDR, Dresden.
- The VERDI fission fragment spectrometer was reassembled with new preamplifiers and new digital DAQ systems, and a two-arm measurement of ^{252}Cf (sf) will be prepared by A. Gomez Londoño, Zhihao Gao, and A. Al-Adili, Uppsala visiting JRC, Geel.
- The fine structure in the prompt fission neutron angular distribution with respect to the fission axis of ^{235}U$(n_{\rm th}, f)$ was theoretically investigated by N. Carjan, Bucharest, visiting JRC, Geel.
- The neutron capture of ^{103}Rh was measured at the GELINA 12 m measurement station, and ^{241}Am(n, γ) time-of-flight data in the resolved resonance region were analyzed, and resonance parameters were determined by A. Oprea, Bucharest, visiting JRC Geel.
- The simulation of the proton recoil telescope for the ^{235}U(n, f) cross section measurement relative to ^{1}H(n, n)p at n_TOF was completed by Q. Ducasse, Cadarache visiting PTB Braunschweig. The results are relevant for SANDA subtask 2.6.2.
- The ^{155,157}Gd resonance parameters were determined from transmission and capture measurements at GELINA, and a transmission measurement of Mo was prepared by R. Mucciola, Perugia, visiting JRC Geel.
- The feasibility of fast neutron-induced reaction measurements with a laser-driven neutron source of the DRACO Laser at HZDR, Dresden, was determined by M. Millán Callado, Seville.

The transnational access to neutron beam facilities and education and training activities were partially delayed due to the pandemic conditions. For the final three calls of the project until February 2024, about 15 new experiments with 1735 h of beam time can be supported. This year CERN n_TOF and NFS at GANIL are operational and should be able to receive support from ARIEL for nuclear data research.

Results from completed activities

A long-standing problem at pulsed radiation sources, like neutron time-of-flight facilities, is the occurrence of a high-intensity burst of gamma-rays and particles close to the

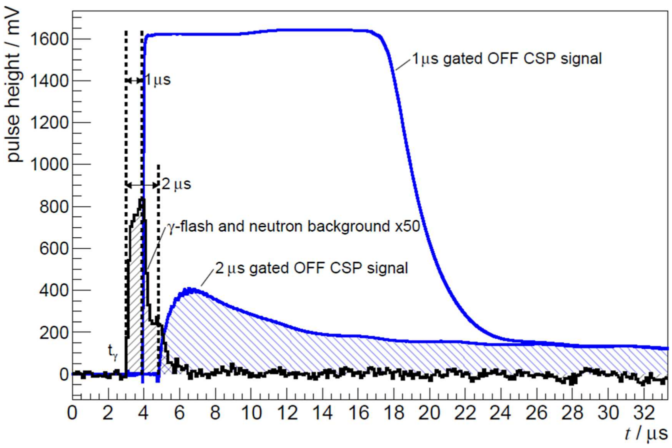

Fig. 3. Averaged Frisch Grid Ionization Chamber (DFGIC) anode signal traces from a detector test at CERN N_TOF EAR2. The directly measured detector current (without using a preamplifier) is depicted as black hatched line. It contains the gamma-flash superimposed with neutron-induced background. The γ-flash starts at $t = 3\,\mu s$. The charge-sensitive preamplifier has a short decay shaping time of $3\,\mu s$. The preamplifier signals are shown in blue with two different gate lengths ($1\,\mu s$ and $2\,\mu s$) for gamma-flash, for gating off the signals by the switch. The $1\,\mu s$ gated off preamplifier signal is saturated for about $15\,\mu s$. The $2\,\mu s$ gated off preamplifier signal (hatched area) has no more saturation. (Figure courtesy S. Urlass, PhD thesis TU Dresden, 2022).

speed of light, which saturates the detection setups meant for the detection of neutrons that arrive only a few tens to 100 ns after. A novel switch circuit was developed to connect the detector output to the ground and, therefore, effectively drain the charge while the detector is saturated with the high-intensity gamma-flash. After the burst and before the first neutrons arrive, the switch connects within a few ns time the detector input to the charge-sensitive preamplifier, and later arriving particles can be detected. A combination of this switch with a charge-sensitive preamplifier can be used to extend the usable neutron energy range at facilities that have a high instantaneous intensity, e.g., spallation sources [6].

Figure 3 shows a Frisch Grid Ionization chamber signal at n_TOF@CERN that is saturated from the gamma-flash for up to 20 ms if the detector is not gated off during the charge collection time related to the gamma-flash.

The production and detection of neutrons at the Peta-Watt LASER facility DRACO at HZDR, Dresden, was investigated using neutrons produced on different pitcher-catcher target assemblies consisting of Cu or LiF. Short, intense pulses of protons or deuterons accelerated up to 60 MeV were created by laser shots of the DRACO laser (30 J, 30 fs) on pitcher targets using the TSNA acceleration mechanism [7]. These ions created neutrons in nuclear reactions in the catcher targets of copper and LiF. A neutron intensity of the order of 10^8 n/shot was reached. In total, about 1200 laser shots were used to systematically study neutron production with different types of detectors. For example, with a thick single crystal diamond detector, a single event time-of-flight spectrum was recorded, see Figure 4.

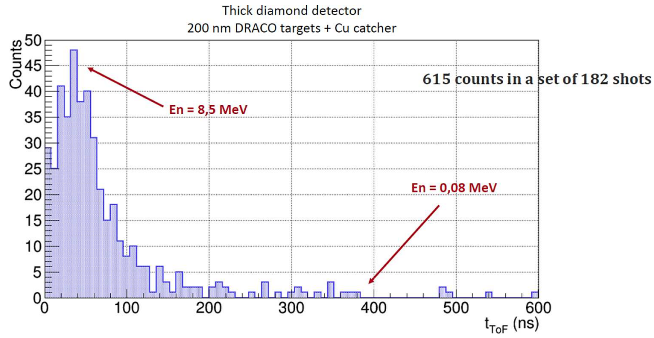

Fig. 4. Single particle neutron time-of-flight spectrum measured with the DRACO PW Laser using 182 laser shots. The flight path from the catcher target to the diamond detector was 145 cm. (Courtesy M. Millan Callado PhD thesis in preparation, Univ. of Seville, 2022).

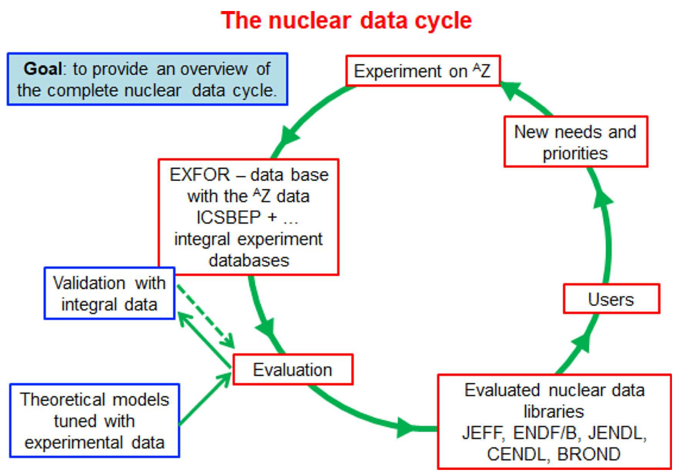

Fig. 5. The nuclear data cycle. All aspects were discussed in supervised online courses in small groups in the Nudatapath school organized by CIEMAT. (Courtesy: Daniel Cano-Ott, CIEMAT).

The International online school on nuclear data: the path from the detector to the reactor calculation was a virtual course on all topics of the nuclear data cycle, see Figure 5. Groups of 4–5 participants worked in supervised groups online with specially developed tools. Hands-on lectures with computer tools developed for this school included: sensitivity analysis of nuclear data for thermal and fast reactors, neutron reaction calculator of transmission, capture and fission experiments simulating experimental effects and backgrounds, visualization and processing of nuclear data, validation with integral experiments and simulations. The hands-on lectures were accompanied by introductory and overview online lectures.

2.2 Impact of SANDA

SANDA, as proposed, has made the most efforts and got achievements mainly on the developments of new innovative detector devices, differential measurements, and target preparation, initiating the work on data evaluation and validation with integral experiments.

Large achievements on new detectors for fission include the experimental validation of a new Gaseous Proton Recoil Telescope, the simulation, and calibration of FALSTAFF-FIPPS (Milestone MS1), the design and test with sources of the new 4pi-neutron detector BRIKEN, the design and test of other neutron detectors (Stilbene, SCONE) and the test of the new facility for measurements of half-lives at CEA/DRT/LNE-LNHB. In addition, large progress has been made for gamma detectors, including new electronics and tests for HPGe at n_TOF and the construction and tests of the sTED and validation of i-TED for n_TOF (EAR2). Attention is also being devoted to detectors for non-energy applications (DDX data for the n-induced emission of light-charged particles).

As for target preparation, the first set of samples has been identified, and the preparation of these targets started. Additionally, the design and simulations of beam optics for developing an isotope separator (IS) have been achieved, and the preparation of the site for the IS at PSI has also started. This device will become a key element to allow important measurements once operative.

SANDA is also preparing and performing new nuclear data measurements, including:

- data have already been taken and partly analyzed at n_TOF for neutron-induced fission cross sections of ^{235}U, ^{230}Th, ^{241}Am, and ^{239}Pu, and nubar data taken at MONNET@JRC-Geel.
- Key detectors (MEDLEY, SCALP) have been moved to NFS for in beam tests and measuring ^{16}O(n,α) and $^{\rm nat}$C(n,chp) and other (n,chp) reactions (chp – charged particle).
- Construction of the fission tagging chamber for the ^{239}Pu(n,γ) and preparation of Mo(n,γ) reactions to being measured at GELINA and n_TOF.
- New data taking and analysis of the ^{238}U(n,inel) reaction is completed; see reference [8], and new data taken for ^{233}U(n,inel), ^{209}Bi(n,γ) and ^{209}Bi(n,tot).
- Improved analysis methods have been developed with better results for decay data taken with DTAS – the segmented total absorption gamma-ray spectrometer [9].
- Preparation of fission yield measurements for ^{235}U at ILL with LOHENGRIN and a new methodology for the evaluation of the database of thermal neutron-induced fission yields.
- For non-energy applications: data for dosimetry have been measured and analyzed (^{117}Sn(n,inl)$^{117\rm m}$Sn), and the measurement of production and analysis of long-lived beta+ emitters (^{11}C and ^{13}N) is also done.

For most of the other experiments proposed, the simulation and some tests with radioactive sources have already been done.

In parallel, great efforts are being applied to improve processing and sensitivity calculations that have already helped to improve JEFF3.3. Work for new evaluations is ongoing, already resulting in a new version of the GEF model [10]. Furthermore, the identification of the most relevant experimental benchmarks for validation with existing databases has already been achieved, and validations are ongoing. Additionally, new integral experiments are being prepared at GELINA, MINERVE, LR-0, and TAPIRO, and although the actual experiments had to be postponed some months (COVID-19), progress has been made on their simulations.

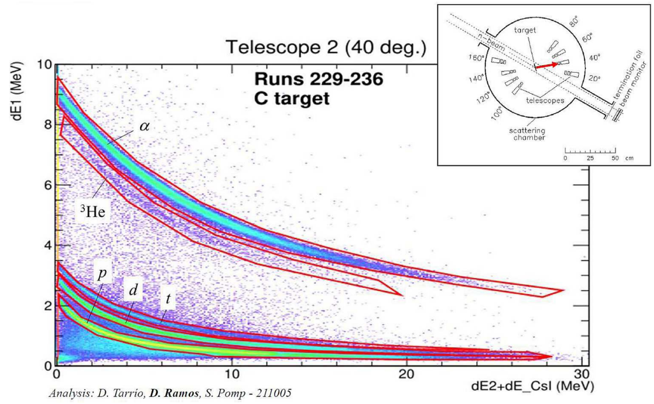

Fig. 6. Preliminary particle identification of light charged particles ($p, d, t,\ \alpha,\ ^3$He) from the LIONS experiment at NFS. (Courtesy: S. Pomp, Uppsala).

2.3 Synergy of ARIEL and SANDA

The transnational access to neutron beam facilities and education and training activities available through ARIEL and the joint research activities for new nuclear data measurements and innovative detector developments from SANDA offer a synergetic research program to improve relevant nuclear data through measurements evaluation and validation. The synergies are related to several aspects. The mobility support of ARIEL has been made available for young scientists to participate in several research projects that relate to SANDA experiments or related scientific questions. Below is only a small fraction of the projects listed that have already been completed.

The measurements of neutron-induced light-charged particle emission on carbon at the Neutrons for science facility at GANIL by a group from the Uppsala University are task 2.1.2 of SANDA and have also received support for transnational access to neutron beam facilities from ARIEL. A first particle identification $\Delta E-E$ plot is shown in Figure 6. The SCALP measurement at nELBE with ARIEL support contributes to the same SANDA task.

The validation of a stilbene detector response matrix by the Rez group is relevant for the validation subtask 5.3.2. A stilbene single crystal detector was characterized at PTB for use as a compact fast neutron spectrometer development in SANDA task 1.2.1.

ARIEL also supported theoretical and simulation studies that are relevant for the detector development in SANDA task 2.6.2 and for the fission yield evaluation of task 5.1.2.

In addition, close collaboration is supported with JRC Geel with several projects involving young researchers from Uppsala and Perugia, as well as the exchange of knowledge in fission theory with senior experts from Bucharest. The VERDI fission spectrometer setup has been supported by ARIEL and has a crucial effect on the time resolution, the plasma delay time in silicon detectors has been studied at the ILL Lohengrin spectrometer.

The radioactive target and sample production strongly collaborate with JRC Geel and target-making groups at PSI Villigen and the University of Mainz. A future concept of an isotope separator for enriched isotopic materials is being investigated.

3 Future strategy organization of nuclear data activities within European joint programs

The SANDA and ARIEL projects intend to contribute to the development of instruments like new detectors, new laboratories for target preparation, commissioning of new neutron sources, and new devices for integral experiments and new IT codes. These developments are important to make possible in the near term, but not necessarily within the project duration, the measurement and preparation of well-identified nuclear data that cannot be made with the presently available tools. So, within SANDA, there are coordination efforts to make sure that there is a coherent organization and support of the partners and other European nuclear data research groups, projects, and financing programs to guarantee that the data, tools, and methods produced will effectively serve the end-users, and will become part of a sustainable vehicle for nuclear data research within the EU.

Indeed, within the nuclear data EU research community, it is clear that there are already known data needs that cannot be solved within the scope of SANDA (because resources are limited and because they are beyond our present technical capabilities). We also know that there are new nuclear data needs being identified from the developments of new proposals like for small modular reactors (SMR) of different technologies, including a range of molten salt reactors (MSR) and new fuels and fuel cycles as well as new applications of nuclear technologies. We also know that the new detectors, methods, and laboratories being developed will progressively clear present technical barriers.

This is a well-known situation that has repeated over the years for several decades and that, indeed, shows the need for a continuous effort of the nuclear data R&D community to improve the technical limits and continuously provide the nuclear data needed for the new technological developments within the required uncertainties. In this sense, it is important to acknowledge those needs and to organize the corresponding support resources, preferably in the form of a coordinated European partnership, and SANDA includes actions to inform of these needs and to try mobilizing the different Member States to promote sustainable solutions. The new partnership could include activities for other basic data needed for safety and sustainability and simulation tools.

4 Conclusions

ARIEL and SANDA are two projects of EURATOM H2020 that support the measurement, evaluation, and validation of nuclear data that will improve the safety of present reactors and improve the precision and efficiency of the new advanced reactor and fuel cycles designs and of the applications of nuclear technologies. They respond to the high priority request list of nuclear data (HPRL) collected by the international organizations IAEA and NEA/OECD from the inputs and discussions with nuclear data users and producers. In addition, they provide significant progress on the detectors, neutron sources, methodologies, and laboratories that will allow future experiments to measure and evaluate data that today are beyond our technical capacities.

Despite the large delays introduced by the COVID pandemic (between 6 and 12 months on different activities of SANDA and ARIEL), both projects have already achieved significant results in developing and improving detectors, commissioning new neutron sources, performing some new measurements, and improving the tools and environment for evaluation and validation.

Despite the improvements in nuclear data already made and expected from both projects, it is clear that there will be remaining needs from the HPRL and the new needs identified in the research and demonstration of innovative nuclear system designs and technologies. It is important to focus and coordinate within a EURATOM framework all the available resources at the European level to prepare an efficient and sustainable R&D responding to those needs.

Special attention is given to the use of the research in SANDA and supported by ARIEL for training young scientists and engineers who will learn by doing during their PhD. Also, special care will be applied to the early and efficient dissemination of the project results to the EU community of nuclear data users.

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Conflict of interests

The authors declare that they have no competing interests to report.

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Data availability statement

Data associated with this article cannot be disclosed yet due to legal reasons.

Author contribution statement

All authors contributed equally to the conception and writing of the paper. A.J., C.F. and A.P were responsible for the parts concerning the project ARIEL; E.G. was responsible for the parts concerning SANDA.

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