Book of abstracts

The shell model Monte Carlo approach to level densities: recent advances and prospects*

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The nuclear level density is among the most important statistical properties of nuclei. However, its microscopic calculation in the presence of correlations is a challenging many-body problem. Most approaches are based on empirical models such as the back-shifted Fermi gas model and the constant temperature formula, and on mean-field theories. The configuration-interaction shell model approach offers an attractive framework that includes correlations beyond mean-field theory and shell effects, but its applications have been limited by the size of the required model space. The shell model Monte Carlo (SMMC) method enables calculations in model spaces that are many orders of magnitude larger than those that can be treated in conventional diagonalization methods, and is a powerful state-of-the-art method for the microscopic calculation of nuclear level densities.

We discuss recent advances and prospects of the SMMC approach for calculating level densities. These include (i) a method to circumvent the odd-particle Monte Carlo sign problem [1], enabling the first accurate SMMC calculation of level densities in odd-mass nuclei [2]; (ii) the microscopic calculation of collective enhancement factors of level densities in heavy nuclei and their decay with excitation energy [3]; (iii) projection methods for calculating the spin-parity dependence of level densities, and (vi) a method to calculate the probability distribution associated with the quadrupole operator [4], which might facilitate the modeling of level densities as a function of deformation, an important input for the calculation of fission rates.

*This work was supported in part by the U.S. DOE grant No. DE-FG02-91ER40608.

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Nucleon elastic scattering off doubly closed-shell nuclei with HF+RPA with Gogny force

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This work is dedicated to a microscopic derivation of the optical potential involved in nucleon elastic scattering off doubly closed-shell target nuclei. We use the "nuclear structure approach" developed by N. Vinh Mau and A. Bouyssy. We present results for a calculation using the Gogny force consistently to generate both the real Hartree-Fock term and the complex Random-Phase Approximation term of the optical potential. Resonances in the intermediate wave are taken into account and we found they play a crucial role in accounting for the measured reaction cross section. The issue of the double counting of the particle-hole second order contribution is carefully addressed. This potential is non-local complex and energy dependent. The integro-differential Schrödinger equation corresponding to the scattering problem is solved without any localization procedure. The method is applied to neutron and proton elastic scattering from ^{40}Ca. We compare our potential with available phenomenological non-local potentials. A successful account of all elastic scattering observables (differential and integral cross sections and analyzing powers) is obtained for incident energies between 5 MeV and 30 MeV. Discrepancies observed at higher energy are related to the too large volume integral of the real potential for large partial waves.

Overview on nuclear data evaluation challenges

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Modern evaluations of nuclear data rely heavily on nuclear models to produce complete evaluated nuclear data files. A methodology to evaluate nuclear data producing the average values and corresponding uncertainty and covariance data of relevant physical quantities is reviewed. In addition to the modelling, the use of differential measurements combined with selected integral data within the evaluation loop is highlighted. Examples from on-going IAEA evaluation efforts for the CIELO project are discussed including challenges in evaluation of inelastic cross sections (e.g. Fe-56 and U-238) and prompt fission neutron spectra (e.g. U-235(n,f)).

Some future nuclear science experimental opportunities

M.B. Chadwick

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I will give a summary of some of the future measurements Los Alamos is planning, for nuclear cross sections. Advances that are coming from precise fission cross sections and spectra measurements will be noted, as well as for fission products. Work on fission gamma-gamma ray outputs will be useful to support a future concept LANL is developing: neutron diagnosed subcritical experiments. This concept will be discussed briefly.

Can we improve the cross sections calculation for deuteron-induced reactions?

P. Chau

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Deuteron induced reactions are a useful tool both to investigate the nuclear structure (e.g. via inelastic scattering (d,d') or (d,p) processes) and to produce isotopes relevant for medical or material applications. Therefore it is important to get nuclear data library of high quality for d-induced reactions.

Nevertheless at the present time, the agreement between the experimental excitations functions for d- induced reactions and the theoretical ones is often poor and improvements of the theoretical approaches have to be achieved in order to build more reliable evaluated cross sections.

Some difficulties in the calculation stem from the fact that the projectile is a composite and weakly bound system: one has to deal with a 3-body quantum problem and one should also include continuum effects into the calculations. In the seventies, R. C. Johnson and P. J. R. Soper then proposed an approximation of the three-body problem now known as the Continuum Discretized Coupled Channels (CDCC) approach. Within this formalism, the deuteron-target interaction is treated as a three-body problem which explicitly includes breakup channels and in which the deuteron optical potential is obtained by a folding of the nucleon-target optical potentials. Since then, it has been widely studied and quite successfully used to calculate the elastic cross sections.

In this contribution, focusing my attention on transfer reactions ((d,p) and (d,n) ones), I will show how the CDCC formalism can also be used to compute these cross sections and I will present a systematic comparison between the theoretical results and experimental measurements for both the differential cross sections and the excitation functions.

Perspectives of research and education in nuclear data after Fukushima

S. Chiba

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After experiencing the accident at Fukushima Daiichi Nuclear Power Station (1F), popularity against nuclear energy has been drastically changed in Japan. Although majority of Japanese people tend to think that nuclear energy is an important source of electricity, great attention is placed on the safety of nuclear reactors, decommissioning of normally- and accidentally-terminated nuclear power plants, and treatment of nuclear waste in terms of nuclear transmutation as a near term concern. Nuclear data field must be responsible to respond to these social requirements.

Under this circumstance, important remaining fields in nuclear data may include (in my view)

1. Understanding of dynamics of nuclear fission as basis of nuclear power generation
2. Surrogate method to determine nuclear data of unstable nuclei, and theoretical support for it to correct obtained results
3. Understanding of β-decay process to make microscopic summation calculation of decay-heat and delayed-neutron data
4. Combination of nuclear structure and reaction theories for better understanding
5. Application of microscopic theory such as TDHF and MD-based theories for dynamical calculation of nuclear reactions
6. Proper treatment and understanding of data uncertainties
7. International collaboration and good interface of these advanced methods to new comers, which are realized in many other fields of science and engineering, which will attract students to enter to this field

I wish to talk some of the selected issues from these considerations.

High performance computing at the horizon 2020

G. Colin de Verdière

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This talk will cover the evolution of processing elements we will have in the forthcoming supercomputers. From this technological survey we will explain the impacts that technology will force on the simulation codes and why we won't avoid them. This talk will be targeted towards physicists who are not computer scientists.

From low to high energy nuclear data evaluations
Issues on nuclear reaction models and covariances

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Neutron induced reactions between 0eV and 20MeV are based on various physical properties such as nuclear reaction models, microscopic and integral measurements. Most of the time, the evaluation work is done independently between the resolved resonance range and the continuum, giving rise to mismatches for the cross sections, larger uncertainties on boundary and no cross correlation between high energy domain and resonance range. In addition the use of integral experiment is sometimes only related to central values (evaluation is “working fine” on a dedicated set of benchmarks) and reductions of uncertainties are not straightforward on cross sections themselves: working fine could be mathematically translated by a reduced uncertainty.

This paper will present several ideas that could be used to avoid such effects. They are based on basic physical principles, recent advances in terms of covariances evaluation methodologies, intensive use of Monte-Carlo methods and high performance computing as well as on some elaborated new models to make a clear connection between resonance energy range and the continuum (fission channels, optical models parameters, width fluctuation factors…). In addition, this paper will focus on a review of the use of integral experiments as physical additional constraints during the evaluation analysis. In particular, a comparison of a traditional multigroup adjustment with a data assimilation based on nuclear models parameters will be presented on specific integral experiments (JEZEBEL, PROFIL, CERES…).

Self-consistent adiabatic description of the fission process

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We describe the fission process with a two-step microscopic approach consisting in the production by HFB+Gogny D1S/D1M of static, adiabatic and self-consistent potential energy surfaces (PES) followed by the TDGCM+GOA calculation of the propagation of a wave packet representing the whole system, using the previous PES as basis functions. In this presentation, we will describe the models used, their numerical implementations and some of the issues we have had to deal with, namely hysteresis and discontinuities for the PES production, and numerical stability for the TDGCM+GOA solver. We will present some results and discuss how we plan to use this description in the near future.

Interplay between ab-initio and energy density functional approaches

T. Duguet

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I will elaborate on the emergence of ab initio many-body methods for mid-mass nuclei in the last ten years and on their potential future interplay with the more effective energy density functional methods applicable to the whole mass table.

Connecting structure and direct reactions modeling

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Accuracy in cross-sections evaluations, for nucleon induced reactions on a large variety of target nuclei, is increasingly required for the elaboration of nuclear data files that are used in many applications. As a medium energy nucleon hits a nucleus, direct, pre-equilibrium and compound nucleus reactions mechanisms occur, followed by a fission process in the case of actinides. Numerous nuclear reactions models have been developed to calculate the contributions to a particular exit channel stemming from these different reaction mechanisms. However, these models are usually built from phenomenological ingredients and may also contain one or several parameters that are directly fitted to match a selected set of experimental data. Consequently, any extrapolation to mass and energy regions where measurements are missing could be uncertain.

In order to improve nuclear reactions modeling, microscopic approches are developped starting from a quantum mechanical description of the target states that are relevant in a direct reaction process. These states consist in excitations of particle-hole character as well as collective states, such as rotation, low energy surface vibrations and giant resonances. For many targets, these excitations are well described within the quasi-particle random phase approximation (QRPA) nuclear structure model implemented with a suitable effective interaction [1]. By combining this microscopic descriptions of target states and an effective projectile-target's nucleon interaction, such as a g-matrix (JLM, Melbourne g-matrix ...), we satisfactorily account for direct inelastic scattering to discrete states as well as the first step of direct pre-equilibrium emission. Besides, such direct reaction models allow to precisely determine initial conditions for compound nucleus models, such as the direct inelastic cross sections component and the spin-parity distribution of the residual nucleus.

In this talk, we will first present an overview of what has been achieved from a microscopic description of direct nucleon inelastic scattering for spherical [2] and axially deformed targets. We will more particularly focus on (n,xn), (n,xnγ) cross sections for neutron induced reactions on actinides. We will then talk about possible perspectives:

- extend the present model to account for multistep pre-equilibrium processes,
- reduce its complexity for practical applications,
- make the most of the multi-particle - multi-hole (mpmh) nuclear structure predictions [3] in direct reaction models to account for target excitations that are out of the space of the QRPA model in light an medium mass nuclei
- and finally, following the ideas contained in the microscopic RPA optical potential model [4], consistently describe direct reactions at low and medium energy using the same effective interaction for both nuclear structure and reactions.

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The surrogate reactions: status and prospects

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Providing reliable nuclear cross section data for applications remains a formidable task, and direct measurements have to be complemented by theoretical predictions and indirect methods. Indirect approaches come with their own challenges, as experimental observables have to be related to the quantity of interest. The surrogate method, for instance, aims at determining cross sections for compound-nuclear reactions on unstable targets by producing the compound nucleus via an alternative (transfer or inelastic scattering) reaction and observing the subsequent decay via γ emission, particle evaporation, or fission. A complete theoretical treatment involves integrating descriptions of direct and compound-nucleus reactions, including modeling of compound-nuclear decays. This presentation will give an outline of the surrogate approach and the challenges involved in extracting cross sections from the measurements. Progress made in understanding and describing the nuclear processes involved in a surrogate reaction will be discussed, and applications to neutron-induced fission, neutron capture, and (n,2n) reaction will be presented. Open questions and prospects will be considered.

*This work is performed under the auspices of the U.S. Department of Energy (DOE) by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Fission studies in inverse kinematics: impact on experimental and evaluated data files

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Inverse kinematics is a new tool to study nuclear fission. Its main advantage is the possibility to measure with an unmatched resolution and precision the atomic-number of fission fragments, leading to new observables in the properties of fission-fragment distributions. In addition to the resolution improvement, the study of fission based on inverse kinematics benefits from a larger view with respect to neutron-induced fission investigations, as the number of fissioning systems as well as the excitation energy range are widened.

As an illustration, the understanding and parameterization of the even-odd effect in the fission-fragment yields in evaluated nuclear files has been recently reassessed based on the large systematics brought about by the inverse kinematics. Even-odd effect may play an important role in the description of the fission yields as they can be as large as 40% of fluctuations.

With the use of spectrometers, mass and kinetic-energy distributions may now be investigated as a function of the proton- and neutron-number sharing. It is then possible to separate the influence of proton and neutron shell-closures on the fragment distribution.

In addition, the bulk properties of the deforming nucleus as a function of the proton to neutron asymmetry of the nascent fragment may be investigated as well. With the use of inverse kinematics, the charge polarization of fragments at scission is now revealed with high precision.

It will be shown that charge polarization is not only a result of shell effect, but also of the macroscopic properties of the nucleus energy, and that improvements in the description of the deformed liquid drop still need to be developed.

Uncertainties propagation with URANIE

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A standard way of describing a complex physical phenomenon implies a development of a relevant mathematical or computational model. A mathematical model is defined by a series of equations, input factors, parameters, and variables aimed to characterize the phenomenon being investigated. The inputs of the model are subject to many sources of uncertainty including errors of measurement, through lack of data or knowledge, occurrence of stochastic events, etc… This imposes a limit on our confidence in the outputs of the model.

Then, good modeling practices require that the modeler provides an evaluation of the confidence in the model. The variability of the model outputs can be characterized by various quantities of interest: statistics (such as mean, standard deviation, and confidence interval), exceedance of a threshold etc…

This talk will present methodologies of the Uncertainty Quantification and the URANIE platform, developed by the CEA/DEN, to treat the Sensitivity Analysis, Uncertainty Quantification and the Parameter Calibration for computational models.

Radiochemical measurements of neutron capture and isomeric data at the NIF

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The neutron luminosity of a NIF implosion can produce observable concentrations of activation products from nanograms of target material. Solid radiochemistry has recently been added as a new NIF diagnostic capability and is providing important insights regarding nuclear reactions in high-energy-density-plasmas. This talk will focus on recent results from the NIF Solid Radiochemistry (SRC) diagnostic as well as provide details on future experiments and capabilities developed for performing measurements relevant to nuclear science.

Towards more accurate and reliable predictions for nuclear applications

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The need for nuclear data far from the valley of stability, for applications such as nuclear astrophysics or future nuclear facilities, challenges the robustness as well as the predictive power of present nuclear models. Most of the nuclear data evaluation and prediction are still performed on the basis of phenomenological nuclear models. For the last decades, important progress has been achieved in fundamental nuclear physics, making it now feasible to use more reliable, but also more complex microscopic or semi-microscopic models in the evaluation and prediction of nuclear data for practical applications. In the present contribution, the reliability and accuracy of recent nuclear theories are detailed and compared for most of the relevant quantities needed to estimate reaction cross sections and beta-decay rates, namely nuclear masses, nuclear level densities, gamma-ray strength, fission properties and beta-strength functions. It is shown that nowadays, mean-field models can be tuned at the same level of accuracy as the phenomenological models, renormalized on experimental data if needed, and therefore can replace the phenomenological inputs little by little in the prediction of nuclear data. While fundamental nuclear physicists keep on improving state-of-the-art models, e.g. within the shell model or ab-initio models, nuclear applications could make use of their most recent results as quantitative constraints or guides to improve the predictions in energy or mass domain that will remain inaccessible experimentally. Uncertainties in the model predictions will also be discussed.

Single-particles degrees of freedom in fission

H. Goutte

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Fission is obviously a very complex process. At first glance, the fission process is a collective movement of large amplitude, which starts from an initial state, goes through elongated shapes of the nucleus and leads to scission. Considering only the collective movement seems justified by rather different characteristic times between collective motion (slow) and intrinsic excitations (fast). This led to the development of macro-microscopic models, as well as formalisms based on collective approaches. In this context, the results obtained for the kinetic energy, mass and charge distributions of fission fragments are surprisingly good and seem to corroborate this hypothesis.

However, there are areas of fission that cannot be tackled without the explicit treatment of individual excitations and their coupling to the collective motion; this is particularly the case if one wants to explain and describe i) the very large differences between the lifetimes of even-even and odd isotopes, ii) scission and the formation of odd fragments, iii) fission fragment spins... In this case, it is essential to go beyond the usual adiabatic approaches and address individual excitations.

In our presentation we will try to show these different aspects of the fission process, a few recent studies on the subject and the necessary developments to be made in the future.

Nuclear level densities from an experimental point of view

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The Oslo method allows the simultaneous extraction of level density and γ-ray strength function from particle-γ coincidences [1,2]. The method is applicable for excitation energies below the particle separation energy. In order to tag accurately the excitation energy, light-ion reactions with only one charged ejectile are exploited such as the (p,p'), (d,p) and (^{3}He, ^{4}He) reactions. A short introduction the Oslo method will be given.

Level densities measured for several mass regions [3] are presented and common features are commented on. We find interesting "kinks" in the level densities that have their clear physical origins. Pairing and shell gaps are important physical ingredients for the detailed understanding of the shape of the level density. The data will be discussed within the constant temperature (CT) and Fermi gas (FG) level density formulas. The experimental data below the particle separation energy clearly favor the CT model. To our knowledge, no theoretical approaches have so far been able to explain the CT behavior.

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Capture and fission with DANCE and NEUANCE

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A long term plan for high precision data measurements on capture and fission using the Detector for Advanced Neutron Capture Experiments (DANCE) at Los Alamos National Laboratory (LANL), will be reviewed. The five year long program, supported by the US Department of Energy (DOE), Office of Science, Nuclear Physics, includes measurements of neutron capture on Uranium isotopes – U-234, U-235, U-236 and U-238. The goal of these efforts is to reduce experimental uncertainties below 3% up to 1 MeV of neutron incident energy. Similarly, new measurements will be carried out for fission cross sections, including U-235 and U-233 neutron-induced fission at DANCE. Detailed information on photon strength functions and nuclear level density in Uranium isotopes will be obtained as well.

The development of the neutron detector array NEUANCE (NEUtron Array at daNCE) is funded by LANL LDRD/DR program. The objective of this development is to measure new data on the short-lived actinides isomer production after neutron capture on U-235. Observation of 100 ns isomer in U236, populated after neutron capture at 1 MeV above the ground state, raised the question about how strongly it is being populated. Its yield may directly influence the uranium inventories in high neutron fluence environment. After the successful development of NEUANCE, we will give an overview of what type of new data can be measured in the next decade on fissile actinides.

Finally, the first measurements of correlated data on fission observables are supported by the Office of Defense Nuclear Nonproliferation Research and Development, US Department of Energy, NNSA. Fission fragments detectors are under development, and after the completion will be used in DANCE-NEUANCE array to provide fully correlated data on prompt-fission neutrons, gamma-rays and fission fragments. Such correlated data will be used to benchmark the fission models, currently under development at LANL, and their optimization for the future use in the MCNP transport code.

Challenges beyond Hauser-Feshbach for nuclear reactions modeling

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It is well-known that the Hauser-Feshbach theory provides successful description of nuclear reaction process in the fast energy range, with help of modeling for other nuclear reaction mechanisms such as the direct reaction or the pre-equilibrium process. Although the theory has been playing a central role in the nuclear data evaluation as well as in other nuclear physics studies over the decades, some open questions still exist. These problems might be classified into three categories; (1) the model parameters for practical calculations, (2) applicability of the theory itself, and (3) perturbative contributions from the other reaction mechanisms. Since the item (1), such as microscopic or phenomenological inputs, has been discussed extensively in the past, we focus on several topics that fall in the second and the third categories in this paper. The topics to be discussed include the direct reactions, direct capture, and pre-equilibrium reactions.

The Hauser-Feshbach theory is for the compound nuclear reactions, in which the particle decay widths can be replaced by the energy-averaged particle transmission coefficients for the inverse channel. This reciprocal relation is well understood for a spherical nucleus. However, issues in the energy-averaged cross section including direct reaction channels recently came to light, especially related to cross-section calculations for actinides. We show that this can be done rigorously by diagonalizing the scattering matrix, and the direct reactions can be included in the Hauser-Feshbach model calculation in such a way.

The pre-equilibrium process and the direct/semidirect capture process, albeit they are considered as a sort of perturbative contributions, are essential to incorporate into the reaction model calculation. We discuss a possible extension of these reaction models inside the statistical model framework by combining a nuclear structure model.

(n,xnγ) cross sections: relevant tests for nuclear reactions codes?

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Since 10 years, our collaboration has demonstrated that the measurement of (n,xnγ) cross sections is a good mean to study (n,xn) reactions. Large sets of new experimental data have been produced on a variety of nuclei from ^{7}Li to ^{238}U. Comparisons with nuclear reaction code calculations have shown that the predictions of these exclusive cross sections are a real challenge for the theoretical codes as many processes are involved: optical model, direct and pre-equilibrium reactions, level densities, decay scheme, fission (if fissionable nucleus)… should be simultaneously well described by the models.

In this presentation, we would like to make a status of what we have learned since the last P(ND)^2 workshop and to highlight how we can continue to progress on this field in order to provide new, complete, accurate and relevant experimental data to the evaluators.

Current activities and future plans for nuclear data measurements at J-PARC

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Accurate data of neutron-capture cross sections for minor actinides (MAs) and long-lived fission products (LLFPs) are important in detailed engineering designs and safety evaluations of innovative nuclear reactor systems. However, accurate measurements of these cross sections are very difficult due to high radioactivity of these samples. To overcome the difficulty, “Accurate Neutron-Nucleus Reaction measurement Instrument (ANNRI)” has been constructed in the Materials and Life science experimental Facility at the Japan Proton Accelerator Research Complex, and measurements of neutron-capture cross sections for MAs and LLFPs with high intensity pulsed neutrons have been performed. In this presentation, the current status, a brief view, measurement activities and results, and future plans will be presented.

From nuclear data evaluations to nuclear reactors

A. Koning

NRG Petten – The Netherlands

A nuclear data system is presented which connects basic experimental and theoretical nuclear data to a large variety of nuclear applications. This software system, built around the TALYS nuclear model code, has several important outlets:

- The TENDL nuclear data library: complete isotopic data files for 2430 nuclides for incident gamma's, neutrons and charged particles up to 200 MeV, including covariance data, in ENDF and various processed data formats. In 2014, TENDL has reached a quality nearing, equalling and even passing that of the major data libraries in the world. It is based on reproducibility and is built from the best possible data from any source.
- Total Monte Carlo: an exact way to propagate uncertainties from nuclear data to integral systems, by employing random nuclear data libraries and transport, reactor and other integral calculations in one large loop. For example, the entire ICSBEP database can now be predicted including uncertainty estimates.
- Automatic optimization of nuclear data to differential and integral data simultaneously by combining the two features mentioned above

Both the differential quality, through theoretical-experimental comparison of cross sections, and the integral performance of the entire system will be demonstrated. The impact of the latest theoretical modelling additions to TALYS on differential nuclear data prediction will be outlined, while integral validation will be presented for a selection of cases from criticality benchmarks, safety-related (Doppler and void) coefficients, burn-up, radiotoxicity, 14 MeV structural material shielding for fusion, and proton-induced medical isotope production.

Comparisons with the major world libraries will be shown. Since the system is designed with a high level of QA and reproducibility and at the same time is based on high quality experimental and theoretical nuclear physics, we expect that the features mentioned above will soon play an important role in the analysis of any nuclear application.

Neutron facilities

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Numerous facilities around the world provide accurate nuclear data that are essential for reliable evaluated data bases. The observables to be measured, such as cross-sections, multiplicities of reaction products, or neutron and gamma spectra, for a given reaction type ranging from scattering, fission, (n,xn) reactions, neutron capture to light particle production, require very specific characteristics. These include particular energy ranges extending from the thermal to the GeV region, and experimental techniques for which pulsed beams, high fluxes, fine energy tuning or low background conditions are essential. A broad spectrum of facilities, mainly reactor- or accelerator-based, is needed to fulfill these requirements. An overview of facilities currently involved in measurements for nuclear data for neutron-induced reactions will be presented. A special emphasis will be placed on current and upcoming facilities that will ensure new nuclear data measurements in the next decade.

Fisson modelling with FIFRELIN

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The fission process gives rise to emission of fission fragments and particles (n, γ, e^-). The particle emission can be prompt and delayed. We present here the methods used in the code FIFRELIN, developed at CEA Cadarache, which simulates the prompt component of the de-excitation process (before beta-minus decay). The methods are based on phenomenological models associated with macroscopic and microscopic ingredients. Input data can be provided by experiment as well as by theory. The fission fragment de-excitation can be performed within Weisskopf (uncoupled neutron and gamma emission) or a Hauser-Feshbach (coupled neutron/gamma emission) statistical theory. We consider five free parameters to describe the initial distributions required by the code that cannot be provided by theory or experiments. This set of parameters is chosen to reproduce a very limited set of *target observables* (the total average prompt neutron multiplicity for instance, which is a simple scalar value). At this point we can predict all other fission observables and distribution of fission observables as a function of any kind of parameter.

The goal in the next decade will be (i) to replace some macroscopic ingredients or phenomenological models by microscopic calculations when available, (ii) to be a support for experimentalists in the design of detection systems or in the prediction of necessary beam time or count rates with associated statistics when measuring fragments and emitted particle in coincidence (iii) generate covariance matrices related to spectra or multiplicities thanks to evaluation codes by using a Bayesian approach, (iv) extend the model to be able to launch a calculation when no experimental input data are available, (v) account for multiple chance fission and gamma emission before fission, (vi) account for the scission neutrons.

Several efforts have already been made to replace macroscopic ingredients and phenomenology by microscopic ingredients provided in various libraries (HF+BCS+QRPA model for E1 photon strength functions in RIPL-3, HFB level densities, moment of inertia in AMEDEE database, …) and results will be presented during this workshop and compared with experimental results when available.

Mass-measurement techniques and mass-measurement programs

D. Lunney

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The nuclear binding energy is of fundamental importance for a diverse range of physics. Its determination results from mass measurements, employing an equally diverse range of experimental techniques. This diversity, provides an interlinked data set, and requires a global evaluation procedure that results in the so-called atomic mass table (not to be confused with a compilation). The mass table is unique in its role as universal starting point for the development of mass models and a benchmark for their performance.

The role of the atomic mass evaluation is examined in light of the different physics applications. An overview of mass measurement programs is also given, including planned projects, as well as mass measurement programs devoted to the determination of nuclear binding energy.

The SOFIA experiment: measurement of the isotopic fission fragments yields in inverse kinematics at relativistic energies

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Data on fission fragments yields are still up to now incomplete and often inaccurate despite decades of investigations. So far no experiment has been able to measure unambiguously the mass and the charge of the fission fragments for the light and heavy groups. The lack of high resolution data constitutes an obstacle to the development of predictive and reliable models and is at the origin of uncertainties both in the field of technical applications of fission and in more fundamental aspects.

In this context, the SOFIA (Studies On Fission with Aladin) program was developed to provide accurate measurements of the isotopic yields of fission fragments. A first experiment was performed in August 2012 at GSI (Darmstadt, Germany), the only facility delivering heavy ion beams at relativistic energies. For the first time, it was possible to measure the charge and the mass of both fission fragments in coincidence for a broad range of fissioning nuclei, from Hg up to Np, with a resolution never reached yet. This was only possible because inverse kinematics at relativistic energies was used to induce low energy fission.

This talk will present the advantages of this method. Mainly, the charge, mass and neutron yields can be obtained for both fission fragments in coincidence. The neutron multiplicity can be extracted. These observables are available for a wide range of actinides. The illustration will be done with the results obtained during our first campaign in August 2012. The upgrade for the second campaign (in October 2014) will be briefly mentioned, before to sketch out what will be the future of this experiment for the next decade.

Designing a new format for storing nuclear data

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The Evaluated Nuclear Data Format (ENDF) has been used for nearly 50 years to store and exchange evaluated nuclear data. It serves as a standard, computer-readable form for nuclear scientists and engineers to provide recommended nuclear reaction data for use in reactor design and other applications. While ENDF continues to play an important role in nuclear physics and engineering, it is showing signs of age. ENDF was originally designed to be stored on 80-column punch cards, with 14 characters out of each line reserved for identifiers such as line numbers. Plain text documentation is allowed, but can only appear at the start of each file (that is, only once per projectile/target combination). ENDF files are difficult for humans to read, and frequently contain subtle errors that can remain hidden for years, partly due to the complexity of the format. Most importantly, a new generation of scientists and engineers are increasingly disinterested in learning the details of a legacy format like ENDF, preferring instead to work with modern software practices and tools (like XML) with which they are more familiar and that they find more useful. At a time when the nuclear data community is losing expertise to retirements, it needs to be willing to adopt new practices in order to attract a new generation of talent. For all these reasons, a modern replacement for ENDF has become an important priority.

The Working Party on Evaluation Cooperation sub-group 38 (SG38) was formed in 2012 to oversee the design and implementation of a modern replacement for ENDF. The replacement should take advantage of the many advances in computer technology since ENDF was created, and should be flexible, extensible, and both human- and computer-readable.

In this paper we will present on the progress that has been made by SG38 towards defining a new standard for storing nuclear data, and on the open challenges and questions that still need to be addressed before the new standard will begin to be fully utilized. We also present on the status of the Generalized Nuclear Data structure (or GND), which was developed at Lawrence Livermore National Lab and should serve as a good starting point for defining a new format.

Overview of the NEA activities and challenges related to nuclear data

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The OECD Nuclear Energy Agency (NEA) Data Bank has been a relevant focal point of many Nuclear Data activities over its history. As a member of the International Network of Nuclear Reaction Data Centres (NRDC), The Data Bank addresses the nuclear data needs of its member countries by maintaining large databases of bibliographic, experimental and evaluated nuclear data, and developing specialized software (e.g. JANIS) to make these databases easily and freely available online or upon request. In terms of nuclear data evaluation, the Data Bank is home to the Joint Evaluated Fission and Fusion (JEFF) project and as such organizes the compilation, verification, release and distribution of the JEFF nuclear data library series and co-ordinates regular technical gatherings of the broad nuclear data community. In addition, large collections of integral benchmark experiments for the validation of nuclear data are continuously maintained by the NEA in areas such as criticality safety (ICSBEP), reactor physics (IRPhE), fuel performance (IFPE), radiation shielding (SINBAD) and spent fuel assays (SFCOMPO), among others. The Data Bank provides support to the above mentioned integral databases and to the Working Party on International Nuclear Data Evaluation Co-operation (WPEC) of the NEA Nuclear Science Committee.

Through a review of a selected number of its past or ongoing Nuclear Data activities, our contribution will focus on the role international cooperation has in effectively forging common understandings on key issues around nuclear data. We aim at analyzing the role of the NEA and its Data Bank in the long-term preservation and management of scientific knowledge and identifying lessons learned. We will describe NEA achievements and outline ongoing and future activities in the above mentioned NEA bodies or projects, as well as remaining challenges in areas related to nuclear data measurement, theory/evaluation, processing and validation; fields where the NEA plays a key coordinating role through its diverse programs of work.

Modeling odd-even staggering in fission-fragment yields in the Brownian shape-motion approach; current results and future prospects

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Many actinide nuclei show asymmetric mass distributions in fission. We have previously benchmarked the Brownian shape motion (BSM) model with respect to experimental data in this region, and the encouraging degree of agreement has motivated further development. In particular in its original formulation odd-even staggering in the distributions was not described because the pairing equations were solved for the system as a whole. Therefore it was not possible to consider whether the particle numbers in the emerging fragments were even or odd. Also, the Z/N ratio in both the emerging fragments was that of the compound system, so the calculated charge and mass distributions were identical except for a scaling factor.

To develop a more detailed model one would like modify the BSM model to provide fission-fragment yields Y(Z,N) which include descriptions of odd-even staggering. An obvious approach seems to be that we take the model from five dimensions to six by generalizing the potential-energy model so that the energy can be obtained for different Z/N ratios in the two emerging fragments. This would be a fairly major program. I will discuss some ideas what such a model would look like and current status.

However, we found a way to calculate odd-even staggering in fission-fragment CHARGE distributions without taking these major steps. We obtain surprising agreement with observations. These results may show that it would indeed be worthwhile to develop the more complete model so that we can obtain Y(Z,N) distributions, which would also include odd-even staggering effects.
Current status and results of these efforts will be discussed.

Future research program on prompt gamma-ray emission in nuclear fission

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In recent years the measurement of prompt fission gamma-ray spectra (PFGS) has gained renewed interest [1,2], after about forty years since the first comprehensive studies of the reactions ^{235}U(n_{th},f) [3–5] and ^{252}Cf(sf) [3]. These new experimental efforts were motivated by requests for new values especially for gamma-ray multiplicity and mean photon energy release per fission in the thermal neutron induced fission of ^{235}U and ^{239}Pu [6]. Both isotopes are considered the most important ones with respect to the modelling of innovative cores required for the fast Generation-IV reactors [7–9]. The majority of those reactors work with fast neutrons. As a consequence of recent instrumental advancements like the development of new detectors as well as digital data acquisition systems, the determination of new and improved PFGS characteristics became possible with high precision. An example of that is a recent study on the PFGS from the spontaneous fission of ^{252}Cf (see Ref. [1] and references therein).

In recent years we conducted a systematic investigation of prompt gamma-ray emission in fission [1]. We were able to obtain spectral data for thermal neutron induced fission on ^{235}U [2] and ^{241}Pu [3] as well as for the spontaneous fission of ^{252}Cf [1,4] with unprecedented accuracy. From the new data we do not have any indication that those reactions considerably contribute to the observed heat excess and suspect that other reactions play a significant role. Possible contributions may come from fast-neutron induced reactions on ^{238}U, which is largely present in the fuel or from gamma-induced fission from neutron capture in the construction material.

The recently installed neutron source LICORNE [12], where neutrons with energies between 0.5 and 4 MeV are produced in inverse kinematics, will enable us to explore prompt gamma-ray emission from fast-neutron induced fission testing our assumptions. A first experiment campaign at LICORNE was successfully conducted on ^{235,238}U targets.

Based on our experimental data we established a systematic trend up to incident neutron energies of 20 MeV that compares well with modern theoretical calculations. Some ideas for future measurement campaigns exploiting dedicated neutron- and photon-beams as well as new detector assemblies will be discussed.

[1] R. Billnert et al. Phys. Rev. C87, 024601 (2013)
[2] A. Oberstedt et al., Phys. Rev. C87, 051602(R), 2013
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[6] Nuclear Data High Priority Request List of the NEA (Req. ID: H.3, H.4), http://www.nea.fr/html/dbdata/hprl/hprlview.pl?ID=421and http://www.nea.fr/html/dbdata/hprl/hprlview.pl?ID=422.
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[8] G. Rimpault et al., Phys. Procedia 31, 3 (2012).
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[10] S. Oberstedt et al., submitted for publication
[11] A. Oberstedt et al., submitted for publication
[12] M. Lebois et al., Nucl. Instr. Meth. A735 (2014) 145-151.

SPY: A new scission-point model based on microscopic inputs to predict fission fragments properties

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Despite the difficulty to describe the whole fission dynamics, the main fragments characteristics can be determined in a static approach based on the so-called scission point model. Within this framework, a new Scission Point model for the calculations of fission fragment Yields (SPY) has been developed. This model, mainly based on the approach developed by Wilkins in the late seventies, consists in performing a static energy balance calculation at scission, where the two fragments are supposed to be completely separated so that their macroscopic properties (mass and charge) can be considered as fixed. More specifically, the fissioning system at scission is modelled by two coaxial spheroids separated by a fixed distance and the energy balance, function of the two fragment quadrupolar deformations, is calculated from the individual and interaction energy of each fragment. Thanks to the introduction of state densities, averaged quantities such mass and charge yields, mean kinetic and excitation energy can then be extracted in the framework of a microcanonical statistical description. These observables can finally be compared with experimental data. The main advantage of the SPY model is the introduction of one of the most up-to-date microscopic description of the nuclei for the individual energy of each fragment and, in the future, for their state densities. These quantities are obtained in the framework of HFB calculations using the Gogny nucleon-nucleon interaction, ensuring an overall coherence of the model.
After a description of the SPY model and its main features, a comparison between the SPY predictions and experimental data will be discussed for some specific cases, from light nuclei around Lead and Mercury [1] to major actinides. Moreover, extensive predictions over the whole chart of nuclei will be discussed, with particular attention to their implication in stellar nucleosynthesis [2]. Finally, further developments, mainly concerning the introduction of microscopic state densities, will be presented.

[1] S. Panebianco et al., Phys. Rev. C 86, 064601 (2012).
[2] S. Goriely et al., Physical Review Letters 111, 242502 (2013).

Why do we still need nuclear data?

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Nuclear data measurement, evaluation, validation and use have a long history in science and technology. The role of nuclear data for reactor physics and engineering is highlighted in the books from Weinberg and Wigner (1958) to those of Stacey (2001) and Cacuci (2010). Similar historic time lines may be found for medical, analytical and security applications. However, one may also argue that the most important nuclides have been studied over and over and that little more may be found out about the nuclear data for them.

The latter point of view is a superficial one that may easily be transliterated into an argument against any scientific endeavour in fields with a certain level of maturity. It only holds up if one insists in not looking too closely.

In the case of nuclear data it is well known that accuracies required by applications are often not met and that this is especially true if new materials and applications are foreseen. On the other hand the continued development of new measurement equipment and methodologies, together with a vastly increased capacity for modelling and computation allows pushing boundaries beyond those previously established. Here the main limits appear to be resources, not ideas, potential or the interest in nuclear data. It should however be clear that expensive large scale experiments and thus also industrial developments require accurate modelling in the design, implementation, testing and operation phase and that such modelling will be less accurate without good (nuclear) data and this ultimately leads to increased costs.

The presentation will address the above points and highlight nuclear data needs from present day interests as well as the need for high level collaborations around priority issues.

The truth about TENDL

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After seven years of development, the TENDL library is on its way of becoming an important part of the nuclear data community and their users. It contains unique features (among which completeness, format unity, covariances and quality), but its major strength lies in the fact that it is a product of an automated process, often incorrectly associated with blindness. Therefore this nuclear data library is not the starting point, but rather an intermediate step between fundamental physics and applications. How to explain this change of attitude followed by such a success? To answer this question, we will now tell the truth about TENDL and its immoderate ambition.

The inverse problem: would it be possible?

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It seems increasingly accepted that the surrogate experiments do not allow to get back to an "equivalent" induced neutron cross section. However, for the case of fission we have already referred [1] to the fact that it might be possible to reconstruct a fission barrier, only from a fission probability coming from surrogate measurements. Moreover, with this kind of surrogate experiments, the “compound" nucleus can be created in excited energy states well below the separation energy of the last neutron, which is very important to get information on the structure of the fission barriers.

In order to "reconstruct" fission barriers, we will use the inverse problem way. In fact, rather than adjusting barrier shapes, as usual, to fit the experimental fission probability, the idea is the following: once fission probability measured (with very good energy resolution), how is it possible to reconstruct an associated fission barrier shape?

[1] P. Romain, H. Duarte et B. Morillon Phys. Rev. C 85, **044603** (2012).

Revealing hidden regularities with a general approach to fission

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A general approach to nuclear fission [1] is described which explains the complex appearance of fission observables by universal principles of theoretical models and considerations on the basis of fundamental laws of physics and mathematics.

The most prominent features of this approach are the evolution of quantum-mechanical wave functions in systems with complex shape, memory effects in the dynamics of stochastic processes, the influence of the Second Law of thermodynamics on the evolution of open systems in terms of statistical mechanics, and the topological properties of a continuous function in multi-dimensional space.

It is demonstrated that the model reproduces the measured fission barriers and the observed properties of the fission fragments, prompt neutrons and prompt-gamma radiation with a remarkable precision.

Calculated fission observables comply with the needs for applications in nuclear technology. The relevance of the approach for examining the consistency of experimental results and for evaluating nuclear data is demonstrated.

The approach reveals a high degree of regularity and provides a considerable insight into the physics of the fission process.

[1] K.-H. Schmidt, B. Jurado, Ch. Amouroux, "General View on Nuclear Fission", http://hal.in2p3.fr/in2p3-00976648, April 2014

Quantifying uncertainties in nuclear density functional theory

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Nuclear density functional theory (DFT) theory is a global and consistent framework to describe low-energy nuclear structure across the nuclear chart. Two formulations of DFT coexist. In the self-consistent mean-field theory, the main ingredient is an effective interaction, or pseudopotential, such as the Skyrme or Gogny force; Correlations are described explicitly by the choice of the anszatz for the nuclear wave function. By contrast, the energy density functional (EDF) theory relies on the Kohn-Sham theorem and the knowledge of the energy density, which is not necessarily related to some underlying potential but may encode many-body correlations. Both approaches have proved very successful over the past 40 years to describe a number of nuclear properties from ground-state systematics to excited states and large amplitude collective motion. One of their (many) common features, however, is that they rely on the determination of a handful of parameters that are not given by the theory and are typically ajusted to experimental data in nuclear matter of finite nuclei. Ultimately, the predictive power of the theory depends on how exactly this fit is performed. In the USA, the SciDAC collaborations UNEDF and NUCLEI have been developing rigorous optimization protocols for the nuclear EDF. Very recently, the collaboration has also begun to apply Bayesian techniques to quantify and propagate optimization uncertainties to DFT predictions. In this talk, I will review some of the recent progress in the area both of functional optimization and uncertainty quantification.

Processing: the end of an era?

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The maturity of modern truly general-purpose nuclear data libraries such as TENDL-2013 encompassing thousands of target isotopes, the evolution of the ENDF nuclear data format and the capabilities of the latest generation of processing codes: PREPRO-2013, NJOY-2012 and CALENDF-2010 is allowing modern transport and activation codes to be fed with more robust, complete and appropriate data forms: cross-sections with covariance, correct energy angle distributions, probability tables in the resolved and unresolved resonance ranges, prompt kerma, dpa, gas responses, radionuclide productions, and flanked with up to 24 decay types also decay heat and secondary radiation source terms. All such data for the five most important incident particles (n, p, d, alpha, gamma) are stored in evaluated data files with information up to an incident energy of 200 MeV. From the earlier days, in the 70s those irreplaceable processing codes have had to compensate for the lack of robustness in many aspects of the contents and format of the evaluations they were supposed to seamlessly convert into forms useful for practical applications. The applications themselves; criticality safety, transport, shielding analysis often having a direct impact on the specifications, quality and format of the forms they needed. Forty years of progress in processing, often performed in the shadow, for and in tune with the release of the major libraries have shaped their capabilities and specialise their output forms usually to a specific client: MCNP for NJOY, TRIPOLI-ERANOS for CALENDF although many other applications, codes, processes rely on their generous aptitudes. This talk provides a description of the actual system’s capabilities, summary description of the method used but also anticipates the likely possibility that in a near future modern Monte Carlo code directly connect to the forms outputted by nuclear physics code such as TALYS.

Uncertainties and correlations in nuclear fission data: the role of models and experiments

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Nuclear fission is a very complex and rich physical process. A full experimental coverage of one fission event would comprise: the characteristics in mass, charge and kinetic energy of the fission fragments, their angular distribution; the characteristics (multiplicity, energy, angle) of the prompt neutrons accompanying most fission events; the same type of information for the prompt photons; other light-charged particles accompanying fission, as in ternary fission; characteristics of the b-delayed neutrons and photons; time information about the occurrence of the fission event, and in particular the role of fission isomers; etc… Obviously, the list of fission data is long, complex, and fully correlated.

Experimental data sets come out mostly uncorrelated, e.g., the measurement of the average prompt neutron multiplicity $\bar{\nu}_{\mathrm{p}}$ is performed in an apparatus quite different from the measurement of the energy spectrum of those neutrons. In other cases, however, e.g., the measurements of fission cross section ratios, correlations are very important and need to be treated appropriately in nuclear data evaluations.

On the other hand, an ideal theory of fission should be able to predict all data consistently, with as few model input parameters as possible. To date, such a lofty goal remains unmet, and we are compelled to use less ambitious fission models that compute less data with more parameters. Absolute uncertainties on predicted fission cross sections, fission fragment yields, prompt neutrons and photons, etc…, remain high, often too high for application needs.

However, models do bring correlations that can help extrapolation efforts to isotopes that cannot be (easily or not) measured. Some of these model correlations, however, do stem from the rigidity of a too simple model, and can lead to unjustifiably small evaluated uncertainties.

In this talk, I will review the role of both models and experiments to better estimate nuclear fission data, and illustrate the importance of correlations, good and bad, in the evaluation of uncertainties.

Fission studies with TPC and SPIDER: current status and future directions

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Two new instruments for fission studies have been developed for experiments at the Los Alamos Neutron Science Center (LANSCE): a Time Projection Chamber (TPC) and the Spectrometer for Ion Determination in fission Research (SPIDER). The TPC was designed with the primary objective of measuring fission cross sections with high precision and SPIDER was designed for measuring fission mass yields. There are however several other potential applications of these instruments: the tracking capability of the TPC could be used to study ternary fission, angular distribution of fission fragments and neutron-induced charge particle emission. The SPIDER instrument could provide correlations between fragment masses and kinetic energy release, as well as charge yields. Both instruments could be combined with neutron and/or gamma-ray detectors for coincidence measurements. The current status of these projects and future plans will be presented here.

Photonuclear reactions at Extreme Light Infrastructure - Nuclear Physics (ELI-NP)

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Extreme Light Infrastructure - Nuclear Physics (ELI-NP) is under construction in Bucharest-Magurele, Romania and will be operational in 2018. It is meant as a unique research facility to investigate the impact of very intense electromagnetic radiation on matter with specific focus on nuclear phenomena and their applications. Besides very high intensity optical lasers (more than 10^{23} W/cm^2), the facility will benefit of photon beams (E_γ = 0.2 – 19.5 MeV) of unprecedented quality with respect to both photon intensity and spectral intensity. The proposed photonuclear studies using these quasi-monochromatic γ beams are of great interest for nuclear physics and astrophysics. The description of the future ELI-NP facility and of the planned experiments will be presented.