Nuclear data for Minor Actinides: The Am-Cm cases.

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Minor actinides transmutation has been proposed as an alternative way to the high level radioactive waste depositary problem. Several studies of minor actinide burners promote a fast neutron reactor in which minor actinides can be incinerated efficiently by fission. High quality fast neutron induced reaction cross sections (capture and fission) are crucial to provide reliable neutronic design and fuel assessments. But the existing evaluated data files show that neutron data for Americium and Curium isotopes of interest are often of poor quality. The reasons being: the difficulty of obtaining pure minor actinide samples and their huge α radioactivity complicate direct neutron cross section measurements.

We will present an original experimental method that allows overcoming these difficulties. This indirect method consists of measuring the fission probability of a compound nucleus produced via a few-nucleon transfer reaction. The transfer reaction chosen is such that the resulting compound nucleus is on the average the same as the one that would be formed if a neutron would be directly absorbed by the minor actinide. The neutron-induced fission cross section as a function of neutron energy is then deduced from the product of the measured fission probability with the compound nucleus cross section obtained from semi microscopic optical model calculations.

This surrogate technique has already been applied successfully to the determination of the neutron-induced fission and capture cross sections of the 27days short-lived $^{233}$Pa. Comparison with existing (n,f) measurements shows that the method could be a feasible approach for obtaining neutron cross sections where direct measurements are not possible. In a recent experiment, we have again applied this method to determine the neutron-induced fission cross sections of $^{242,243,244}$Cm and $^{241}$Am. The results will be presented. The calculation of the reaction cross sections has been performed with a Hauser-Feshbach statistical model. These theoretical developments will be discussed with examples.
MCAS: A Multichannel Algebraic Scattering theory of low energy nuclear scattering and sub-threshold spectra.

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Low energy cross sections from the collision of nucleons with light mass nuclei show sharp as well as broad resonances upon a smooth, energy dependent background. Those resonances may correlate to states in the discrete spectrum of the target. To interpret such scattering data then requires use of a complex coupled-channel reaction theory. Such a theory is the multi-channel algebraic scattering (MCAS) theory, which has been developed by the collaboration of groups in Melbourne\textsuperscript{1}, Padova\textsuperscript{2}, and Winnipeg\textsuperscript{3}. The theory is quite general being a methodology for solution of the coupled Lippmann-Schwinger equations for the scattering of two quantal systems. For many practical considerations, we have limited study so far to nucleon scattering from light mass targets of zero ground state spin.

The prime information sought are the scattering (S) matrices which are easily extracted from the T-matrices generated by MCAS. The approach involves using matrix methods built using sturmian-state expansions of the relevant nucleon-nucleus potential matrix. The important ingredient found is the matrix form of the Green’s function for the scattering. The matrix structure of those Green’s functions not only facilitates extraction of the sub-threshold (compound nucleus) bound-state spin-parity values and energies but also readily gives the energies and widths of resonances in the scattering regime. It is the nature of the MCAS approach, that facilitates a resonance finding scheme. Thus, in a chosen energy range, all resonances, no matter how narrow, can be identified with their centroids, widths, and spin-parities. A similar procedure also yields all bound states of the compound system sub-threshold, with their energies and spin-parities.

It has long been assumed that collective model prescriptions of nucleon-nucleus scattering violated the Pauli principle. The MCAS procedure enables use of an orthogonalizing pseudo-potential approximation by which such Pauli principle violation can be alleviated. Doing so is crucial to finding the parameter values of the interaction that simultaneously gives the sub-threshold compound nucleus spectrum and the low energy scattering cross sections.

Results are presented for the well-studied scattering of neutrons and protons from \textsuperscript{12}C. For energies up to 10 MeV in the compound nucleus, all compound and quasi-compound resonances observed in total cross-section data are well reproduced, and the sub-threshold states in \textsuperscript{13}C and \textsuperscript{13}N are predicted with correct spin-parities, and at reasonable energies. The results of calculations, in the limit of zero deformation of the target, give precise information on the structure of both the bound states and the compound and quasi-compound resonances in scattering. These results give confidence to proceed to calculations of less well-studied systems. Preliminary results for proton and neutron scattering from \textsuperscript{6}He will be shown as will a more ambitious use for the sub-threshold information on the \textsuperscript{3}He+\textsuperscript{12}C system.

Any form for the initial matrix of coupled-channel potentials can be used and we are studying those arising from a vibration model of nucleon-nucleus reactions as well as those of a shell model description of the target structure. The MCAS theory also lends itself to specification of an equivalent optical model potential and first results indicate that such is extremely non-local. Examples will be shown, time permitting.

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Direct-Semidirect Neutron Capture Calculations in the Resolved Resonance Region

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Abstract

For nuclear data evaluations in the resolved resonance region, where R-Matrix evaluations are commonly performed using the Sammy code, direct capture may be significant between resonant capture peaks, as well as at very low neutron incident energy below the lowest resonance (e.g. thermal capture). The experimental data for which the R-Matrix analysis are performed is subject to background effects that, at energies below 10 keV, could be sufficiently large to obscure the direct capture cross section. Consequently, nuclear data evaluation needs a theoretical model for computation of direct capture cross section.

A method for computing direct-semidirect (DSD) neutron radiative capture is presented, and applied to DSD capture on $^{19}$F, $^{27}$Al, $^{28,29,30}$Si, $^{35,37}$Cl, $^{39,41}$K, $^{56}$Fe, and $^{238}$U, in support of recent and ongoing nuclear data evaluations of these nuclides performed by the Nuclear Data Group, ORNL.

The DSD method includes both direct and semidirect capture; the latter is a core-polarization term in which the giant dipole resonance is formed. We compare our results with those obtained from the TEDCA code that has been commonly used in computations related to astrophysics, as well as in nuclear data evaluations. We also compare our results with those obtained from analytical expression for external capture derived by T. Lane and E. Lynn in 1960, and its later generalization to include internal capture.

The DSD method is implemented in a code CUPIDO, in which, for the sake of simplicity, a spherical symmetry was imposed. While this is a reasonable approximation for many nuclei, it is probably inaccurate for computing DSD capture on $^{238}$U and $^{15}$F, whose quadrupole deformations of 0.215 and 0.275, respectively, indicate highly non-spherical nuclear shapes. Hence, we use these two nuclei to study the effects of non-spherical nuclear wave-functions.

A large discrepancy between experimentally observed $\gamma$-branching ratios for thermal capture on $^{56}$Fe and their corresponding theoretical values was used by Feshbach, Kerman, and Lemmer in 1967 in support of the doorway state hypothesis. We will discuss attempts to compute capture through a doorway state.

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The evaluation of atomic masses - present and future

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Abstract

Different types of experimental data require different procedures for collection and evaluation. In nuclear physics in particular, we might be interested in data on nuclear levels, their energies, their gamma decays,... These “static” data are collected and evaluated “vertically” in a network worldwide (ENSDF). I am more directly concerned with the evaluation of the experimental masses of nuclei - to be more precise their atomic masses - in what we call the Atomic Mass Evaluation (AME). And also, directly connected to the masses, by the experimental properties of ground-states and long-lived isomers of nuclei, their spins, half-lives, excitation energies and decay modes, called the NUBASE evaluation. Masses as well as nuclear and decay properties (both are also “static” data) have in common to require “horizontal” collection and evaluation.

After developing some general ideas about evaluations and explaining the various concepts above, I will describe the most prominent features of the AME, the reasons for its complexity, how they are faced and solved. I will explain why it was found essential to create the NUBASE evaluation and how we finally succeeded in having AME and NUBASE co-ordinated and published for the first time together in December 2003.

The immediate (2008) and far future of the two evaluations will then be sketched and a couple of scenarios presented.

Generalizing the subject to the other evaluations, I will discuss the difficulties in having laboratories, institutes and funding agencies involved in evaluation processes. And also the difficulties in having non-evaluators understand an evaluation process and its differences from a simple compilation of results.

Abstract of a presentation to the P(ND)^2 workshop
“Perspectives on Nuclear Data for the next Decade”
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Differential cross-sections of complex particle emission reactions

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Particle production reactions play a crucial role in nuclear energy and radiation effects. Secondary neutrons in the neutron induced reactions dominate the performance of nuclear energy systems using fission and fusion, and also require special attention in view of the shielding and safety aspects. Charged particles emitted in neutron induced reactions provide prime mechanism of radiation effects in fission, fusion and accelerator-based reactors.

Complex charged particles such as deuteron, α-particles and ones heavier than Lithium (fragments) are of importance in the radiation effects to semiconductor such as single-event upset and latch-up, and may have effects also on the radiation dose to human in the environment of high energy accelerators and the space. The complex particles by heavy ions are of concern as the source extra dose by fragmentation in the heavy ion therapy.

The prediction of cross sections for complex-particle production reaction seems a challenging task to be explored further both in experiments and theory. Experimental works for the complex-particle production and the status of evaluated data or theory will be introduced and discussed.
Experimental neutron data above 20 MeV: What can be done? - What should be done?

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Abstract

The existing and planned facilities worldwide for experimental studies of neutron-induced cross sections above 20 MeV are reviewed. The present status of experimental data is outlined, and future possibilities are discussed.
Isospin dependent dispersive coupled channel optical model potential for actinides

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Abstract

An isospin dependent coupled channel optical model potential (OMP) containing a dispersive term including non-local contribution is used to simultaneously fit the available experimental database (including strength functions and scattering radius) for neutron and proton scattering on strongly deformed actinide nuclei. The energy range 0.001-200 MeV is covered. A dispersive coupled-channel OMP with parameters that show a smooth energy dependence and energy independent geometry are determined from fits to the entire experimental data set. Inclusion of nonlocality effects in the absorptive volume potential and its corresponding dispersive contribution to the real potential is needed to achieve excellent agreement above 100 MeV.

Extensive efforts have been instigated to develop a library of validated nuclear-model input parameters, referred to as the Reference Input Parameter Library (RIPL). An update of the RIPL-2 optical model segment was carried out. Analytical integration of the dispersive relations was included in the RIPL retrieval code, and the format of the optical model database was extended to allow for coupled-channel dispersive potentials and to include recently derived optical model parameters, including those obtained in this work. The majority of new entered data sets are coupled-channel potentials.

The new OMP parameters are highly relevant to other projects of the Agency, namely the ongoing Coordinated Research Project (CRP) on Evaluated Nuclear Data Files for Thorium-Uranium fuel cycle and the CRP on the Reaction Cross Section Data for Minor Actinides which is in preparation.

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Neutron Matter and Binding Energies with a New Gogny Force

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The Gogny force was first introduced in 1980 [1]. The first parametrization D1 gave satisfying results for masses, radii and pairing properties of many nuclei. Unfortunately, the surface energy was too high and D1 was not able to reproduce fission barriers.

To correct for this deficiency, a new parametrization: D1S was proposed [2]. In spite of the numerous advantages of this new interaction compared to D1, we have observed that D1S was still unable to reproduce the Neutron Matter (NM) Equation Of State (EOS).

The NM EOS was predicted by different authors [3,4,5]. Their results, obtained by variational calculations, are very similar. We have chosen the EOS proposed by Friedman-Pandharipande (FP) as our benchmark.

The aim of the present study is to build a new Gogny force which fits the EOS of FP. We have called this new parametrization: D1N. Its properties in nuclei (binding energies, pairing effects, moment of inertia …) are presented.

Systematic study of deuteron induced reactions in the CDCC framework.

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Deuteron is a weakly bound two nucleons system with no excited states. While studying deuteron induced reactions in the early 70's, Rawitscher proposed the Continuum Discretized Coupled Channel (CDCC) approach which takes into account both the deuteron ground state and the continuum states allowing an explicit treatment of breakup. Since then, this approach has been tested and successfully used to analyse these reactions. I have recently written a new computer code to solve the set of ordinary coupled differential equations deduced from CDCC formalism. After briefly reminding the formalism and the numerical approach, I will present a systematic study of deuteron induced reactions with this code using two kinds of global parametrisations (Koning-Delaroche and CH89) for the nucleon optical potentials. This study spans the energy range from 3 MeV to 200 MeV and the mass range from 40 to 208. When experimental data are available, a comparison is performed for elastic differential and reaction cross sections. I will also compare the folding potential derived from CDCC and the global deuteron optical potentials proposed the litterature.
Covariance of energy-averaged cross section depends on dilution of resonant nuclide of target system because of the resonance self-shielding effect.

In the present study, we evaluate the dependency using a covariance processing code, ERRORJ. We show that not only covariance of large resonances but also those of small ones are important when we consider the resonance self-shielding effect in covariance processing. We also evaluate the resonance self-shielding effect on uncertainty propagation to neutronic parameter.
In the recent years, the development of Random Matrix Theory (RMT) [2] has been applied in a great variety of fields that study many-body systems, such as atomic, molecular and nuclear physics, condensed matter theory, electronic and, more recently, RMT was even applied successfully in financial analysis and provided a framework for the study of classical and quantum chaos. Originally, Random Matrix theories have been introduced by Wigner to study the statistical properties of resonance spectra [1]. The energy levels, seen as the eigenvalues of a nuclear hamiltonian, can in principle be obtained by diagonalizing large matrices whose properties preserve usual space-time symmetries. Wigner first suggested a special ensemble of real symmetric matrices, the Gaussian Orthogonal Ensemble (GOE), whose elements are independent and randomly distributed. Subsequently, under the efforts of Dyson, Metha, Porter and others, several random-matrix ensembles were introduced to study the non-conservation of some space-time invariants such as the Gaussian Unitary Ensemble (GUE) of complex matrices and the Gaussian Sympletic Ensemble (GSE) of quaternion matrices. With the development of nuclear shell model calculations, other ensembles such as the so-called Two-Body and k-Body Random hamiltonian Ensembles (TBRE, k-BRE) were also investigated.

The predictive power of RMT, which do not contain any adjustable parameters, is striking and the application is rather simple and fast. Nevertheless, in the evaluation of cross sections in the resolved range, only few results from RMT are routinely used. The goal of this paper is to show how the predictions of the random matrix theory could be used to check the quality of the resolved-range evaluations and guide the evaluator in his choices (spin assignment, detection of spurious levels, doublets or multiplet). Using Monte Carlo simulation of random matrices and recent resonance-parameters evaluations of uranium (see [3] for instance), plutonium and fission product, the present paper illustrates various examples of application. Furthermore, statistical analysis of partial widths with the help of random-matrix theories is also discussed. The use of random-matrix theories is also suggested to study the cross-section fluctuations observed in the unresolved range and detect so-called intermediate structure (such as doorway state). Using neutron resolved-range data, original use of RMT to study the breaking of symmetry/invariance (time reversal, parity, isospin) is also briefly mentioned.

References


Inelastic scattering microscopic calculations with second order Born approximation, link with FKK preequilibrium formalism.

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In a collision between a nucleon and a target nucleus at medium incident energy, several reactions occur, among them elastic and inelastic scatterings, particles emissions, nucleon transfer, knock-out …. In order to describe or predict the observables associated with these reactions, different kind of reaction processes are involved, such as direct, preequilibrium reactions, and compound nucleus formation and decay.

Our goal is to describe elastic and inelastic scattering off double-magic nuclei coming from direct and preequilibrium processes by avoiding phenomenological ingredients. For direct processes, we will review our previous results obtained from fully microscopic optical model potential (OMP) calculations. This OMP is constructed from the Melbourne-g matrix taken as the two-body interaction between the projectile and target nucleons and a RPA (Random Phase Approximation) description of the target nucleus, including correlated ground state. Inelastic scattering is then calculated using RPA description of the target excited states, within the DWBA framework. The results are in fair agreement with experimental data.

This allows us to go further and use these ingredients to describe processes beyond the scope of direct reactions. Among such processes, inelastic scattering with high energy transfer cannot been described using only DWBA calculations. We will focus on inelastic scattering calculations using the Born expansion of the transition amplitude up to the second order and its link with theoretical approaches of preequilibrium reactions such as the FKK (Feshbach, Kerman, Koonin) model. Indeed the FKK approach involves several kind of approximations of the Born expansion of the transition amplitude which have not yet been tested. Comparisons between second order calculations and FKK model predictions allow us to test these approximations, and allows us to discuss on the validity of the FKK model and give some directions to improve the theory.
Indirect methods for nuclear reaction data*

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Nuclear reaction data play an important role in nuclear physics applications. Unfortunately, for a large number of reactions the relevant data cannot be directly measured in the laboratory or easily determined by calculations. Direct measurements may encounter a variety of difficulties: The energy regime relevant for a particular application is often inaccessible; cross sections for charged-particle reactions become vanishingly small as the relative energy of the colliding nuclei decreases; and many important reactions involve unstable nuclear species which are too difficult to produce with currently available experimental techniques or too short-lived to serve as targets in present-day set-ups. Calculations are highly nontrivial since they often require a thorough understanding of both direct and statistical reaction mechanisms (as well as their interplay) and a detailed knowledge of the nuclear structure involved; nuclear-structure models can provide only limited information and very little is known about important quantities such as optical model potentials or spectroscopic factors for nuclei outside the valley of stability.

In order to overcome these limitations, several innovative indirect methods have been proposed in recent years, all of which rely on a combination of theory and experiment for success: *Coulomb Dissociation* has been used to extract cross sections for radiative-capture reactions by studying the time-reversed breakup reaction in which the Coulomb field of a highly-charged target provides a virtual photon that is absorbed by the projectile. The *ANC (Asymptotic Normalization Coefficient) method* has been explored for low-energy reactions which are dominated by processes occurring far outside the nuclear radius; the asymptotic behavior of the nuclear overlap function that determines the reaction cross section is obtained via a peripheral transfer reaction that involves a different target-projectile combination. The *Trojan-Horse method* provides a mechanism for circumventing the Coulomb suppression in low-energy charged-particle reactions by selecting a reaction with a composite projectile consisting of the desired projectile and a spectator fragment. The *Surrogate Nuclear Reaction technique* aims at determining the cross section for a two-step ("desired") reaction that proceeds through a compound nuclear state; the first step of the desired reaction is replaced by an alternative ("Surrogate") reaction and the desired cross section is obtained by combining a calculation of the compound-nucleus formation in the desired reaction with a measurement of the compound-nucleus decay in the Surrogate reaction.

The above methods will provide valuable new information to the international nuclear data effort. It will be important for evaluators to understand the strengths and limitations of these approaches. This presentation will give a brief outline of the indirect methods discussed above and provide some examples. The primary focus of the discussion will be the current status of the theoretical and experimental efforts of the Surrogate Nuclear Reaction approach.

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Microscopic models for nuclear data evaluation and prediction

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Abstract

Most of the nuclear data evaluation and prediction is 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 the global phenomenological and microscopic nuclear theories are detailed and compared for most of the relevant quantities needed to estimate reaction cross sections, namely nuclear masses, nuclear level densities and γ-ray strength. It is shown that nowadays, microscopic 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 evaluation of nuclear data. The added value of microscopic models will be illustrated on some specific examples. The uncertainties associated with the use of different physical models will be discussed. The latest developments as well as the need for further theoretical investigations are stressed.
Microscopic calculations applied to nuclear fission: fission barriers, fragment mass distributions and fission fragment properties.

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Among the different approaches able to describe the fission process, microscopic ones have the advantage of making reliable predictions where few or no data exist. Recent time-dependent microscopic calculations have been performed to derive fission fragment distributions taking into account the full dynamics of the fission process in a consistent framework, where the sole input is the effective nucleon-nucleon D1S Gogny force. The main interest of this study is to describe both the structure effects and the dynamical aspect of the fission process without including any phenomenological parameters. In this talk we will present recent results about fission barriers, fragment mass distributions and fission fragments deformations.
Nuclear Level Densities

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With increasing interest in nuclear structure and reactions concerning nuclei off the stability line, questions regarding the systematics of nuclear level densities in this region are being examined. A recent study based on resolved level counting produced evidence that for a given A level densities were lower for neutron- or proton-rich nuclei than for nuclei in the valley of stability. The effect was small, however, because the nuclei off the stability line were only one or two units in Z away from beta stability.

Currently, both experimental and theoretical work is underway to test these conclusions. It is thought that the reason for reduction in level density is the reduction in single-particle states with narrow width above the Fermi energy. Either the proton (for proton-rich nuclei) or neutron (for neutron-rich nuclei) single-particle state density will be cut off at a low energy if only bound or quasi-bound states are included in the basis. Partially compensating this effect is the fact that the density of the other particle type is extended for such nuclei. Some calculations to test these ideas will be reported.

Measurements to improve the data base for these nuclei are also underway. Proton-rich compound nuclei can be formed with $^3\text{He}$ bombardment; neutron-rich compound nuclei require neutron-rich targets and possibly radioactive beams as well. Some early results will be reported. A Hauser-Feshbach code has been upgraded to allow automatic searches on level density parameters; results obtained with such a procedure will be presented.
R-matrix analysis of low energy neutron cross sections.

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Neutron cross sections in the resolved resonance region can be represented in a concise way using the R-matrix formalism. From measurements of neutron induced reaction cross sections R-matrix resonance parameters can be extracted. The procedure of measuring data and subsequent data reduction and the analysis of the reaction yield will be discussed.
In the next 10-15 years, significant developments of possible importance to evaluators of nuclear data will take place in experimental facilities, techniques, personnel and regulatory environments. Improved facilities based on spallation neutron sources will allow the study of smaller samples so that radioactive isotopes can be used as targets, thereby providing data to test nuclear reaction models for nuclides away from the valley of stability, e.g. fission product nuclides. Improvements in detector arrays and data acquisition systems will make possible more data, relevant to interrogation programs as well as to basic science, on the correlation of radiations emitted from radioactive decay or following neutron-induced reactions. High-resolution measurements of gamma rays will provide new data on reactions, and the interpretation of the data will require an even closer interaction between nuclear-reaction and nuclear-structure specialists. Certain areas of experiments will need to face serious challenges including the de-emphasis of monoenergetic sources, improvements in cross section standards of conventional as well as new types, availability of well-characterized and pure isotopic samples, measurement of inelastic scattering cross sections, creation of a new generation of experimentalists, and the increasingly strict regulatory environment.
Integral Measurements for Nuclear Data Validation

R. Jacqmin

Considerable reliance is placed today on computer-code simulations for nuclear systems design, operation or safety studies. Attempts to optimize or improve the system’s performance translate into requests for reduced uncertainties in the code predictions. In many applications, as uncertainties in nuclear data tend to represent an increasing fraction of the overall uncertainty, such requests for improved nuclear data files have become more pressing. This trend is expected to grow in the coming decade and beyond.

In practice, a measure of improvement will be provided by the reduction in the uncertainties assigned to the code outputs. The evaluation of these uncertainties is part of a formal validation process which makes use of specific integral experiments representative of the applications of interest. This validation process not only entails calculation-versus-measurement (C/E) comparisons, from which average errors and uncertainties can be derived, but also detailed sensitivity and perturbation studies aimed at identifying the origin of the C/E discrepancies in terms of input parameters, in particular the (average) input nuclear data. There are well-established and powerful techniques for doing this.

Inferring meaningful trends in nuclear data from C/E comparisons requires that the integral experiments be sufficiently analytic and diverse, and the corresponding measurements sufficiently accurate and numerous. The large set of reactor physics experiments available at CEA fulfills these conditions; this validation database has made it possible to recommend many improvements in the JEF-2 evaluated nuclear data files.

Progress and growing expectations in the accuracy and reliability of simulation predictions will require better C/E diagnostics, which will in turn require advances in integral experiments such as higher-precision absolute measurements, optimised configurations and measurements. Experiments specially aimed at measuring sensitivities could even be considered. However, there remain challenging situations, such as systems in which important characteristics cannot be measured directly, while depending on many nuclear data.

It is suggested that high-quality integral experiments should progressively be considered as part of the nuclear data evaluation process, together with differential information, rather than being considered separately, as a posteriori information.
Most models of the nuclear density of states are based upon the no interacting Fermi gas, using the single-particle density of states. Advanced Fermi gas calculations build in various aspects of the residual two-body interaction: pairing, deformation, and so on. Alternately one can work in a formalism that fully accounts of the residual interaction from the beginning, such as path integral (Monte Carlo) formulations, and spectral distribution theory (also known as statistical spectroscopy). Using the latter, I will argue that one must fully account for the residual interaction to get the correct density of states. I will also show that contributions from the residual interaction have some useful universal features that may make this task more tractable.
The spin distribution in the pre-equilibrium process is one of the missing issues we have not investigated in the nuclear reaction calculation, since we expect a small impact on the cross sections. However, gamma-ray transition cross section measurements at LANSCE with the GEANIE detector and analysis of those experimental results showed that the spin distribution has a big influence on the gamma-ray transition probability from the high spin states to lower ones. The realistic treatment of the spin distribution may improve the accuracy of calculations of isomer production cross sections with the statistical Hauser-Feshbach model with the pre-equilibrium process. The spin distribution is calculated with the Feshbach-Kerman-Koonin (FKK) quantum mechanical pre-equilibrium theory, and it is incorporated with the GNASH results. The influence of inclusion of FKK on the gamma-ray production cross section is discussed.
Coupled Discretised Continuum Channels Calculations for Nuclear Data Applications

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Coupled Discretised Continuum Channels (CDCC) calculations have become a standard tool in the analysis of reactions involving weakly bound nuclei, at least for systems that break into two fragments (core plus valence particle). However, the technique has not to date been utilised in nuclear data applications, due to the computationally intensive nature of these calculations.

Recent advances in the availability of fast PCs enable us to contemplate for the first time the possibility of employing CDCC calculations for nuclear data evaluations involving light weakly-bound nuclei. A brief introduction to the technique will be given and some of the possibilities and practical difficulties of its potential uses in nuclear data applications will be discussed.
Current status and future of nuclear model-based data evaluation

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Abstract

Nuclear reaction models, and their computational implementation, have become indispensable in modern nuclear data evaluation. To perform adequate inter- and extrapolation on the energy and angular grids per reaction channel, technological software (e.g. a reactor code) relies on a complete representation of a nuclear reaction in a data file, and not only on the data that happen to be available through measurements. For nuclear model evaluation, future research is seen to proceed in two directions simultaneously: broad scale nuclear model calculations (dripline-to-dripline) and the associated comparison with the experimental database and global parameter determination, (b) precise determination of nuclear data for very important nuclides and reaction channels. For (a), microscopic physics, or trends derived from it, is necessary to obtain a credible prediction for unmeasured reactions, while for (b) the experimental data that are of high quality need to be identified from the existing database, or otherwise, need to be re-measured. For both cases, uncertainties play an important role, and the current abilities to generate covariance data will be demonstrated. Next, an outlook is presented for nuclear models and reaction channels that should become routine in the coming 10 years, such as microscopic optical models, quantum-mechanical multi-step theories, microscopic level densities, fission fragments and their neutron spectra, etc. The crucial interplay with experimental data, including the aspects of their storage, will be emphasized.
Mysteries of the smallest nuclear systems

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The great challenge of theoretical nuclear physics is description of nuclear interaction. This goal can be achieved only developing powerful tools (ab-initio methods) to study nuclear structure and reaction mechanisms starting from the first principles, i.e. interaction of single nucleons. Recently big progress has been made in describing the structure of stable nuclei, with A up to 12 [1,2]. However description of simplest nuclear reactions meets serious theoretical drawbacks already on the formal level and achievements in this domain are much more modest [3].

The aim of this contribution is to discuss the current status and perspectives of a few-nucleon calculations, when realistic nucleon-nucleon and three-nucleon interaction are considered. In particular, the formalism of Faddeev-Yakubovski equations [4] will be highlighted, which enables consistent description of scattering and bound states for non-relativistic systems. Some results, obtained employing this formalism for describing scattering process (including break-up and rearrangement reactions) in three and four-nucleon systems will be presented.

References
Does chaos set fundamental limits to our predictive abilities?

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Chaos is an ubiquitous property of dynamical systems, and lurks behind all thermodynamical properties of atomic nuclei. The typical size of its contribution to specific quantities like the nuclear masses or the level densities, may be estimated, and coincides with the observed differences between measurements and calculations. Does this mean that theoretical models have reached the limits of predictability.
Basic Statistics and Consistent Covariances for Nuclear Data Files

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Evaluated nuclear data files are an essential ingredient for the design and construction of nuclear facilities, the radiation safety and the development of novel nuclear technologies. For optimization of the design as well as for the estimate of safety margins reliable information on the uncertainties of nuclear data are required. Therefore, there is an ongoing effort of the nuclear data community to include covariance information into the evaluated nuclear data files. At present, there are only few isotopes for which complete files including covariance information are available.

The generation of covariance matrices and the evaluation of uncertainties is a well defined process in Bayesian statistics. As a starting point it requires a prior which takes into account our complete apriori knowledge of the data and the associated uncertainties. Usually, the prior is based on model calculations and the evaluation of the corresponding covariance matrices is still an open problem and is one of the central objectives of this contribution. The information stemming from experimental data is entered into this procedure in an iterative way and requires a careful study of the measurements, the analyses and possible uncertainties. This so-called Bayesian update procedure is tedious, but straightforward and has been successfully performed for several isotopes at energies up to 20 MeV.

In this contribution we start from the basic concepts of statistics and propose a method for the generation of a prior including covariance matrices. The prior is based on model calculations (optical model, statistical model and coupled channel calculations) in the energy range beyond 1 MeV. The method distinguishes between parameter uncertainties and model deficiencies. Uncertainties due to numerical and algorithm errors are ignored. Emphasis is given to obtain the appropriate probability distributions of the model parameters and their correlations from a basic data set which is not included in the Bayesian update procedure. In addition mean model deficiencies are determined via normalisation of the model calculations to fit the basic experimental data set.

First examples on $^6$Li and $^{208}$Pb are given in order to demonstrate the ability of the method to generate useful priors. We restrict ourselves to integral date and covariances of the type $\langle \Delta \sigma_\alpha(E_i) \Delta \sigma_\beta(E_j) \rangle$, where the indices $i, j$ denote different energies and $\alpha, \beta$ different reaction channels, respectively.

In addition we present a Bayesian update procedure for these two nuclei using an advanced code system for nuclear data purposes. For this purpose a subset of experimental data is studied and corresponding covariance matrices are determined.
Mass Determinations for Nuclear Structure and Astrophysics*

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The binding energy of the nucleus, from its mass, is of great importance for nuclear structure as well as for related branches of physics such as explosive stellar nucleosynthesis. Measuring masses is a particularly challenging task and recent results from dedicated programs world-wide reflect exciting experimental achievements using a panoply of techniques.

Despite the increasing number of mass measurement programs, the masses of many exotic nuclei of interest will remain unmeasured for many years to come. Thus, the interplay between theory and experiment is crucial and new measurements are now used as diagnostics in the development of new microscopic mass models.

We will briefly define the interest of the mass for various problems in nuclear and related physics, introduce the various experimental programs now underway with emphasis on the broad and expanding horizons. We will attempt to quickly review and compare nuclear mass models in order to emphasize the interplay between theory and experiment. The special bridging role played by the Atomic Mass Evaluation will also be illustrated.

The presentation will build on a recent review article [1] and include an update on some of the many results that have appeared in the short time since.

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Nuclear applications of inverse scattering, present ... and future?

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Abstract

There now exists a practical method (iterative-perturbative, IP, method [1]) for the routine inversion of S-matrix elements to produce the corresponding potential. It can be applied to spin-$\frac{1}{2}$ projectiles and spin-1 projectiles. The range of ways that the method can be applied in nuclear physics, both by inverting $S_{ij}$ derived from theory and by inverting $S_{ij}$ derived from experiment (perhaps by means of $R$-matrix fits to experimental data) will be surveyed. An important extension of the method is to ‘energy-dependent-inversion’, i.e. inversion in which $S_{ij}(E)$ over a range of energies is inverted to produce an energy dependent potential $V(r, E) + 1\cdot\sigma V_{ab}(r, E)$, see [2] and references therein. This has allowed us to pin down the parity-dependent (Majorana) component that is present in the interaction between pairs of light nuclei.

The IP algorithm can be convoluted with a direct search on the $S$-matrix to produce ‘direct data $\rightarrow$ V inversion’ an alternative and economical form of optical model fit that can fit many observables (e.g. for polarized deuterons) for many energies to produce a potential with many parameters (e.g. tensor potential for deuterons) fitting the data over a range of energies [3].

This procedure exploits the property of IP inversion that it can be applied to noisy data and produce meaningful interactions because the departure of the final potential from the ‘starting potential’ of the iterative method is under control. Thus, ‘direct data $\rightarrow$ V inversion’ becomes an alternative method [4] for determining phase shifts from data with the constraint that the phase shifts correspond to a ‘reasonable’ potential.

The IP algorithm is flexible and now has far wider applications than originally envisaged, so are there new applications to nuclear data evaluation?

In recent years it was shown that precise measurements of gamma-production cross sections for gammas associated with inelastics scattering and (n,xn) reactions can be performed at a white spectrum time-of-flight facility. This first of all leads to continuous energy excitation curves characteristic of the decay of excited states in the residual nuclei. With enriched samples the different reaction channels leading to the same residual nucleus are disentangled. At GELINA modern data-acquisition techniques have allowed access to the range from threshold to 20 MeV with excellent incident energy resolution (1 keV at 1 MeV, 36 keV at 10 MeV). Since typically for inelastic scattering excitation curves are measured of the decay of the first 15-20 excited levels, these experiments provide detailed information for the validation and optimisation of nuclear model calculations. The relevant aspects are the optical model, direct and pre-equilibrium reactions, level densities, the discrete level and decay scheme and gamma-ray strength functions. Examples will be shown for $^{209}$Bi, $^{207}$Pb and $^{208}$Pb.
Status of the Photonuclear Activation File (PAF): reaction cross sections, fission fragments and delayed neutrons

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Recently a renewed interest in photonuclear processes has appeared. It is motivated by a number of different applications where progress in reliable and, in some cases, very high intensity electron accelerators was awaited. A particular today’s interest is linked to the nuclear material interrogation and non-destructive nuclear waste characterization, both based either on prompt neutron, or delayed neutron, or delayed gamma emission following photo-fission [1].

Major problems in modelling photonuclear reactions are the lack of photonuclear data on corresponding cross sections despite the huge efforts of the IAEA, where evaluations are provided for 164 isotopes only. In addition, no material evolution-depletion code including photonuclear reactions is available. For this reason, in a close collaboration with the LANL, we have been working on the development of a new photonuclear activation file (PAF) to be included into the CINDER’90 evolution code or any other material depletion code [2]. The HMS-ALICE and GNASH reaction codes have been used to calculate photonuclear reaction cross sections for more than 500 isotopes. For photo-fission fragment distributions we employ the fission-evaporation code ABLA from GSI known to give good results in the case of high energy spallation reactions [3]. The release of the 1st version of this photo-activation data file is previewed by the end of 2005.

The photo-nuclear activation data file should also include the information on photo-fission delayed neutrons. These were obtained by the summation techniques of delayed neutron precursors at equilibrium, resulting from the ABLA predictions [3]. In addition, due to the lack of consistent data on photo-fission delayed neutron yields we started an experimental program in a close collaboration with CEA/DAM. Both absolute yields and time spectra of delayed neutrons will be measured for a number of high priority nuclei as uranium and plutonium isotopes in the energy range of Bremsstrahlung photons from the photo-fission threshold up to 19 MeV, i.e. covering the entire GDR region. Preliminary data on photofission delayed neutrons from 238U will be presented.

Finally we add that the GNASH evaluations for some of the most important actinides as 235U, 238U and 239Pu are being prepared in the ENDF format to be included in transport codes. In addition, for the first time, we performed the evaluations of photonuclear cross sections on 237Np and 241Am, which are based on earlier measurements. Good agreement with integral measurement for photofission cross section was obtained using these new evaluations. These evaluations are scheduled to be included in ENDF/B-VII. Both theoretical, data evaluation and experimental parts of the above work will be addressed during this presentation.


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NEA Nuclear Data Services: 
EXFOR, JANIS and the JEFF project

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Abstract. The OECD Nuclear Energy Agency (NEA) Data Bank is part of an international network of data centres in charge of the compilation and dissemination of basic nuclear data. Through its activities in the nuclear data field, the NEA participates in the production of data and their dissemination to nuclear data users. The NEA thus provides an essential link between producers and users of nuclear data. The NEA web site (http://www.nea.fr) offers interfaces to the main nuclear databases with evaluated data, bibliographical information and experimental data.

The NEA administrates the collection, format testing and validation as well as the distribution of the Joint Evaluated Fusion and Fission (JEFF) library. The JEFF project has evolved from the two separate EFF and JEF projects, to JEFF with the release of JEFF-3.0. The release of JEFF-3.1 was on May 2005. A pre-release benchmarking exercise was done prior to its release in order to guaranty the quality of the library.

Within the framework of the JEFF-3 project, the JEFF Working Group on Radioactive Data and Fission Yields decided to produce improved versions of the decay-data and fission-yield libraries. The Activation file was released little time before the release of the General Purpose file. The Decay-Data, Fission-Yields and Activation libraries were released at the same time as JEFF-3.1. A CD with the complete set of libraries is distributed upon request (http://www.nea.fr/html/dbdata/pubs).

The display program JANIS (JAva-based Nuclear Information Software) has been developed at the NEA, and its latest version was released in August 2004. JANIS is designed to facilitate the visualisation and manipulation of nuclear data, and to allow the user access to numerical and graphical representations without prior knowledge of the storage format. In this paper an overview will be given of the nuclear reaction databases EXFOR and CINDA as well as the JEFF evaluation library project. The JANIS display program will also be presented with examples.

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Abstract for the 2005 meeting on the future of theory- and experiment-based nuclear data evaluation.

Nuclear-data measurements at relativistic energies in inverse kinematics

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With the proposition of accelerator-driven systems for the transmutation and incineration of nuclear waste, nuclear reactions up to the GeV range have gained importance for nuclear technology. Thus, the energy range to be covered by dedicated experiments, model developments and evaluation has increased by about two orders of magnitude during the last years.

Previous experimental approaches and conventional evaluation methods are not adapted to the specific characteristics of relativistic nuclear collisions:

1. The large variety of reaction products. (For the system $^{238}$U (1 A GeV) + $^1$H, 1368 nuclide production cross sections have been determined, see figure 1.)
2. The production of very short-lived nuclides. (The products must be identified very fast.)
3. The low energies of most products with respect to the spallation source. (In experiments using normal kinematics, most products do not leave the target.)
4. The large variety of possible target-projectile combinations and the large energy range. (It is illusionary to perform enough experiments to cover all this variety.)

On the experimental side, these requirements have lead to the development of the inverse-kinematics method at GSI, Darmstadt, using a powerful heavy-ion accelerator and a high-resolution magnetic spectrometer. But also the models have changed from predominantly empirical systematics to physical descriptions of the relevant processes with codes rather developed for fundamental research. Finally, it seems to be necessary to develop also new approaches for the evaluation of this kind of nuclear data. The evaluation process should be extended from assuring the quality of the experimental results to providing “data” from the most realistic models for the numerous cases which cannot directly be covered by experiments.

![Figure 1: Measured nuclide production cross sections from the reaction $^{238}$U (1 A GeV + $^1$H)](image)

Specific difficulties for the evaluation process arise from fact that some kind of experiments using the most advanced technique can be performed at only one experimental facility.

In order to assure a productive and reliable evaluation process, the following requirements should be met:

1. The evaluators should be experts of the experimental techniques in order to judge the strengths and eventual problems in the data.
2. The evaluators should be experts of the nuclear-reaction models.

A possible solution to this problem could be a closer collaboration between the “professional” evaluators, providing the sense of reliability and critical mind, on the one side, and the scientists working in fundamental research, providing the scientific (experimental or theoretical) knowledge, on the other side.
Monte-Carlo Simulation of the Fission Fragments
Evaporation Process

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We have developed a Monte-Carlo code to simulate the decay of primary fission fragments by sequential emission of neutrons, followed by gamma-rays, until the fission products reach their ground-state. In addition to average quantities such as the prompt neutrons spectrum and the average neutrons multiplicity, which can be compared to results of the Madland-Nix model, more detailed information such as the neutron multiplicity probability distribution and n-n correlations can be assessed. Several hypotheses for the partitioning of the total excitation energy at scission were made to best account for experimental data.
A microscopic derivation of the nucleon-nucleus optical potential

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In a microscopic many body theory we will show that the nucleon-nucleus optical potential is given by the mass operator of the one-particle Green's function. This operator can be expanded in terms of one and two-particle Green's functions. The first term is the Hartree Fock potential. Further terms contain, on one hand, the coupling of the incident nucleon with the collective RPA states of the target nucleus, on the other hand, the coupling between the incident nucleon and one nucleon of the target, which, under some conditions, is related to the G-matrix. The relative contributions of these two types of correlations will be discussed in terms of incident energy in a very schematic model. The problem of double counting will be also discussed.
Preequilibrium light cluster production in nucleon-induced reactions at intermediate energies

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Abstract

Preequilibrium models have so far been improved in their application to cross section evaluations for nucleon-induced reactions at intermediate energies up to 200 MeV. It is recognized that their predictive powers have reached a satisfactory level for description of nucleon emission processes that are dominant in the nucleon-induced reactions. In this report, we focus on production of light clusters, i.e. deuteron, triton, $^3$He and alpha, in intermediate energy nucleon-induced reactions, whose data are required particularly for estimation of nuclear heating and radiation damage in matter. Any current preequilibrium models are not necessarily complete to account for light cluster production, and their improvement and proposal of new models are desired. Present status of two preequilibrium models for light cluster production, the phenomenological exciton model and the quantum molecular dynamics model, is shown with some comparisons with recent measurements of light cluster production cross sections. The related problems and possible prescriptions are discussed. Finally, a topic of cosmic rays induced single-event upsets (SEUs) in microelectronic device in space and terrestrial environments is presented as one of the needs for intermediate energy nuclear data. Impact of nuclear reaction data on estimation of SEUs is discussed.