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# INDC International Nuclear Data Committee

Summary Report of Consultants' Meeting

# Compilation and Evaluation of γ-Ray Data

IAEA Headquarters, Vienna, Austria

4 - 6 November 2013

Prepared by

Paraskevi Dimitriou
IAEA Nuclear Data Section
Vienna, Austria

Richard. B. Firestone
Lawrence Berkeley National Laboratory
California, USA

and

Sunniva Siem
University of Oslo
Oslo, Norway

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IAEA Nuclear Data Section
Vienna International Centre, P.O. Box 100, 1400 Vienna, Austria

Nuclear Data Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna
Austria

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## Abstract

A summary is given of a Consultants' Meeting assembled to assess current needs in reaction γ-ray data. Participants reviewed the state-of-affairs regarding experimental techniques, new measurements, and new evaluation methods. They concluded that there is urgent need for a Reference Database that would contain a compilation and evaluation of the available reaction γ-ray data. To achieve that they recommended that the IAEA initiate a Coordinated Research Project.

December 2013

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# *1. MOTIVATION*

Gamma-ray data from nuclear reactions are important for a large range of applications, as well as for basic sciences. In particular, γ-ray data to extract Photon Strength Functions (PSF) and photonuclear cross sections are necessary for energy, safety and medical applications as well as for nuclear physics and astrophysics.

There is an explosion of γ-ray data related to PSFs and photonuclear reactions in recent years that needs to be compiled and evaluated, and made available to researchers worldwide. These data are important sources of information for experimental data files such as EXFOR and evaluated data files such as RIPL, ENDF, EGAF, ENSDF etc supported by the IAEA. However, there is currently no comprehensive database that includes all these data, which are also of use in the development and improvement of theoretical models describing the electromagnetic response of the nucleus.

The reaction γ-ray community, at the 4th Level Density and Photon Strength Workshop in Oslo, May 2013, expressed a strong interest to have a reaction γ-ray database under the auspices of the IAEA.

# *2. PRESENTATIONS*

## 2.1. Photoneutron reaction cross sections: new approach for analysis and evaluation (Vladimir Varlamov, Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University)

The majority of partial reactions cross sections as well as of neutron yield and total photoneutron reactions cross sections were obtained using quasi-monoenergetic annihilation photon beams at the Lawrence Livermore National Laboratory (USA) and France Centre d'Etudes Nucleaires de Saclay [1]. Both laboratories employed similar methods to identify reactions with different multiplicities based on the same assumption that the neutron spectra of (γ,1n) and (γ,2n) reactions are quite different. However the methods for neutron kinetic energy measurement used for multiplicity determination were significantly different. Systematic discrepancies (~ 60 %) in partial photoneutron reaction cross sections are a well-known problem [2]: in many cases for the same nuclei the (γ,1n) reaction cross sections are noticeably larger at Saclay, whereas the (γ,2n) cross sections are larger at Livermore.

Many efforts were made to resolve those discrepancies with contradictive recommendations: to multiply Livermore data, to divide Saclay data, to recalculate Saclay data to make them consistent with the Livermore data, etc. It was clear that objective criteria were needed to determine the reliability of the data. After investigation of many sums, differences, and ratios of various cross sections, such objective criteria were found in the form of the transitional multiplicity functions [3] – the ratios of the definite partial reaction cross sections σ(γ,xn) to the neutron yield reaction cross section $\sigma(\gamma,S_n) = \sigma[(\gamma,1n) + 2(\gamma,2n) + 3(\gamma,3n) + \ldots]$. For example, according to the definition $F_2 = (\gamma,2n)/\sigma(\gamma,S_n)$ cannot exceed 0.50 in magnitude under any conditions: its value above this absolute limit would mean a physically incorrect determination of both (γ,2n) and (γ,1n) reaction cross sections. The appearance of regions of physically unreliable values $F_2 > 0.50$, means too large (γ,2n) cross sections in correlation with obviously unreliable negative (too small) values of the (γ,1n) cross section. Correspondingly, the limits for the other multiplicity functions are $F_1 = (\gamma,1n)/\sigma(\gamma,S_n) < 1.00$, $F_3 = (\gamma,3n)/\sigma(\gamma,S_n) < 0.33$, etc. If these functions (ratios) go beyond the absolute limits mentioned, that means that the neutron multiplicity sorting was erroneous.

Investigations of many ($^{90,91,94}$Zr, $^{115}$In, $^{112,114,116,117,118,119,120,122,124}$Sn, $^{159}$Tb, $^{165}$Ho, $^{181}$Ta, $^{188,189,190,192}$Os, $^{197}$Au and $^{208}$Pb) experimental data obtained using neutron multiplicity sorting show [4] that as a rule they do not satisfy the proposed criteria of data reliability. A new experimental-theoretical method of evaluation, based on the well-tested combined theoretical model of photonuclear reactions, was proposed as a method to obtain data that satisfy the introduced criteria. The initial data are experimental neutron yield reaction $(\gamma,S_n)$ cross sections and the neutron multiplicity sorting is calculated according to the model - $\sigma^{eval}(\gamma,in) = F_i^{theor} \cdot \sigma^{exp}(\gamma,S_n)$. That means that the competition of partial reactions (γ,1n), (γ,2n) and (γ,3n) is in accordance with the equations of the model and the sum of evaluated partial reaction cross sections - $\sigma^{eval}(\gamma,S_n) = \sigma^{eval}(\gamma,1n) + 2\sigma^{eval}(\gamma,2n) + 3\sigma^{eval}(\gamma,3n)$ - is equal to the experimental $\sigma^{exp}(\gamma,S_n)$.

The data evaluated using such an approach noticeably disagree with both Saclay and Livermore data obtained using neutron multiplicity sorting but agree with the data obtained using the alternative activation method of identification of the final nucleus in the definied partial reaction channel. Moreover, in many cases, the new evaluated data noticeably disagree with data evaluated in the frame of the IAEA Co-ordinated Research Project on Compilation and Evaluation of Photonuclear Data for Applications [5] - 164 isotopes of 48 elements (from $^{2}$H to $^{241}$Pu).

That CRP played an important role in photonuclear reactions research and applications (systematics, many evaluations, digital data library, etc.) but it has the following definite shortcomings:

- evaluations have been based on the total photoabsorption reaction cross section $\sigma(\gamma,abs) = \sigma(\gamma,1n) + \sigma(\gamma,1n1p) + \sigma(\gamma,2n) + \sigma(\gamma,2np) + \sigma(\gamma,3n) + \ldots + \sigma(\gamma,F) + \sigma(\gamma,\text{charged particles})$;
  for medium and heavy nuclei $\sigma(\gamma,abs) \approx \sigma(\gamma,tot)$, in many cases $\sigma(\gamma,tot)$ have been used instead of $\sigma(\gamma,abs)$;
- because $\sigma(\gamma,tot) = \sigma(\gamma,S_n) - \sigma(\gamma,2n)$, systematic errors in $\sigma(\gamma,2n)$ lead to systematic errors in $\sigma(\gamma,tot)$ and correspondingly to those partial cross section data evaluated on the basis of $\sigma(\gamma,tot)$; in many cases evaluations have been done in order to model accurately the Saclay data and therefore do not satisfy the new reliability criteria;

- evaluations have not been done (though experimental data exist in Berman's EXFOR library [1]) for 37 isotopes for which data are needed not only for applications but for basic research (not only nuclear physics but nuclear astrophysics) also: $^{3}$H, $^{3}$He, $^{6,7}$Li, $^{10,11}$B, $^{14}$C, $^{19}$F, $^{45}$Sc, $^{75}$As, $^{76,78,80,82}$Se, $^{89}$Y, $^{103}$Rh, $^{115}$In, $^{138}$Ba, $^{139}$La, $^{140,142}$Ce, $^{142,143,144,145,146,148,150}$Nd, $^{153}$Eu, $^{160}$Gd, $^{175}$Lu, $^{186,188,189,190,192}$Os, $^{237}$Np;
- many experimental data have been obtained since the end of the CRP using methods other than the neutron multiplicity sorting method;
- new advanced theoretical models have been developed since then.

Therefore a new Coordinated Research Project (or a smaller-scale Data Development Project) would be useful for improving the situation for photonuclear data. Similar to the IAEA CRP (1996 to 1999), the IAEA should coordinate the efforts of experimentalists, theoreticians and evaluators.

## 2.2. Gamma-ray strength functions below the GDER maximum (Milan Krticka, Charles University in Prague)

The presentation gave an introduction to the concept of the PSFs, listed the main methods used in determining the PSFs for energies below the threshold for the particle emission, and summarized some basic features of PSFs in this energy region.

Specifically, it was stressed that the concept of the PSFs for different multipolarities is, in theory, applicable only in the region of sufficiently high level density where we could use the statistical approach. In reality, people routinely use the concept also in the region of not very high density. The use of PSFs in this region is probably not completely justified but we do not have any alternative approach for the description of $\gamma$ decay from the region where the spectroscopic information is incomplete at the moment. On the other hand, the analysis of some experimental data from (n,$\gamma$) reactions indicated that the concept of the PSFs seems to be reasonably justified even at relatively low excitation energies. The importance of a simple treatment of intensities of $\gamma$-ray transitions between excited states for reasonable applicability of the PSFs paradigm was emphasized. The concept of the Brink hypothesis, which was originally suggested only for description of the Giant Electric Dipole Resonance, is almost exclusively used for the description of transitions between excited states. In fact, some of the models of E1 PSF slightly violate the hypothesis as they introduce a dependence of PSFs on nuclear temperature (excitation energy). It was also stressed that knowledge of the fluctuation properties of individual quantities involved in the $\gamma$ decay/absorption is needed for the correct description of the interaction of a photon with a nucleus. The main fluctuations which play a role are the Porter-Thomas fluctuations of partial radiation widths.

In the second part of the presentation, a list of the main experimental methods used for deducing information on PSFs, was mentioned. The problem that almost all the mentioned methods are, to some degree, model dependent was emphasized. It was also stressed that measurements using additional methods, that would carry information on the PSFs, would be of great interest.

Finally, the basic facts on the PSFs which come from experimental data at energies below the particle separation energy were summarized. It was illustrated that there is surely no universal

PSF model which could describe the decay of all medium-weight or heavy nuclei. The illustration also indicated that there are, at least in some nuclei, resonance structures in a PSF at relatively low γ-ray energies. In particular, it was shown that especially the scissors mode M1 resonance, which resides at about 3 MeV in deformed rare-earth nuclei and at about 2-2.5 MeV in actinides, plays a very important role in transitions between excited states. Analysis of data from particle-induced reactions using the "Oslo method" and coincidence data from neutron-induced reactions (Cascade methods) clearly indicate that the scissors mode follows, at least approximately, the Brink hypothesis. In addition, it was mentioned that we do not know sufficiently well the shapes of the PSFs at the above-mentioned energies and that different experimental methods lead to inconsistent PSFs results.

## 2.3. Neutron Capture γ-ray Data (Richard B. Firestone, Lawrence Berkeley National Laboratory)

Neutron capture γ-ray data are an important source of experimental information about γ-ray strength functions. Thermal γ-ray cross section data are maintained in the IAEA/LBNL EGAF database [6], and (n,γ) resonance data are compiled in the ENSDF database [7]. Relevant information can also be found in the CSISRS/EXFOR and ENSDF Adopted Levels, Gammas databases. Thermal neutron capture measurements can be performed with guided neutron beams at the Budapest and Garching FRM-2 reactors, while resonance neutron capture data can be measured at the LANL DANCE facility, CERN nTOF, and other laboratories.

Cold/Thermal (n,γ) measurements with guided neutron beams have the advantage over reactor measurements of much lower backgrounds at the target station and a complete absence of fast neutrons. Measurements at the Budapest and Garching FRM-2 reactors were performed using Compton suppressed HPGe detectors that reduce the background in the high-energy primary γ-ray region by over an order of magnitude. These measurements are internally calibrated with primary cross section standards to precisely determine the cross sections for production of neutron capture γ-rays. The primary γ-rays can provide sensitive measurements of the average strength and statistical distribution of radiative widths selectively for E1, M1 and E2 transitions. Primary γ-ray photon strength are defined by the equation

$$f(E_\gamma) = P_\gamma \Gamma_\gamma / (d_0 \cdot E_\gamma^3), \qquad (1)$$

where $E_\gamma$ is the primary γ-ray energy (MeV), $\Gamma_\gamma$ is the capture state width (eV), and $d_0$ is the average level spacing at $E_{\mathrm{excit}}$ (eV). For EGAF thermal capture data $E_{\mathrm{excit}} = S_n$ and $P_\gamma = \sigma_\gamma / \sigma_0$, where $\sigma_\gamma$ is the primary γ-ray cross section (barns) and $\sigma_0$ is the total radiative neutron cross section (barns). $\Gamma_\gamma$, $d_0$, and $\sigma_0$ are available in Mughabghab's Atlas of Neutron Resonances [8]. The experimental photon strengths can be compared to theoretical predictions such as Brink-Axel [9, 10] for E1 transitions defined as

$$f_{BA}^{E1}(E_\gamma) = \frac{1}{3(\pi\hbar c)^3} \sum_{i=1}^{i=2} \frac{\sigma_{G_i} E_\gamma \Gamma_{G_i}^2}{(E_\gamma^2 - E_{G_i}^2)^2 + E_\gamma^2 \Gamma_{G_i}^2}\ , \qquad (2)$$

where $E_{G_i}^2$, $\Gamma_{G_i}^2$, $\sigma_{G_i}$ are the energy, width, and cross section for the Giant Dipole Resonance (GDR). In deformed nuclei the summation is over two (i = 1, 2) sets of GDR parameters. For M1 transitions no such general theory is available.

For thermal neutron capture each primary γ-ray provides a single photon strength measurement. The strength averaged over many transitions can be directly compared to modeled strengths if all transitions to the final state excitation region are observed. This is the case for $^{197}$Au(n,γ), as shown in Fig. 1 where the systematics of binned average experimental E1 primary γ-ray strengths for 14 nuclides are compared to Brink-Axel, KMF [11], and GLO [12] models. Although agreement with Brink-Axel seems best, corrections for weak, unobserved transitions, especially at low energies are necessary. Fig. 2 shows the systematics of binned average experimental M1 primary γ-ray strengths for 10 nuclides compared to the Brink-Axel model.

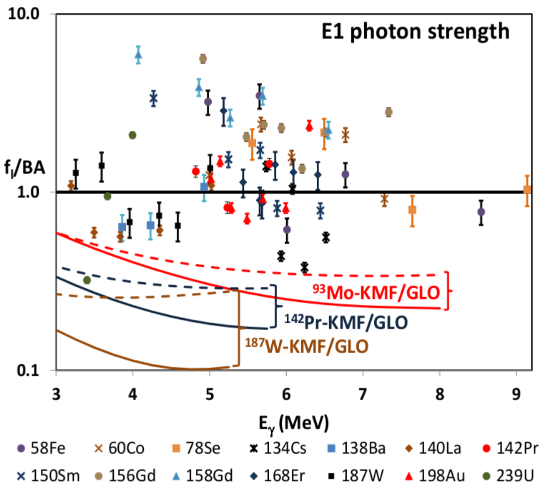

***FIG. 1.*** *Binned average E1 primary γ-ray strengths for 14 nuclides are reduced by the Brink-Axel predictions. Although this comparison appears inconsistent with KMF and GLO E1 models, corrections for unobserved transitions may be important.*

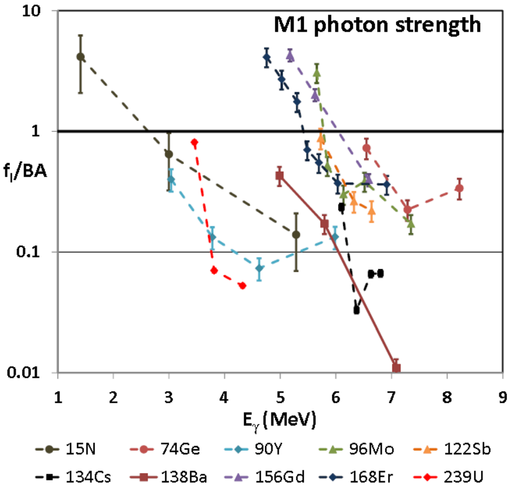

***FIG. 2.*** *Binned average M1 primary γ-ray strengths for 10 nuclides compared to the Brink-Axel predictions. These strengths need to be corrected for unobserved transitions, especially at low energies.*

Each example shows a significant increase in M1 photon strength at low energies apparently exceeding E1 strength at these energies. These results suggest that while M1 strengths may be ignored at higher energies, they must be accounted for below the neutron separation energy. Similar analyses of photon strengths can be determined from average resonance capture (ARC) data where the average strength from the resonance region populating levels of known spin and parity can be analyzed as described above. Although ARC data are primarily s-wave capture, contributions from p-wave capture may also be important and must be accounted for. Similarly, individual resonance decay data from TOF measurements [13] can also be analyzed to determine photon strengths. Additional photon strength information in the resonance region can be obtained with the LANL DANCE 4π-BaF$_2$ array, although analysis of data from that facility has proven challenging due to detector cross talk.

Although (n,γ) capture data can provide a wealth of information about photon strengths below the neutron separation energy, there is little data available for very low-energy γ-rays. Another source of photon strength information can come from the ENSDF Adopted Level, Gammas data where the lifetimes of many low-lying levels are known. In these cases individual photon strengths can be determined, as described above, where $d_0$ is either observed experimentally or can be calculated accurately from level density models. An example is shown in Fig. 3 for $^{158}$Gd [14] where photon strengths down to 50 keV can be determined. Preliminary results suggest that the Brink-Axel model is applicable for E1 transitions down to very low energies.

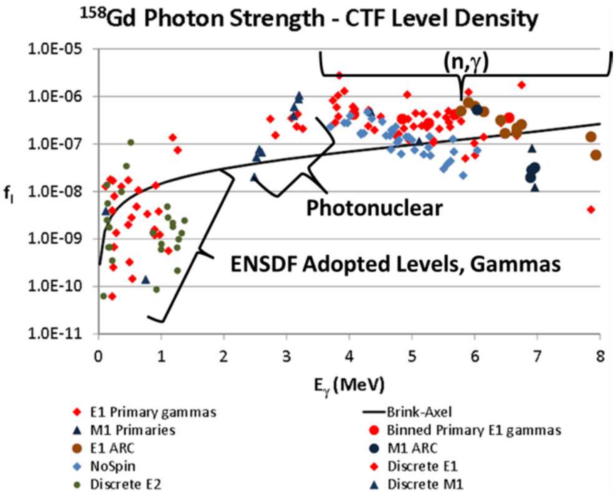

***FIG 3.*** *Comparison of photon strengths from EGAF (n,γ), ARC, and ENSDF photonuclear and Adopted Level, discrete γ-ray data.*

## 2.4. Simulation of γ cascades emitted by highly excited nuclei (František Bečvář, Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic)

Many nuclear reactions lead to the formation of a highly excited compound nucleus which decays to the ground state by cascade emission of γ rays. There exists a wide class of experiments designed for studying this decay mode. In general, the observables in these experiments are sensitive to intensities of enormous number of individual transitions responsible for γ-ray emission, so that energies of these transitions cannot be resolved from each other. This kind of experiments are thus of integral character in the sense that only global characteristics of the γ decay can be inferred.

Ignoring direct processes, the γ-ray intensities are proportional to the corresponding partial radiation widths. Within the statistical model of the nucleus the *expectation* value of partial radiation width $\Gamma_{a\gamma b}$ for γ transition from level $a$ to level $b$ is uniquely determined by the photon strength function $S_\gamma^{XL}(E_\gamma)$ for a given multipolarity $XL$ and level density $\rho(E_a)$, where $E_\gamma$ and $E_b$ are the γ-ray energy and energy of final level $b$, respectively. In accordance with predictions of the random matrix theory, the value of $\Gamma_{a\gamma b}$ itself behaves as a sample drawn at random from the Porter-Thomas distribution.

The knowledge on PSFs in a broad γ-ray energy region is of importance for nuclear physics, nuclear spectroscopy and nuclear astrophysics, but also for nuclear technologies and other applications.

Almost as a rule, the observables in experiments devoted to study of γ decay are not originating exclusively from contribution of primary γ rays, which carry the needed information on PSFs, but also from undesired contribution of the remaining γ rays forming the cascades. In addition, all contributing transitions are subject to Porter-Thomas fluctuations. To retrieve the data on PSFs in these adverse conditions, the trial-and-error approach is evoked: (i) models for level density and PSFs for individual *XL* are postulated, (ii) adopting these models, γ cascades are simulated, and (iii) having a large number of these cascades, the observables from a fictitious experiment are deduced from all γ-ray energies, forming the cascades, and compared with their corresponding values obtained from the real experiment. Then, depending on the outcome of the comparison, another set of PSF models is postulated and a next trial-and-error iteration is carried out until the best agreement is reached.

For the purpose of simulation of γ cascades, an algorithm DICEBOX has been developed [15]. It respects the basic postulates of the statistical model, including the validity of the concept of photon strength functions. Among others, the algorithm takes properly into account the Porter-Thomas fluctuations of partial widths and optionally the short- and long-range correlations between level energies.

The algorithm involves two ranks of simulations. Any of rank-I simulations yields level energies for individual values of $J^\pi$ and a set of *all* partial radiation widths for *each* simulated level, except for the levels below an adjusted critical energy, where the complete decay scheme is known from experiments. So to speak, a fictitious nucleus is created. As for each of these nuclei the decay rate for any transition $a\gamma b$ is known, the rank-II simulations, mimicking the cascading process proper, can be performed to yield all attributes of individual cascades. With this knowledge, predictions of cascade-related observables can be obtained. Having these predictions for a large set of artificial nuclei, expectation values of the observables of interest can be estimated together with their irreducible uncertainties due to Porter-Thomas fluctuations.

This difficult task has been solved with the aid of the so-called precursors (random-generator seeds) ascribed to each simulated level prior to launching type-II simulations of Markovian process of γ cascading, see Ref. [15].

The class of observables which can be simulated is wide. Concerning the studies of PSFs, it includes, e.g. γ-ray spectra of two-step γ cascades following the thermal neutron capture [16], spectra of multi-step cascades accompanying neutron capture at isolated or unresolved neutron resonances [17, 18] and side-feeding contributions to populations of low-energy levels from neutron capture [16]. However, simulations according to DICEBOX algorithm have also found applications in such distant areas like in design of an antineutrino detector for cooperative monitoring of nuclear reactors [19] and in the development of large detectors for particle physics [20]. Thanks to its adaptability, the DICEBOX algorithm could be used for validation of model-independent approaches to studying photon strength functions [21].

The most important feature of the DICEBOX algorithm is that it evaluates Porter-Thomas uncertainties of the simulated observables. This made it possible to draw the first, *firm-enough* conclusions about existence of *M*1 scissors-mode resonances built on excited levels in deformed nuclei [16].

DICEBOX algorithm seems to be a promising tool for future efforts towards upgrading of the Evaluated Gamma-Ray Data File [22] and potentially for solving persisting discrepancies in some data on PSFs from different experiments.

The existing implementations of DICEBOX algorithm have already been used in several laboratories - in LANL, LLNL, LBNL, TUNL, CERN, FZD (Dresden), R.P.I., ILL (Grenoble), University of Oslo, CEA (Saclay) and others.

## 2.5. Measuring the photon strength function below $S_n$ (Mathis Wiedeking, iThemba LABS)

In this presentation a recently developed experimental approach to extract the photon strength function (PSF) using charged particle reactions is presented. The PSF for $^{95}$Mo was extracted [23] and compared to results from the Oslo Method [24]. In particular, the existence of the low-energy enhancement in the PSF could be confirmed independently for the first time. An overview of PSF data, below the separation energy, obtained with several experimental techniques is presented and some of the inconsistencies are discussed. The need for specific measurements which are needed to resolve existing problems with the data is presented.

The new technique is based on the simultaneous detection of correlated particle-$\gamma$-$\gamma$ events. The charged particles from the reactions are detected in particle telescopes and are used to infer the entrance excitation energy of the residual nucleus. Simultaneously, two $\gamma$-rays in coincidence are detected in high-resolution, high-purity germanium detectors. Transitions from low-lying discrete levels are tagged to extract the primary $\gamma$-ray transitions in coincidence. Additionally, the energy sum of the two $\gamma$ rays are required to be equivalent to the excitation energy within the value of the particle telescope's full-width have maximum. These stringent conditions allows for an unambiguous extraction of primary transitions to individual discrete levels from which the PSF can be extracted. The PSF in $^{95}$Mo, which was populated in the (d,p) reaction was compared to data from ($^3$He, $^4$He) reactions extracted using the Oslo Method.

An unexpected low-energy enhancement in the PSF was first presented in Ref [25] and has since been reported for other medium- to light-mass nuclei utilizing the Oslo Method. The results, obtained with the new technique, confirm the existence of the low-energy enhancement independently for the first time. The origin and underlying physical mechanism for this enhancement remains unexplored although the first theoretical calculations which have recently become available suggest very different mechanisms for its origin being either 1) E1 transitions in the single-(quasi) particle continuum [26] or 2) M1 transitions due to the re-alignment of proton and neutron angular momenta [27].

Open questions remain not only regarding the physical mechanism of the low-energy enhancement but also on its extent across the nuclear chart. Features of the PSF below the particle threshold are often used to estimate reaction rates for nucleosynthesis models. For example, it has been shown that r-process rates are enhanced by orders of magnitude if the low-energy enhancement exists [28]. Despite its central role, information on the PSF for very neutron-rich nuclei (amongst others) are based on extrapolations from data obtained using stable beam and targets.

Generally, there is a lack of data regarding the following aspects of the PSF:

- The persistence of features, such as the low-energy enhancement, to very neutron- (or proton-) rich systems.
- Extent of the low-energy enhancement and other features across the nuclear chart.
- Inconsistencies between results from different experimental techniques.
- Dependence of the PSF on the reaction mechanism.
- Effect of nuclear structure effects (deformation, triaxiality, K-quantum number…) on the PSF.
- Differences and inconsistencies in the normalizations between different results.
- Validity of the Brink Hypothesis.

## 2.6. Charged-Particle Reaction Data (Sunniva Siem, University of Oslo)

The nuclear physics group in Oslo has developed a unique technique (the so-called Oslo method) to extract simultaneously the level densities and $\gamma$ strength function from primary $\gamma$-ray spectra, in the region below the particle separation energy. These are fundamental properties of the atomic nucleus and important input parameters in reaction cross-section calculations, used in reactor physics simulations and astrophysics models of formation of heavy elements in explosive stellar environments.

In this presentation a short description of the experimental facility in Oslo, the Oslo method and recent experimental results obtained for the $\gamma$ strength function was discussed.

The Oslo Cyclotron can deliver light-ion beams of protons, deuterons, $^3$He and alpha particles. The charged ejectile particles are detected in coincidence with $\gamma$ rays from the excited residual nucleus by the multi-detector system CACTUS. Charged particles are detected by the $\Delta$E-E particle telescope called SiRi (Silicon Ring). One of the main components of the Oslo method is the extraction of the primary $\gamma$ rays as a function of excitation energy. The distribution of primary $\gamma$ rays contains information on both the level density and the $\gamma$ strength functions, which are then extracted simultaneously in an iterative procedure [29]. The Oslo method yields the functional form of the level density and $\gamma$ strength functions, but for the absolute normalization, auxiliary data such as the neutron resonance spacing and the average radiative width are needed. The level density and $\gamma$ strength function has been studied for a wide range of nuclei, from the light Si to the heavy U isotopes.

The $\gamma$ strength function is dominated by the Giant Electric Dipole Resonance (GEDR) and often one uses the extrapolation of the tail of the GEDR to describe the strength function at low $\gamma$ energy. But an unexpected enhancement of the $\gamma$ strength function at low $\gamma$ energy has been observed in several nuclei [24,25]. The origin of this low energy enhancement is still an open question, but it´s existence was recently confirmed in a new model-independent method to extract $\gamma$ strength functions [23]. This low energy enhancement has the potential of increasing neutron-capture rates with up to two orders of magnitude if also present in very neutron-rich nuclei [28], which can influence the results of large network calculations of supernova explosions.

In resent data on actinide nuclei, relevant for the Thorium fuel cycle, we observe a large orbital scissors strength for several actinide nuclei [2]. This scissors strength leads to an increased neutron-capture cross section, so it should be included in reactor simulations to get more accurate results.

The Oslo method has been tested using the DICEBOX algorithm in collaboration with Charles University, Prague. Different level densities and γ strength functions were used as input in the DICEBOX algorithm. The resulting total γ spectra from the simulations were then analyzed with the Oslo method. The agreement was very good.

## *3. OVERVIEW OF EXISTING DATA*

### 3.1. Photonuclear data (γ,xn/xp)

A database of photonuclear data was generated under an IAEA CRP in 2000. The database, which is available at the IAEA website (http://www-nds.iaea.org/photonuclear), includes γ absorption data, total and partial photo-neutron reaction cross sections, neutron emission energy spectra for 164 isotopes (from $^{2}$H to $^{241}$Pu), primarily for structural, shielding, biological and fissionable materials.

Although this database has been extremely useful to a broad community, it is now evident that it needs to be revised especially since:

- Some of the data are unreliable and discrepant.
- For 37 isotopes ($^{3}$H, $^{3}$He, $^{6,7}$Li, $^{10,11}$B, $^{14}$C, $^{19}$F, $^{45}$Sc, $^{75}$As, $^{76,78,80,82}$Se, $^{89}$Y, $^{103}$Rh, $^{115}$In, $^{138}$Ba, $^{139}$La, $^{140,142}$Ce, $^{142,143,144,145,146,148,150}$Nd, $^{153}$Eu, $^{160}$Gd, $^{175}$Lu, $^{186,188,189,190,192}$Os, $^{237}$Np) there exist data that have not been evaluated but can be used in basic research (not only nuclear physics but nuclear astrophysics also).
- There exist improved evaluation techniques.
- Many new data have become available in the recent years.

### 3.2. Photon scattering cross-section data (γ,γ')

These data are important for the investigation of the PSF below the neutron separation energy in an energy region which is so far poorly explored. There has been an increase in new photon scattering cross-section data (γ,γ') coming from recently commissioned facilities. Currently, there is no database that compiles these data for easy access by the user community.

### 3.3. Charged-particle reaction γ-ray data

There has been a growth in the development of large detector arrays for the measurement of reaction γ rays in coincidence with emitted charged particles. These experiments provide a capability for investigating the PSF below the particle emission threshold. Although some data (obtained using the Oslo method) are made available through the website: http://www.mn.uio.no/fysikk/english/research/about/infrastructure/OCL/nuclear-physics-research/compilation/, there is no dedicated database which provides all these data to the applications and basic research community.

### 3.4. Neutron-capture γ-ray data

Recently there has been significant development of guided neutron beam facilities for the measurement of thermal and cold neutron-capture γ rays. Primary γ rays from these experiments have been compiled in the IAEA EGAF database (http://www-nds.iaea.org/pgaa/) and can be useful in investigating the distribution of individual primary γ-ray strengths. These data are supplemented by average resonance-capture data and neutron time-of-flight data that provide additional measurements of photon strengths.

Additionally, coincidence measurements of γ rays allow the investigation of the PSF in the so-far poorly explored quasi-continuum region [30]. There are several experimental facilities where coincidence measurements of γ rays are being performed. These data are complementary to the measurements mentioned above, but have not been compiled in a dedicated database so far.

## 4. *EXPERIMENTAL METHODS*

A list of the main experiments that are used to extract PSFs and photonuclear cross sections is given in this section. Each experiment has unique strengths and weaknesses that need to be assessed. Additionally, new experiments may also need to be proposed to resolve questions that cannot be addressed with the current methods.

### 4.1. Photonuclear cross-section measurements (γ,xn/xp)

The majority of partial photonuclear reaction cross sections have been obtained using the method of neutron multiplicity sorting which in many cases does not give reliable results. The criteria of partial photoneutron reaction cross section data reliability are the especially introduced multiplicity transitional functions $F_i$ – ratios of the definite partial reaction cross sections σ(γ,xn) to the neutron yield reaction cross section $\sigma(\gamma,S_n)$ (see Section 2.1). For example, according to the definition $F_2$ cannot exceed 0.50 in magnitude under any conditions: its value above this absolute limit would mean a physically incorrect determination of the (γ,2n) reaction cross section and the corresponding (γ,1n) reaction cross section. Investigations have shown that many experimental data as well as previous evaluations of IAEA CRP (1996 - 1999) do not satisfy the introduced criteria (for more details see Refs. [3, 4, 31-33])

## 4.2. Photon scattering cross-section measurements (γ,γ')

The photon scattering cross section below the neutron emission threshold is directly related to the PSF. It can be measured by:

- **Using (quasi)mono-energetic beams of photons**
  The photon scattering cross section is determined as a sum of intensities of detected transitions feeding directly the ground state and intensities of transitions de-exciting the lowest excited levels [34]. Unfortunately, there is a part of the cross section which is usually not considered [35]. Recently, it was also shown that the feeding of low-lying levels allows checks of assumptions used in the derivation of PSFs [36].

- **Using Bremsstrahlung photon sources**
  The photon scattering cross section is usually determined from analysis of experimental γ-ray spectra using an iterative method [37].

## 4.3. Charged-particle reactions

- **Oslo method**
  The Oslo method is a technique to extract simultaniously the level densities and γ strength functions from primary γ-ray spectra [38, 39]. Charged particle-γ coincidences are measured, and from reaction kinematics a matrix of total γ-ray spectra as a function of excitation energy, up to the neutron (proton) binding energy is obtained. After correcting for the detector response function the distribution of the primary γ-ray spectra from each excitation energy bin are determined through an iterative subtraction procedure [40]. From the primary γ-ray spectra the level density and γ-transmission coefficient are extracted using the least $\chi^2$ method given in [38]. The power of the Oslo method is that it provides simultaniously the functional form of both the level density and γ strength function. And one can study resonnant decay in the quasi-continuum, like for example determine the strength of the scissors mode buildt on excited states. This method measures only the total γ strength function and cannot give information about the E1 and/or M1 character of the γ strength observed. A weakness of the method is that for the absolute normalization it relies on other experimental data like the neutron resonance spacing to get the level density at the neutron binding energy and the average total γ width.

- **Particle-γ-γ method**
  A model-independent experimental technique has recently been developed [23] to extract the shape of the PSF below the particle threshold. The method involves the use of coupled high resolution particle and γ-ray spectroscopy. Its power lies in the ability to positively identify primary γ-ray decay from well-defined excitation energy regions to individual low-lying discrete states. A key aspect is the detection and extraction of correlated particle-γ-γ events. Proton energies from the silicon telescopes determine the entrance excitation energy into the residual nucleus produced in the reaction. Tagging on γ-ray transitions originating from low-lying discrete levels specifies the states which are being fed by the primary γ rays. When a discrete transition is detected in coincidence with a charged particle, additional requirements are applied to the second γ ray, so that the energy sum of the discrete and primary transition equal to the excitation energy. Any particle-γ-γ event satisfying these conditions provides an

unambiguous determination of the origin and destination of the observed primary transition. Events that do not conform to these requirements are rejected.

## 4.4. Cascade method

Coincident spectra of $\gamma$ rays, measured either with high-resolution Ge detectors or lower-resolution scintillation detectors, that usually originate from the radiative capture of slow neutrons are compared with predictions from simulations using different models of PSFs [30]. The code DICEBOX, see Section 5, is used for producing the simulated spectra.

## 4.5. Gamma-ray cross-section measurements

There are three primary methods for measuring partial $(n,\gamma)$ cross sections for individual $\gamma$ rays. Thermal/cold $\gamma$-ray cross sections have been determined using guided neutron beams, ARC cross sections are measured with filtered neutron beams, and resonance $\gamma$-ray cross sections are measured by neutron time of flight (nTOF). These experiments can be done with neutrons from nuclear reactors, charged particle reactions at nuclear accelerators, or neutron generator facilities.

- Thermal/cold neutron beams can be produced in nickel lined guides that transport the neutrons with few losses to low-background counting stations far from the neutron source. If the guides are curved, no fast neutrons reach the target area. At the Budapest Reactor [41], cold and thermal neutron beams are transported through a curved neutron guide to the Prompt Gamma-ray Activation Analysis (PGAA) target station ≈35 m from the reactor wall. The beam flux at the target is $\leq 1.2\times10^{8}$ $cm^{-2}s^{-1}$. A similar experimental configuration has been constructed at the Garching FRM-2 reactor [42]. The prompt $\gamma$-ray intensities are converted to cross sections using stoichiometric compounds or mixtures containing $\gamma$-ray cross section standards such as H, N, Cl, S, Na, Ti, or Au [43]. These standardizations have been compiled in the Evaluated Gamma-ray Activation File (EGAF) [6] for all elements with Z = 1-83, 90, 92 except for He and Pm. Since thermal/cold neutron capture is completely s-wave, the capture state has a unique parity so that the multipolarity of primary $\gamma$ rays populating levels of known spin and parity can be directly inferred.

- Average Resonance Capture (ARC) data are typically produced with $^{56}$Fe (2 keV) or $^{45}$Sc (24 keV) filters that yield beams a few keV wide. The ARC neutron energy range is sufficiently narrow enough that primary $\gamma$-ray widths are only slightly broadened allowing the discrete $\gamma$-rays transitions to be readily analyzed. ARC experiments usually measure primary $\gamma$-ray relative intensities that can be converted into transition probabilities by either statistical model calculations, or normalizing to the sum of transition probabilities to low lying states to that observed in thermal neutron capture, compiled in the EGAF file. Although ARC data are usually dominated by s-wave capture, significant p-wave capture may also occur and must be corrected for to determine photon strengths.

- Primary $\gamma$-ray intensities observed in neutron time-of-flight (nTOF) experiments are typically converted to absolute partial cross sections by the measured neutron capture rate at each resonance. Typically many resonances can be observed in a single experiment. These data can be analyzed for each resonance to determine the photon strength in the same way as thermal neutron capture data. The individual $\gamma$-ray intensities, which can be converted to primary γ-ray strengths via Eq. (1), are expected to vary randomly by a Porter-Thomas [44] distribution and primary γ-ray strengths populating known final levels can be averaged to determine the average photon strength. Spins and parities of individual resonances observed in nTOF experiments are usually well known.

Data from thermal/cold, ARC, and nTOF neutron capture experiments provide complementary primary γ-ray photon strength information for transitions of known multipolarity. These measurements complement information from charged particle and photonuclear reactions where the multipolarity is often not determined. These data can also be used to investigate the statistical distribution of photon strengths which is assumed to be Porter-Thomas.

## 5. *ANALYSIS AND EVALUATION METHODS*

A list of methods used in the analysis and evaluation of reaction γ-ray experimental data is given below:

- A new approach for evaluating photonuclear cross section data has been proposed combining neutron yield reaction cross sections and model calculations of partial photonuclear reaction contributions. Results obtained for about 20 isotopes [3, 4, 31-33] reveal the unreliability of many experimental and previously evaluated data and therefore, the method should be applied to other isotopes. These data are critical for the determination of the GDR parameters which are needed for calculation of the photon strength models.

- DICEBOX: a Monte Carlo Code for the simulation of γ-ray cascades which takes into account Porter-Thomas fluctuations and the Markovian process of γ-cascade emission [15,16]. The code has been proven highly effective in the analysis of a wide variety of PSF related data. There has been a broad demand for access to the DICEBOX code.

- Nuclear Reaction Codes TALYS [45], EMPIRE [46]: computer codes for the simulation of nuclear reactions involving neutrons, protons, photons and light ions in the energy range from 1 keV to 200 MeV, and for target nuclei of mass heavier than 12. These codes consist of various nuclear models and can be used for the theoretical analysis of nuclear reaction experiments and also for nuclear data evaluation. By considering all the energetically possible decay channels for a particular excited system, these codes can calculate the cascade of γ rays leading to the complete de-excitation of the excited system to its ground state. For this purpose, they rely on up-to-date nuclear structure information [47].

A systematic inter-comparison of the γ-ray cascades and photo-reaction cross sections produced by the above-mentioned codes, as well as a comparison with available photo-reaction data using the same PSFs, may provide useful insight in the implementation of the physics models in the codes, and also in the PSF parameterizations themselves. The evaluation of photonuclear cross sections and PSFs will provide valuable input to a future revision of the IAEA Reference Input Parameter Library (RIPL) [47].

# 6. COMPARISON OF EXPERIMENTAL AND EVALUATION METHODS

From a comparison of the experimental and evaluation methods listed in the previous section, it becomes clear that different methods give different results. These discrepancies need to be resolved before any data can be recommended for use by the scientific and applications community. Some examples are given in the following:

- The situation above the particle threshold emission is illustrated in Fig. 1. Here, one can see the discrepancies in the measured and evaluated cross sections for the photonuclear reaction $^{197}$Au(γ,2n). The evaluation produced by the IAEA CRP on Photonuclear Data (http://www-nds.iaea.org/photonuclear/) (using GUNF and GNASH codes in order to model accurately the Saclay $^{197}$Au(γ,Sn) data [48]) do not satisfy noticeably introduced reliability criteria.

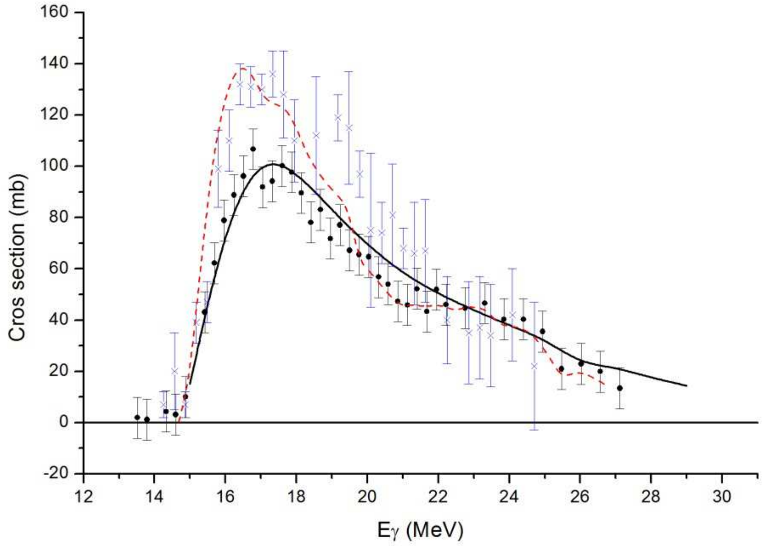

***FIG. 1**. Comparison of experimental data from Saclay [48] (circles) and Livermore [49] (crosses) for $^{197}Au(\gamma,2n)^{195}Au$ reaction cross section with evaluated data (line – IAEA CRP, dotted line - new evaluation based on data reliability criteria $F_2$).*

- There are only a few cases of isotopes for which different methods were used to determine the photon strength below or near the particle separation threshold. Figure 2 shows one such case, $^{98}$Mo [50], which reveals the discrepant results obtained from the different experimental methods listed in the previous section. Specifically, the figure shows that PSFs derived using the Oslo method from data measured in ($^3$He,$^3$He') reaction (green squares) [24] display very different shape from the strength function deduced from a measurement of photon scattering cross section, (γ,γ') – high energy, using Bremsstrahlung beam (black circles) [51]. It is interesting to note that photon strength deduced from measurement of intensities of γ transitions exciting levels near 3 MeV [52] indicate a very good agreement with ($^3$He,$^3$He') data. In addition, the problem with the photon strength derived from radiative neutron capture measurement on isolated resonances is indicated. The only difference in the two data from (n,γ) is the assumed resonance spacing which was taken from two different sources, Ref. [53] for "original" and [54] for "recalculated" data. For details see Ref. [50].

Clearly there is a need to perform an inter-comparison of measurements for one or more isotopes in different mass regions to investigate the potential causes of these discrepancies. The development of a database dedicated to reaction γ-ray data would help such an effort.

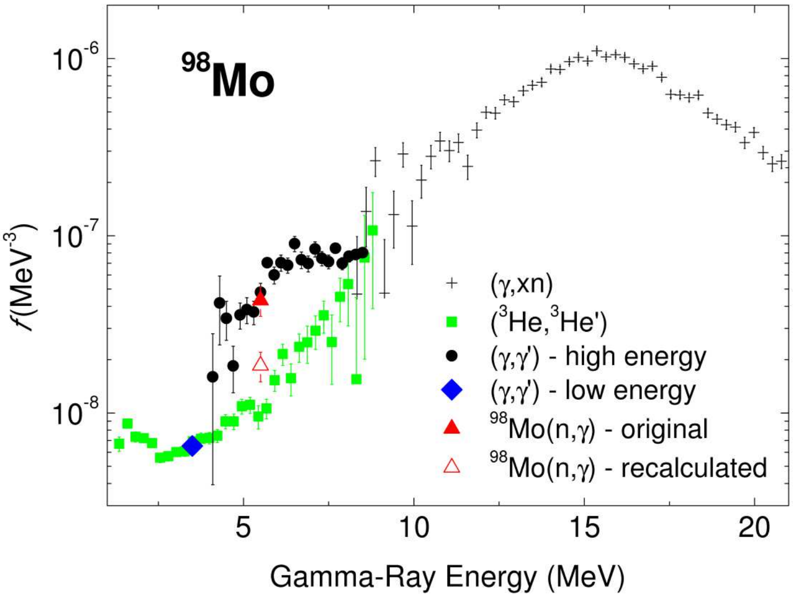

***FIG. 2****. Available data on PSFs for $^{98}$Mo. The sources of data: ($^3$He,$^3$He') [24], (γ,γ') [51, 52], (γ,xn) [55]. In addition, data from intensities of primary transitions following radiative neutron capture in $^{98}$Mo [53, 54] are shown. For a detailed description of these data see text. The figure was taken from Ref. [50].*

- At high photon energies, the PSF is dominated by a collective oscillation of the protons against the neutrons, the Giant Dipole Resonance. However, there has long been a significant uncertainty in the PSF at the lower energies (≤3 MeV) due to a lack of good experimental probes. A decade ago an experiment using charged-particle reactions and particle-γ spectroscopy was performed that indicated the presence of a strong enhancement in the PSF at low γ-ray energies in stable iron nuclei [25]. The results were greeted with scepticism due to 1) the lack of any known theoretical mechanism for the enhancement, and 2) the fact that a measurement of the PSF in the same nucleus using another main quasi-continuum technique showed no evidence of a low-energy enhancement. The low-energy enhancement has since been observed in other light and medium mass nuclei, see e.g. Ref [24], using the same analytical method as in Ref [25]. Recently a new model-independent experimental method, using charged particle reactions and particle-γ-γ coincidence data and stringent gating requirements, has been developed [23] to determine the shape of the PSF. The results of this work shown in Fig. 3, confirmed the existence of the low-energy enhancement in $^{95}$Mo independently for the first time.

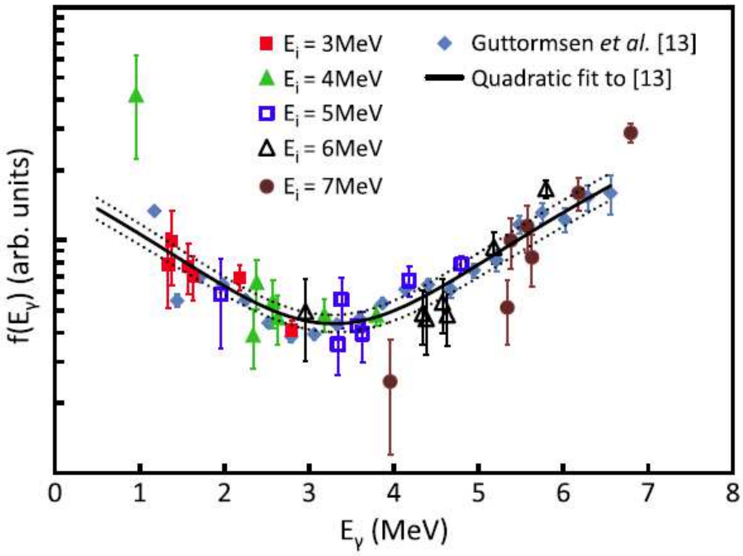

***FIG. 3***. *Comparison of the PSF from the work of Ref. [24] (indicated by colored symbols) with results from Ref. [23]. The quadratic polynomial fit to the PSF of Ref. [23] is shown as a solid black line while fitted upper and lower error bars are shown as dotted black curves.*

- Primary γ-ray strengths from (n,γ) measurements are defined by the equation (1) of Section 2.3. In EGAF [6], $P_\gamma$ is the transition probability for a single primary γ-ray, and in average resonance capture (ARC) data $P_\gamma$ represents the average transition probability from a narrow energy resonance region, typically at 2-keV or 24-keV. For neutron time of flight data $P_\gamma$ is the transition probability for a single primary γ ray from a resonance state, and when many resonances are independently measured, the $P_\gamma$ measurements to a common final state can be averaged to give an average experimental transition probability similar to that obtained in ARC data.

  The precision of the photon strength determined in these measurements is constrained by the number of transitions that can be observed and should be corrected for unobserved transitions whose widths are expected to follow a Porter-Thomas distribution [44]. The average experimental photon strength at a given γ-ray energy can be determined by averaging several individual transition strengths in a region of interest observed in EGAF or ARC data. For nTOF data transitions from several resonances populating the same final state can be averaged to give the experimental photon strength. The photon strength that populates excitation regions where complete level information is known will be the total photon strength, and the photon strength populating higher excitations, where significant strength may be missed, should be corrected for the missing strength with statistical model calculations.

The $^{197}$Au(n,γ)$^{198}$Au reaction provides an excellent example where numerous primary γ-rays are observed populating levels below 1.5 MeV in EGAF, ARC, and nTOF measurements. Since the level scheme is nearly complete below 1.5 MeV in $^{198}$Au, these measurements can be compared to determine the photon strength in the γ-ray energy region from 5.0-6.5 MeV as shown in Fig. 4.

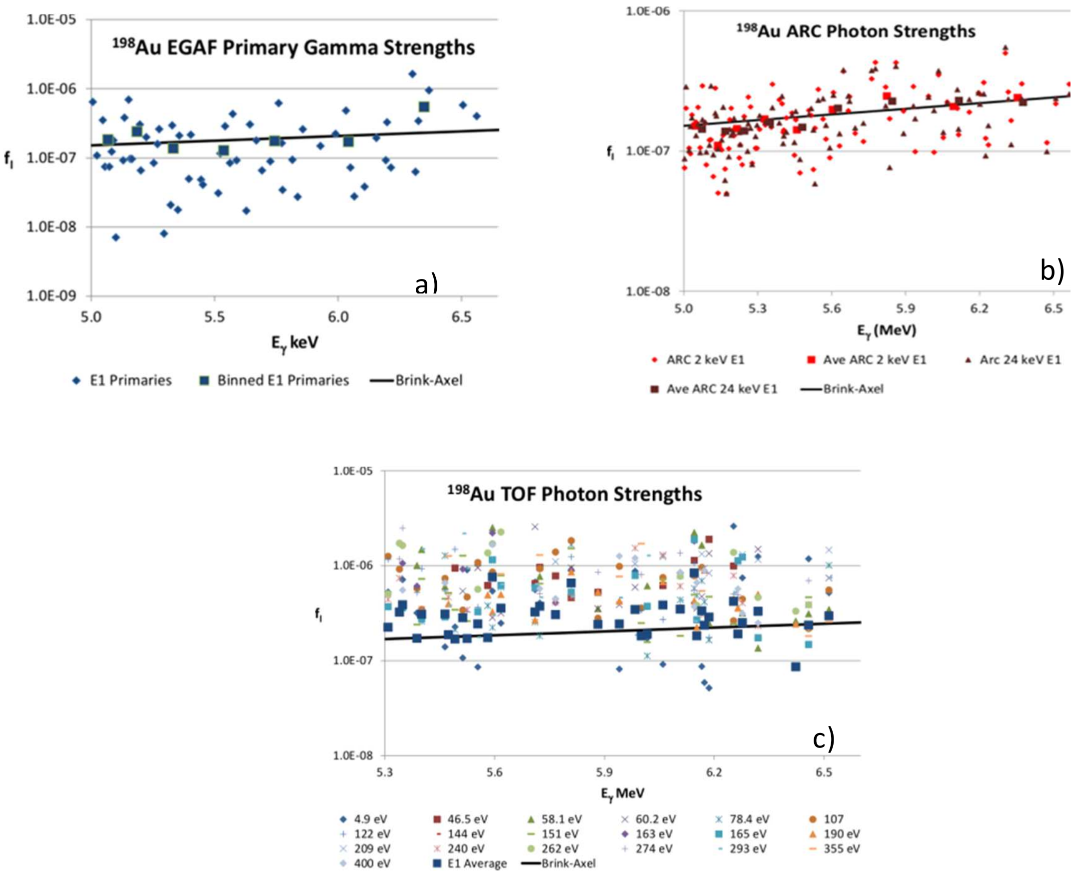

***FIG. 4**. $^{198}$Au photon strengths determined from a) 62 primary thermal (n,γ) transitions from EGAF [6], b) 92 2-keV and 92 24-keV ARC transitions [56], and c) 310 transitions from 19 resonances [13] in the 5.0-6.5 MeV energy region. The data have been binned, as indicated by the large squares, where the binned experimental photon strengths agree well with Brink-Axel calculations.*

## *7. DATABASE*

In the previous sections we demonstrated the wealth of reaction γ-ray data, as well as the variety of the experimental and evaluation methods, and most importantly, the discrepancies that exist among them. It is clear that there is a need for a database of reaction γ-ray data, that would provide all the useful experimental and evaluation information, as well as recommendations to the user community.

The database should include a compilation of all existing data. It should be divided in sections corresponding to the different experiments (photonuclear, photon scattering, charged-particle γ-ray, neutron-capture primary/coincidence γ-ray data). Each dataset should include a short description of the experiment.

The detailed structure and format of the database should be developed in consideration of the ENSDF and RIPL evaluation efforts.

The methodology for the evaluation of the data should be clearly defined and evaluators selected on the basis of expertise in the various sections.

The database should be made readily available and documented for the user community.

## *8. RECOMMENDATIONS*

The CM after reviewing the current situation with regards to photonuclear and reaction γ-ray data that are used for the determination of PSFs, concluded that there is an urgent need for the compilation and evaluation of all relevant data in a dedicated database.

It therefore recommends that the IAEA initiate a coordinated research project, with the primary task of compiling the relevant data, defining the database structure and formats, outlining the evaluation methodology, assessing experimental methods and understanding the source of discrepancies.

The CRP should also propose a priority list for new measurements and perform benchmark comparisons of data from multiple experiments using different techniques on a given isotope.

The project should include participants who have expertise in crucial aspects of photonuclear and γ-ray reaction measurements and analysis. Effort should be made to include participants from institutions across the world.

The consultants also recommend that the IAEA disseminate the DICEBOX code for analysis of γ-ray data in coordination with the group from Charles University in Prague.

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Appendix 1

## Consultancy Meeting on

# *“Compilation and Evaluation of γ-Ray Data”*

IAEA Headquarters, Vienna, Austria
4-6 November 2013

Meeting Room VIC G0E85

## ADOPTED AGENDA

*Monday, 4 November*

**08:30 - 09:30** **Registration** (IAEA Registration desk, Gate 1)

**09:30 - 10:15** **Opening Session**

Welcoming address
Self-introduction of participants
Election of Chairman and Rapporteur
Adoption of Agenda
Introduction and goals of the project – P. Dimitriou (NDS IAEA)

**10:15 - 12:15** **Presentations by participants**

1. Photoneutron reaction cross sections: new approach for analysis and evaluation (V.V. Varlamov) – 45 min
2. Gamma-ray strength function below the GDER maximum (M. Krticka) – 40 min

**12:15 – 12:30** Administrative matters

***12:30 – 14:00*** ***Lunch***

| | |
|---|---|
| **14:00 – 17:00** | **Presentations by participants (cont'd)** |

3. Charged-Particle Reaction Data (S. Siem)
4. Neutron Capture Gamma-ray Data (R. B. Firestone) – 20 min
5. Simulation of gamma cascades emitted by highly excited states (F. Becvar) – 35 min
6. Measuring the photon strength function below $S_n$ (M. Wiedeking) – 20 min

*Coffee break as needed*

***19:00*** ***Dinner at a Restaurant (see separate information)***

*Tuesday, 5 November*

**09:00 - 12:30** **Roundtable Discussions**

*Coffee break as needed*

***12:30 – 14:00*** ***Lunch***

**14:00 – 18:00** **Roundtable Discussions (cont'd)**

*Coffee break as needed*

*Wednesday, 6 November*

**09:00 - 12:45** **Drafting of Summary Report**

*Coffee break as needed*

**13:00** **Closing of the meeting**

Appendix 2

Consultancy Meeting on

# “Compilation and Evaluation of γ-Ray Data”

IAEA, Vienna, Austria
4 – 6 November 2013

## LIST OF PARTICIPANTS

**CZECH REPUBLIC**
František Bečvář
Charles University in Prague
V Holesovickach 2
18000 Prague 8
E-mail: becvarfrank@aol.com

Milan Krticka
Charles University in Prague
V Holesovickach 2
18000 Prague 8
E-mail: krticka@ipnp.troja.mff.cuni.cz

**NORWAY**
Sunniva Siem
Department of Physics
University of Oslo
P.O. Box 1048 Blindern
N-0316 Oslo
E-mail: sunniva.siem@fys.uio.no

**RUSSIA**
Vladimir V. Varlamov
CDFE, Skobeltsyn Institute of Nuclear Physics
Lomonosov Moscow State University
Leninskie Gory
119991 Moscow
E-mail:varlamov@depni.sinp.msu.ru;
vvvarlamov@gmail.com

**SOUTH AFRICA**
Mathis Wiedeking
iTHEMBA LABS
P.O. Box 722
Somerset West 7129
E-mail: wiedeking@tlabs.ac.za

**UNITED STATES OF AMERICA**
Richard B. Firestone
Lawrence Berkeley National Laboratory
(LNBL)
University of California
1 Cyclotron Road, MS 880192
BERKELEY, CA 94720
E-mail: rbfirestone@lbl.gov; rbf@lbl.gov

**IAEA**
Paraskevi (Vivian) Dimitriou
International Atomic Energy Agency (IAEA)
Nuclear Data Section
Division of Physical and Chemical Sciences
P.O. Box 100
1400 Vienna
Tel. + 43-1-2600 21708
E-mail: p.dimitriou@iaea.org

Appendix 3

## GROUP PICTURE

Appendix 4

## Presentations

| # | Author | Title | Link |
|---|---|---|---|
| 1 | V.V. Varlamov | Photoneutron reaction cross sections: new approach for analysis and evaluation | PDF |
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Nuclear Data Section
International Atomic Energy Agency
P.O. Box 100
A-1400 Vienna
Austria

e-mail: *NDS.Contact-Point@iaea.org*
fax: (43-1) 26007
telephone: (43-1) 2600-21725
Web: http://www-nds.iaea.org