Journal of the Korean Physical Society, Vol. 59, No. 2, August 2011, pp. 1510∼1513

Study of Photon Strength Function of Actinides: the Case of ^{235}U, ^{238}Np and ^{241}Pu

C. Guerrero,[1,*] F. Álvarez-Velarde,[1] D. Cano-Ott,[1] T. Martínez,[1] E. Mendoza,[1] D. Villamarin,[1] N. Colonna,[2] M. H. Meaze,[2] S. Marrone,[2] G. Tagliente,[2] R. Terlizzi,[2] F. Belloni,[3] U. Abbondanno,[3] K. Fujii,[3] P. M. Milazzo,[3] C. Moreau,[3] G. Aerts,[4] E. Berthoumieux,[4] W. Dridi,[4] F. Gunsing,[4] J. Pancin,[4] L. Perrot,[4] A. Plukis,[4] H. Álvarez,[5] I. Duran,[5] C. Paradela,[5] S. Andriamonje,[6] M. Calviani,[6] E. Chiaveri,[6] E. González-Romero,[6] Y. Kadi,[6] M. C. Vicente,[6] V. Vlachoudis,[6] J. Andrzejewski,[7] J. Marganiec,[7] P. Assimakopoulos,[8] D. Karadimos,[8] D. Karamanis,[8] C. Papachristodoulou,[8] N. Patronis,[8] L. Audouin,[9] S. David,[9] L. Ferrant,[9] S. Isaev,[9] C. Stephan,[9] L. Tassan-Got,[9] G. Badurek,[10] E. Jericha,[10] H. Leeb,[10] H. Oberhummer,[10] M. T. Pigni,[10] P. Baumann,[11] M. Kerveno,[11] S. Lukic,[11] G. Rudolf,[11] F. Becvar,[12] M. Krticka,[12] F. Calviño,[13] R. Capote,[14,15] A. Carrillo De Albornoz,[16] L. Marques,[16] J. Salgado,[16] L. Tavora,[16] P. Vaz,[16] P. Cennini,[17] M. Dahlfors,[17] A. Ferrari,[17] F. Gramegna,[17] A. Herrera-Martinez,[17] P. Mastinu,[17] J. Praena,[17] L. Sarchiapone,[17] H. Wendler,[17] V. Chepel,[18] R. Ferreira-Marques,[18] I. Goncalves,[18] A. Lindote,[18] I. Lopes,[18] F. Neves,[18] G. Cortes,[19] A. Poch,[19] C. Pretel,[19] A. Couture,[20] J. Cox,[20] S. O'brien,[20] M. Wiescher,[20] I. Dillman,[21] F. Käppeler,[21] M. Mosconi,[21] R. Plag,[21] F. Voss,[21] S. Walter,[21] K. Wisshak,[21] R. Dolfini,[22] C. Rubbia,[22] C. Domingo-Pardo,[23] J. L. Tain,[23] C. Eleftheriadis,[24] I. Savvidis,[24] H. Frais-Koelbl,[14] E. Griesmayer,[14] W. Furman,[25] V. Konovalov,[25] A. Goverdovski,[26] V. Ketlerov,[26] B. Haas,[27] R. Haight,[28] R. Reifarth,[28] M. Heil,[21] M. Igashira,[29] P. Koehler,[30] E. Kossionides,[31] C. Lampoudis,[24,4] M. Lozano,[15] J. Quesada,[15] C. Massimi,[32] G. Vannini,[32] A. Mengoni,[14,33] M. Oshima,[34] C. Papadopoulos,[35] R. Vlastou,[35] A. Pavlik,[36] P. Pavlopoulos,[37] A. Plompen,[38] P. Rullhusen,[38] T. Rauscher,[39] M. Rosetti[33] and A. Ventura[33]

(The n_TOF Collaboration (www.cern.ch/ntof))

[1]Centro de Investigaciones Energeticas Medioambientales y Technologicas CIEMAT, Madrid, Spain
[2]Istituto Nazionale di Fisica Nucleare (INFN), V. Orabona 4, 70126 Bari, Italy
[3]Istituto Nazionale di Fisica Nucleare (INFN), Trieste, Italy
[4]CEA/Saclay - DSM/DAPNIA, Gif-sur-Yvette, France
[5]Universidade de Santiago de Compostela, Spain
[6]CERN, Geneva, Switzerland
[7]University of Lodz, Lodz, Poland
[8]University of Ioannina, Greece
[9]Centre National de la Recherche Scientifique/IN2P3 - IPN, Orsay, France
[10]Atominstitut der Österreichischen Universitäten,Techn. Universität Wien, Austria
[11]Centre National de la Recherche Scientifique/IN2P3 - IReS, Strasbourg, France
[12]Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic
[13]Universidad Politecnica de Madrid, Spain
[14]International Atomic Energy Agency (IAEA), Nuclear Data Sect., Vienna, Austria
[15]Universidad de Sevilla, Spain
[16]Instituto Tecnologico e Nuclear (ITN), Lisbon, Portugal
[17]Istituto Nazionale di Fisica Nucleare (INFN), Laboratori Nazionali di Legnaro, Italy
[18]LIP - Coimbra & Departamento de Fisica da Universidade de Coimbra, Portugal
[19]Universitat Politecnica de Catalunya, Barcelona, Spain
[20]University of Notre Dame, Notre Dame, USA
[21]Forschungszentrum Karlsruhe GmbH (FZK), Institut für Kernphysik, Germany
[22]Università degli Studi Pavia, Pavia, Italy
[23]Instituto de Fsica Corpuscular, CSIC-Universidad de Valencia, Spain
[24]Aristotle University of Thessaloniki, Greece
[25]Joint Institute for Nuclear Research, Frank Lab. Neutron Physics, Dubna, Russia
[26]Institute of Physics and Power Engineering, Kaluga region, Obninsk, Russia
[27]Centre National de la Recherche Scientifique/IN2P3 - CENBG, Bordeaux, France
[28]Los Alamos National Laboratory, New Mexico, USA
[29]Tokyo Institute of Technology, Tokyo, Japan
[30]Oak Ridge National Laboratory, Physics Division, Oak Ridge, USA
[31]NCSR, Athens, Greece
[32]Dipartimento di Fisica, Università di Bologna, Sezione INFN di Bologna, Italy

[33] *ENEA, Bologna, Italy*
[34] *Japan Atomic Energy Research Institute, Tokai-mura, Japan*
[35] *National Technical University of Athens, Greece*
[36] *Institut für Isotopenforschung und Kernphysik, Universität Wien, Austria*
[37] *Póle Universitaire Léonard de Vinci, Paris La Défense, France*
[38] *CEC-JRC-IRMM, Geel, Belgium*
[39] *Department of Physics and Astronomy - University of Basel, Basel, Switzerland*

(Received 26 April 2010)

The decay from excited levels in medium and heavy nuclei can be described in a statistical approach by means of Photon Strength Functions and Level Density distributions. The study of electromagnetic cascades following neutron capture based on the use of high efficiency detectors has been shown to be well suited for probing the properties of the Photon Strength Function of heavy (high level density) and/or radioactive (high background) nuclei. In this work we have investigated for the first time the validity of the recommended PSF of actinides, in particular ^{235}U, ^{238}Np and ^{241}Pu. Our study includes the search for resonance structures in the PSF below S_n and draws conclusions regarding their existence and their characteristics in terms of energy, width and electromagnetic nature.

PACS numbers: 28.20.Fc, 29.30.Kv
Keywords: Photon/Gamma strength functions, Pygmy, Scissor mode, n_TOF, Total absorption calorimeter, TAC, Neutron capture
DOI: 10.3938/jkps.59.1510

I. INTRODUCTION

The decay of an excited nucleus by emission of γ-rays is determined by the levels with given spin and parity available at lower energies and by the transition probabilities towards them. In the extreme statistical model, the partial radiation width for transition of type XL (X: electric or magnetic, L: multipolarity) between individual levels (at energy E^*) and final levels f around E^* - E_γ is:

$$\langle\Gamma_\gamma\rangle = \frac{1}{\rho(J,\pi,E^*)} E^{2L+1} f_{XL}(E_\gamma),$$

where ρ is the level density and f_{XL} is commonly referred to as Photon (or γ-ray) Strength Function (PSF).

The energy dependence of PSF has been studied deeply by means of photo-absorption experiments, always in the region well above the neutron separation energy (S_n) where it is dominated by the Giant Electric Dipole Resonance (GEDR). Experimental data at high energies are adjusted to one, two (for deformed nuclei) or even three [2] Lorentzian functions that reproduce quite well the experimental data. The problems arise when extrapolating to lower energies, where several and significantly different parameterizations are proposed (KMF, EGLO, MLO, QRPA) [1]. The experimental information around or below S_n ($<\Gamma_\gamma>$ from σ(n,γ) experiments, pick-up or inelastic reactions with ^{3}He nuclei [3], two step (n,γ) cascades [4], nuclear resonance fluorescence [5], *etc.*) is scarce and sometimes contradictory. Previous works have reported the existence of structures in the tail of the E1 PSF (pygmy resonance) [6] or of the M1 PSF (scissors mode) [7].

The present work is aimed at (*i*) perform the first experimental study of PSF of actinides at energies below S_n and (*ii*) provide information about the existence of structures in the low energy tail of E1 and M1 PSF.

II. THE MEASUREMENT

The energy and multiplicity of the γ-rays emitted in the cascade following neutron capture reactions is directly determined by the level density and PSF of the compound nucleus. In this work, we have studied the γ-ray cascades from neutron capture on ^{234}U [8], ^{237}Np and ^{240}Pu [9] in order to extract information on the associated PSF of the compound nuclei in the energy range below S_n ($\sim$5.3 MeV). The relation between the capture cascades and the physical quantities of interest is not straightforward and hence the method that we present in the following is not deterministic. However, qualitative as well as quantitative valuable information can be extracted from the present study.

The cascades from neutron capture reactions have been detected using the Total Absorption Calorimeter (TAC) [10] of the n_TOF experiment at CERN. The detector is an array of 40 BaF_2 crystals of 15 cm thickness that covers 95% of 4π. The most important characteristic of the TAC for the purpose of this work are its large efficiency for detecting capture cascades ($\sim$100%), its reasonable energy resolution (16% at 662 keV) and its large segmentation.

The experimental information of interest for this work is the matrix of deposited energy E_{sum} in the TAC as function of the multiplicity m_{cr}, which corresponds to the number of crystals involved in the detection of each

*E-mail: carlos.guerrero@ciemat.es

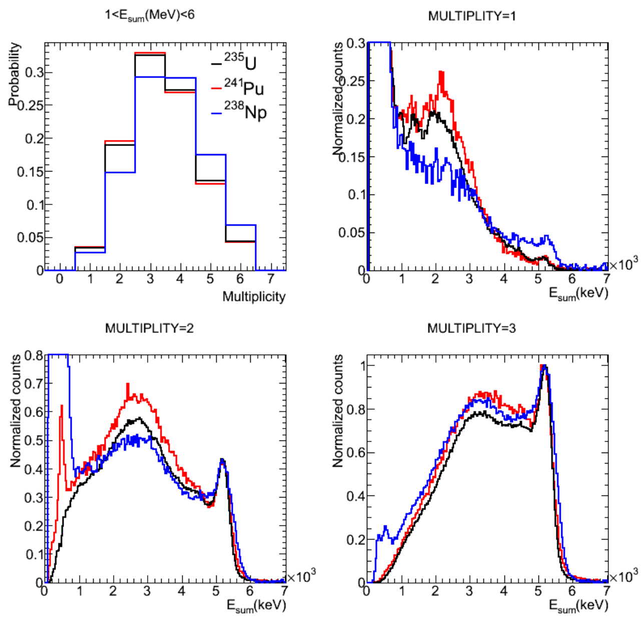

Fig. 1. (Color online) TAC response to capture cascades from ^{235}U, ^{238}Np and ^{241}Pu. Upper left: multiplicity distribution. Rest: total deposited energy distribution for different multiplicities.

capture cascade. This information has been retrieved for individual cross section resonances so that (*i*) the capture to background ratio is maximized and (*ii*) the spin and parity of the capture level in the compound nucleus is well defined: $\frac{1}{2}+$ for ^{235}U and ^{241}Pu, and 1+, 2+ for ^{238}Np.

The experimental E_{sum} distributions for $m_{cr} = 1, 2, 3$ are shown in Fig. 1 together with the m_{cr} distribution. It is clearly observed that both the deposited energy spectra and the multiplicity distributions are very similar for ^{235}U and ^{241}Pu, and very different from those of ^{238}Np, which in addition shows a significantly higher multiplicity. It is important to note that the shape of all E_{sum} distributions differ only at low multiplicities, agreeing pretty well for $m_{cr} > 3$.

III. STRATEGY FOR THE STUDY OF PSF

Monte Carlo simulations allow one establishing the connection between PSF and the TAC response to capture cascades. Simulations of the processes under study have been carried out by using the code DecayGen [11] for the generation of capture cascades and a GEANT4 simulation [12] of the TAC for the subsequent detection of the γ-rays in the detector.

The inputs for DecayGen are the known level scheme at low excitation energies and the parameters from RIPL-2 [1] for the level density (BSFG) and for the PSF for E1, M1 and E2. The PSF for E1 is described by an Enhanced Generalized Lorentzian (EGLO), while a Standard Lorentzian (SLO) is used for the M1 and E2 PSF.

Provided that the level density models describe well the level scheme above the known excitation energy region, the comparison between the simulated and experimental responses of the TAC to capture cascades give indications about the goodness of the PSF used as input for DecayGen. The PSF are then modified accordingly and the new comparison provides information about the new PSF. In this way it is possible to test and validate different models of PSF including or not structures below S_n.

IV. RESULTS

The following discussion is focused on the results for ^{241}Pu and the results for the other nuclei are presented in less detail at the end of the section.

The comparison in Fig. 2 between the experimental (black) and simulated data (blue) with PSF from RIPL-2 (see top-left panel in Fig. 2) indicates that the simulation do not reproduce the measurement, showing clearly a lack of transitions with energies around ~2.3 MeV. In order to investigate the existence of a structures in the tail of the E1 PSF around such energy, we have performed several simulations with variations of the E1 PSF that include a Gaussian like structure with energy and width varying between 1 and 5 MeV and between 0.1 and 3 MeV, respectively. The best reproduction of the experimental data (red line in Fig. 2), both in m_{cr} and E_{sum}, is achieved with a structure at $E_p = 2.3$ MeV with $\Gamma_p = 0.75$ MeV. The modified PSF for E1 transitions is shown in the top-left panel of Fig. 2, where the one from RIPL-2 is displayed as a dashed line. The PSF for M1 and E2, shown as blue and green lines, remain unchanged.

Simulations with different E_p and Γ_p have shown that TAC response is very sensitive to such parameters. Indeed, we can state that the resonance energy is determined within ~200 keV and its width is surely in the range 0.5 ~ 1.5 MeV.

Simulations with the structure in M1 PSF yielded results almost similar to those with E1, this time with the resonance shifted up to 2.9 MeV. Regarding the nature of this structure in the PSF, we are thus unable to conclude whether the structure is in E1 or M1 PSF at the moment. The M1 nature would indicate that the structure is scissors mode which energy is shifted down with respect to rare-earth nuclei.

A similar investigation for the case of ^{235}U reveals that also in this case the experimental data are reproduced only when including a Gaussian like structure in the E1 PSF, with the same energy and width than in the ^{241}Pu case. Indeed, this could be already expected from the comparison of the experimental data (see Fig. 1), where both nuclides show similar structures in the E_{sum} distributions for $m_{cr} = 1, 2$.

The case of ^{238}Np is very different from the other two. It is observed in Fig. 1 that both m_{cr} and E_{sum} distributions are significantly different than those of ^{235}U and ^{241}Pu. Again, the simulations using the recommended PSF from RIPL-2 do not reproduce at all the experimental data. But contrary to the previous cases, the search

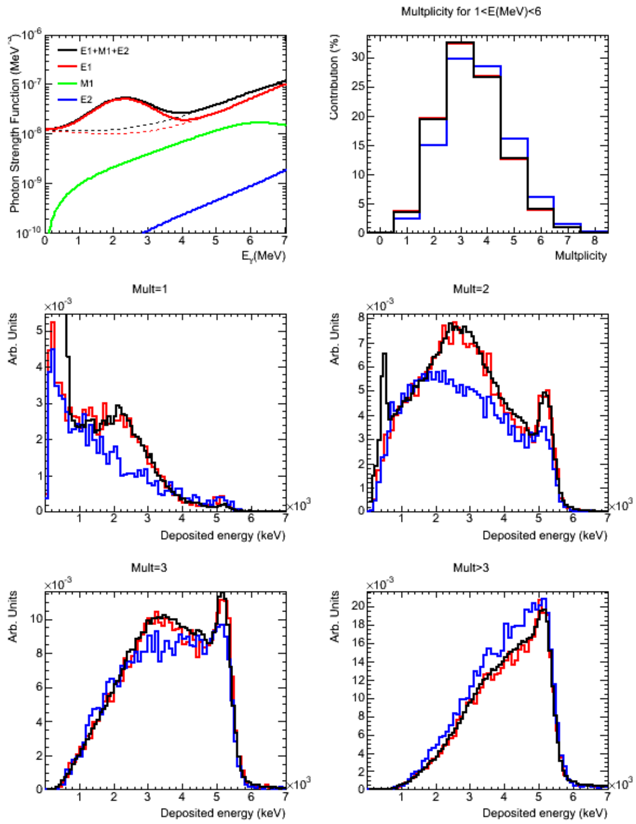

Fig. 2. (Color online) Top left: RIPL (dashed-line) and tuned (solid-line) PSF for ^{241}Pu. Rest: Comparison of the experimental (black) and simulated (color) TAC response to ^{240}Pu(n,γ) using the RIPL (blue) and tuned (red) PSF.

for a suitable enhancement of the E1 or M1 PSF that allows reproducing the data has failed. As it could be expected by the absence of structures in the $m_{cr} = 1$. E_{sum} distribution, it does not seem likely that there is a structure in the PSF. It has been only possible to reproduce the experimental data after an extreme reduction of the E1 over M1 ratio in the complete energy range, for which we have not found any physical explanation. Hence, conclusions can not be reached at this stage of the study for the case of ^{238}Np, but there are indications that E1 transition may not be dominant any longer at energies below S_n, as indicated in some previous works [13].

V. CONCLUSIONS AND PERSPECTIVES

The measurement of neutron capture reactions with the n_TOF Total Absorption Calorimeter provide valuable information about the decay pattern of the compound nucleus, which is directly related to the basic properties of the nucleus such as the level scheme and transition probabilities, *i.e.,* photon strength functions (PSF).

The comparison of the experimental and simulated (with PSF as input) response of the TAC to γ-ray cascades from ^{235}U, ^{238}Np, and ^{241}Pu has revealed clear indications of the existence of a low energy structure in the dipole PSF for the even-odd nuclei ^{235}U and ^{241}Pu. This enhancement would have a width of ∼0.75 MeV and would be center at 2.3 (2) MeV and 2.9 (2) MeV when it considered as E1 or M1, respectively. This structure has not been observed in the study of the odd-odd nucleus ^{238}Np, for which the results suggest that magnetic transitions could be dominating over E1 in large fraction of the energy region below S_n.

Before reaching final conclusions to this study, it will be necessary to exclude that the effects observed are due to structures in the level density instead of in the PSF. In order to do so we plan to perform a similar study using others than the BSFG model, for instance including microscopic calculations of level densities [14].

The final results shall include a detailed discussion on the validity of the conclusions when using other than EGLO shape for E1 transitions, for instance MLO and QRPA [1].

Last, the measurements of ^{238}U(n,γ) and ^{241}Am(n,γ) and their inclusion in this study will help to draw conclusions on systematic trends on actinides, which will most probably depend on the odd or even number of protons and neutrons, as it is the case in the present work.

ACKNOWLEDGMENTS

This work was partially supported by Spanish FPA2005-06918-C03-01 and CSD-2007-00042. grants, by ENRESA under the CIEMAT-ENRESA agreement on “Transmutation of high level radioactive waste”, by the European Commission 6th Framework Programme project IP-EUROTRANS (FI6W-CT-2004-516520).

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