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# **INDC International Nuclear Data Committee**

Summary Report

3<sup>rd</sup> Research Coordination Meeting

# Development of a Reference Database for Particle-Induced Gamma ray Emission (PIGE) Spectroscopy

IAEA Headquarters Vienna, Austria

7 – 11 April 2014

Prepared by

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May 2014

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INDC(NDS)- 0625 Distr. IBA

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## Abstract

The Third Research Coordination Meeting (RCM) of the IAEA Coordinated Research Project (CRP) on "Development of a Reference Database for Particle-Induced Gamma-ray Emission (PIGE) Spectroscopy" was held at the IAEA, Vienna, from 7 to 11 April 2014. Participants reviewed the progress made since the previous RCM and agreed upon the work that remains to be done by the end of the CRP. The contents of the final Technical Document were discussed and individual chapters were assigned. The summaries of participants' presentations as well as the technical discussions and the list of assigned tasks are included in this report.

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#### 1. Introduction

#### 1.1.Background

Particle-Induced Gamma-ray Emission (PIGE) is a powerful analytical technique that exploits the interactions of rapid (~1-10 MeV) charged particles with nuclei located near a sample surface to determine the composition and structure of the surface regions of solids (from ~0 to 50  $\mu$ m) by measurement of characteristic prompt  $\gamma$ -rays. This technique has been used since the early 1960s for different applications ranging from analysis of fission reactor materials to biomedicine, environment, cultural heritage and, more recently, fusion reactor materials. The potential for depth profiling of this technique has long been recognized, however, the implementation has been limited owing to insufficient knowledge of the physical data and lack of suitable user-friendly computer codes for the applications.

Although a number of PIGE cross-section data have already been uploaded to IBANDL (<u>http://www-nds.iaea.org/ibandl</u>) by members of the IBA community, a considerable body of published data remains to be compiled. Furthermore, a preliminary survey of this existing body of unevaluated experimental data has revealed numerous discrepancies beyond the uncertainty limits reported by the authors, and ion beam analysts are faced with the dilemma of trying to decide which (if any) amongst the divergent cross section data they should use.

Using the experience obtained from developing IBANDL [1.1], and the aid of resources and coordination provided by the IAEA, a concerted effort to improve the situation was made within this Coordinated Research Project.

#### **1.2.Overall objective**

This CRP aimed at updating the IBANDL data library with reliable and usable data on charged particle  $\gamma$ -ray emission cross sections that would hence be made freely available to the user community.

#### **1.3.Specific research objectives**

To attain this goal a four-pronged approach was applied:

- identify the most important nuclear reactions for PIGE;
- search the literature and electronic databases and convert relevant nuclear reaction data to the format suitable for use in PIGE simulation programs;
- compare data from different sources and carry out measurements when there are no data available or when unresolved discrepancies exist;
- incorporate all measured data into the database, and make them available to the IBA community.

## **1.4.Expected research output**

An electronic database of cross sections for PIGE is available through the NDS IBANDL interface and on CD. In addition, a comprehensive technical report will be published. The project aims at attaining significant improvements in the knowledge of basic nuclear data for PIGE, thus making this analytical technique as powerful as other IBA methods and even surpassing them in some important cases.

#### 1.5.General information

The project was officially approved in August 2010, and is expected to reach completion by the end of 2014. Three Research Coordination Meetings (RCMs) were planned. In the first RCM [1.2], a detailed work plan was determined and tasks were assigned to participants. In the second RCM [1.3], the progress was discussed and further actions to be taken were elaborated. In this final RCM, the results obtained thus far were reviewed, further actions to finalize the measurements and codes were taken, and the contents and preparation of the final documentation related to the project were discussed.

The third RCM was held at the Agency headquarters in Vienna from 7 to 11 April 2014. The meeting was opened with a welcome address by R. Forrest, Head of the Nuclear Data Section. After short presentations by the participants, the project officer, P. Dimitriou, outlined the main objective of the meeting which was to summarize the progress made thus far in the CRP and begin the preparation of the final technical document. A. Kiss was elected chairman and A. Pedro de Jesus agreed to serve as rapporteur for the meeting. The preliminary agenda was adopted without changes (Annex A). The list of participants can be found in Annex B.

The meeting continued with participants' presentations, discussions of both the work carried out and pending related to measurements and codes, and the preparation of an outline of the final technical document. The last day was devoted to drafting and reviewing the summary report, and approving the assigned tasks. The meeting was closed on schedule. Details of the discussions on different relevant matters are presented below. Links to participants' presentations are included in Annex D.

#### **References:**

- [1.1] Summary Report Third Research Coordination Meeting on Development of a Reference Data Base for Ion Beam Analysis, 27 – 30 April 2009, Vienna, Austria, IAEA Report INDC(NDS)-0555, December 2009.
- [1.2] Summary Report First Research Coordination Meeting on Development of a Reference Data Base for Particle-Induced Gamma-ray Emission (PIGE) Spectroscopy, 16 – 20 May 2011, Vienna, Austria, IAEA Report INDC(NDS)-0589, July 2011.
- [1.3] Summary Report Second Research Coordination Meeting on Development of a Reference Data Base for Particle-Induced Gamma-ray Emission (PIGE) Spectroscopy, 8 – 12 October 2012, Vienna, Austria, IAEA Report INDC(NDS)-0625, March 2013.

#### 2. Participants' Presentations

#### 2.1. Proposal of an interlaboratory PIGE experiment

#### A. Pedro de Jesus

Taking into consideration that:

- 1. There has been within this CRP a great effort to compile nuclear cross section data from the literature and also to measure additional data;
- 2. This effort has included a concerted experiment on  $Al(p,p'\gamma)$  reaction in order to assess and evaluate the experimental difficulties and uncertainties;
- 3. The goals of the CRP have also included the development of codes to calculate gammaray yields from cross section data that has been done (ERYA code);

a proposal is made to measure by PIGE in another concerted laboratory action an unknown sample with one (or more than one) relevant element (isotope) and calculate the concentrations from the yields using the ERYA code. The important outputs of this experiment would be:

- the assessment and evaluation of the effect that uncertainties in the cross section data have on PIGE results;
- a concerted evaluation of the ERYA code;
- a demonstration for the PIGE community of standard-less PIGE and of its capabilities.

In the discussion that followed it was decided that although very pertinent and important, there was no time during this CRP to engage in such an experiment. Furthermore, it was considered a bit out of the main scope of this CRP.

## 2.2. Gamma-ray production cross sections for deuteron induced reactions on C, N & Si

#### Á.Z. Kiss

Last year, the activities of the ATOMKI-IBA Laboratory in the framework of this CRP were concentrated on nitrogen and carbon d-PIGE cross section measurements as it was assigned at the 1<sup>st</sup> RCM. Experimental details were discussed during the 2<sup>nd</sup> RCM. This talk presented the obtained cross section results.

Differential cross sections for  $\gamma$ -ray emissions from the <sup>14</sup>N(d,p $\gamma$ )<sup>15</sup>N reaction (E $_{\gamma}$  = 1885, 2297, 7299 and 8310 keV) were measured simultaneously with the <sup>14</sup>N(d,p<sub>4,5,6,7</sub>)<sup>15</sup>N differential cross sections and (d,d) elastic scattering cross section in the E<sub>d</sub> = 0.65–2.0 MeV energy range. Due to the Si<sub>3</sub>N<sub>4</sub> target used, new results were obtained also for the <sup>28</sup>Si(d,p $\gamma$ )<sup>29</sup>Si (E $_{\gamma}$  = 1273, 2028, 2426 and 4934 keV)  $\gamma$  rays. Angular distributions of the  $\gamma$  rays were measured to determine the possible anisotropy of the  $\gamma$ -ray emissions, and the measured cross section values were converted into total cross sections for most of the  $\gamma$  rays.

In the case of carbon the total cross sections of the <sup>12</sup>C(d,p $\gamma$ )<sup>13</sup>C reaction for three  $\gamma$  rays (E $\gamma$  = 3089, 3684 and 3854 keV), as well as differential cross sections for (d,p<sub>0,1</sub>) reactions and (d,d<sub>0</sub>) elastic scattering were determined in the E<sub>d</sub> = 0.74–2.0 MeV energy range. The validity of the measured  $\gamma$ -ray producing cross sections was tested in benchmark experiments using kapton foils with two different thicknesses. Both the resulted  $\gamma$ - and particle production cross section values were compared with literature data, and in the case of (d,p<sub>0</sub>) the experimental values were compared also with data of a theoretical evaluation.

The obtained results were published in two papers: L. Csedreki et al., Nucl. Instr. Meth. B 328 (2014) 20-26 and Nucl. Instr. Meth. B 328 (2014) 59-64.

#### 2.3. PIGE Data for Material Analysis from Nuclear Astrophysics and other Sources

#### H.-W. Becker

The literature search for nuclear data important for material analysis with proton induced  $\gamma$ -ray emitting reactions proved to be successful in particular in the nuclear astrophysics literature. Many reactions have now been included in IBANDL. Some examples are presented. More specific details are discussed at the example of data for the  ${}^{27}Al(p,\gamma){}^{28}Si$  reaction, where data are available measured angle integrated and summed over all cascades in the exit channel. These data as well as many other cases contain information about resonances, which are useful for depth profiling. Here however the concept of tabulating the energy dependence of measured

yields or cross sections fails for narrow resonances; a measurement gives the integral over the resonance and the essential quantity is the resonance strength. Therefore it is suggested to have for those cases an additional entry in IBANDL, listing resonance strength for resonances used in ion beam analysis.

Data for the resonance at 6.4 MeV in the  ${}^{1}H({}^{15}N,\alpha\gamma){}^{12}C$  reaction, which is widely used for hydrogen depth profiling could be gained in digital form. However, the IBANDL web site does not allow at present to choose  ${}^{15}N$  as an ion beam, so this data as well as data for  ${}^{19}F$  or  ${}^{18}O$  have either to be included together with the data for the reactions in inverse kinematics or additional entries are necessary for these cases.

More generally the goals and the present achievements of the CRP in providing PIGE data were discussed and compared with the particle data in IBANDL. Some ideas and suggestions for future activities were put up for discussion.

# 2.4. Cross section measurements of the ${}^{10}B(p,p'\gamma){}^{10}B$ , ${}^{10}B(p,a\gamma){}^{7}Be$ and ${}^{11}B(p,p'\gamma){}^{11}B$ reactions in the energy range between 2.5 and 5 MeV

#### A. Lagoyannis

In the present work differential cross section data of the  ${}^{10}B(p,\alpha\gamma)^7Be$ ,  ${}^{10}B(p,p'\gamma){}^{10}B$  and  ${}^{11}B(p,p'\gamma){}^{11}B$  reactions have been studied at eight angles for the proton beam energy range between 2.0 and 5.0 MeV. The detection apparatus consisted of three HPGe detectors of 100% relative efficiency and a fourth one of 70%. They were mounted on a motorized turntable at the initial angles of 0°, 55°, 90° and 165° and at a distance of 25 cm from the target. A thin <sup>nat</sup>B target and an enriched <sup>10</sup>B one were used for the cross section measurements. Both targets were prepared by electron gun evaporation on thick Tantalum backings and their thickness was measured using a combination of the EBS and NRA techniques. The thicknesses of the enriched <sup>10</sup>B and of the <sup>nat</sup>B targets were found to be 31.4 and 10.4 µg/cm<sup>2</sup> respectively. In addition, two pellets for benchmarking purposes were prepared; a <sup>nat</sup>B and a MgB<sub>2</sub> one.

In the case of the  ${}^{10}B(p,\alpha\gamma)^7Be$  reaction, two broad structures were observed at  $E_p = 3020$  and 4355 keV. These resonance energies correspond to the excited levels E = 11.44 and 12.65 MeV of the compound nucleus  ${}^{11}C$ . The fact that the observed structures in the excitation functions are broad could be attributed to the rather large width ( $\Gamma = 350$  keV) of the  ${}^{11}C$  excited levels. Both of these structures also appear in the case of  ${}^{10}B(p,p'\gamma){}^{10}B$ , as both of the studied reactions originate from the same compound nucleus. Moreover, the comparison between the eight different detection angles reveals no significant angular dependence of the cross section. This weak angular dependence can in principle facilitate PIGE studies, especially for experimental setups where the gamma detector is placed close to the target, enhancing thus its angular uncertainty.

The present data exhibit large differences compared with previous works. The values given by T.R. Ophel et al. [1] are ~3.5 times lower than the current measurements while the reported cross sections by C. Boni et al. [2] are underestimated by a factor of ~5. The observed discrepancies could not be attributed either to the systematic uncertainties of this work, which do not exceed 8%, or to the ones reported by C. Boni et al. [2] (15%). As the measurements of C. Boni et al. [2] for other light elements are in good agreement with recent studies, the observed discrepancy in <sup>10</sup>B, could be attributed to the reported target thickness.

The soundness of the present data is supported by the fact that the measurements were performed with two different targets, an enriched <sup>10</sup>B and a natural one. The results obtained from both measurements agree within the statistical errors. Furthermore, the reported cross sections were verified through a rigorous benchmarking procedure, using two different thick targets of known composition.

#### References

[1] T.R. Ophel et al, Nucl. Phys. 33, 198 (1962).[2] C. Boni et al, Nucl. Instr. Meth. B35, 80 (1988).

#### 2.5. Gamma-ray production cross sections of proton irradiated nitrogen

#### J. Räisänen

Specifying measurements have been conducted for determination of the total cross sections for the reactions  ${}^{14}N(p,p'\gamma){}^{14}N$ ,  ${}^{28}Si(p,p'\gamma){}^{28}Si$  and  ${}^{29}Si(p,p'\gamma){}^{29}Si$ . The measurements were conducted within the full energy range of 3.586 - 6.920 MeV to be covered in the final work. Available relevant literature cross section data has been collected and submitted to NDS-IAEA.

The cross section values for the  ${}^{14}N(p,p'\gamma){}^{14}N$  reaction were calculated and compared with the available previous literature data [1]. For benchmarking purposes proton induced thick target  $\gamma$ -ray yields were measured at 4.0, 4.5, 5.0, 5.5, 6.0 and 6.5 MeV using thick BN and Si<sub>3</sub>N<sub>4</sub> targets, and a 50  $\mu$ m thick polyimide (Kapton) foil. The elemental compositions of the thick nitride targets were determined by TOF-ERDA measurements. The measured thick target yields were compared with calculated thick target yields, within several energy ranges, deduced from the experimental excitation curve. The results obtained by these two approaches differ more than the error limits. A detailed study on the cause of this discrepancy can be made after the thick target yield measurements are confirmed by other CRP participants. The procedure was carried out also by using the literature cross section data. When comparing the results obtained by both cross section data sets good mutual agreement for the BN and Si<sub>3</sub>N<sub>4</sub> targets was found. Generally reasonable agreement between the values obtained by employing the present and the literature cross section data was noted at the lowest energies. As a conclusion, based on the present standing, it can be noted that both experimental excitation curves overestimate the cross sections.

The cross section values for silicon are still to be calculated from the measured data. Relevant thick target yields are readily available for benchmarking purposes through the data obtained by the  $Si_3N_4$  target. As the excitation curves for the silicon reactions are clearly more structured and the resonances are weaker, more data may still have to be collected.

In connection with the project an article describing a new procedure for accelerator proton energy calibration has been published. In this article the PIGE CRP is acknowledged [2].

#### References

[1] G.W. Phillips et al, Phys. Rev. C5, 297 (1972).

[2] J. Räisänen and P. Tikkanen, Calibration of accelerator proton energy by the  ${}^{14}N(p,p'\gamma){}^{14}N$  reaction resonances, NIM A 723, 5-7 (2013).

#### 2.6. Recent PIGE measurements at the VDG Lab in Tehran

#### O. Kakuee

In the third Research Coordination Meeting on Development of a Reference Database for PIGE Spectroscopy, the following activities were presented:

At first, the qualifications of the fabricated PIGE reaction chamber were outlined as: a) equipped with SB detector b) with maximum attainable solid angle, c) capable of PIXE analysis at 135° and d) with smallest physical volume.

The detector employed for PIGE measurements was a p-type HPGe detector with crystal size of 6.58 cm  $\times$  6.58 cm and active volume of 213 cm<sup>3</sup> placed at right angle with respect to the beamline direction and 5.19 cm from the target centre. The efficiency calibration was performed using <sup>133</sup>Ba, <sup>152</sup>Eu, <sup>60</sup>Co, <sup>137</sup>Cs and <sup>241</sup>Am calibration sources. The calibration curve and the corresponding fitting parameters were obtained.

Energy calibration of the beam was performed using the 1880 keV threshold energy of  ${}^{7}\text{Li}(p,n){}^{7}\text{Be}$  reaction as well as 992 keV resonance of  ${}^{27}\text{Al}(p,\gamma){}^{28}\text{Si}$  reaction. This was achieved by adjusting the magnetic field strength through tuning the NMR frequency. During the measurements the incident beam current was varied within 10-300 nA depending on the beam energy to keep the counting rate of HPGe detector at about 1000 counts/s. In this way, pile up was negligible and the required correction for dead time of HPGe and SB detectors was less than 10% and 1%, respectively.

For Al cross-section measurement, a self-support Ag film with the thickness of 130  $\mu$ g/cm<sup>2</sup> was prepared. Then a thin film of Al of about 30  $\mu$ g/cm<sup>2</sup> was vacuum evaporated on the self-support Ag film. For thick target measurements, polished Al, Au/Si wafer and Ag/P powder pellet were employed.

Cross section measurements of thin Al target was started with incident proton beam of 1000 keV and was continued up to 3 MeV with steps of 10 keV. The measured yield and differential cross sections of the <sup>27</sup>Al(p, $\gamma$ )<sup>28</sup>Si reaction, E<sub> $\gamma$ </sub> = 1779 keV, as well as those of <sup>27</sup>Al(p,p' $\gamma$ )<sup>27</sup>Al reaction for 844 keV and 1014 keV  $\gamma$ -lines were reported.

In addition, 1274 keV thick target yields of  ${}^{29}$ Si(p, p' $\gamma$ ) ${}^{29}$ Si and 1266 keV thick target yields of  ${}^{31}$ P(p,p' $\gamma$ ) ${}^{31}$ P were presented.

#### 2.7. PIGE measurements performed at the Ruder Bošković Institute

#### I. Bogdanović Radović

Differential cross sections were measured for proton energies from 2.51 to 3.05 MeV with 15 keV step and beam energy resolution of 0.06%. An HPGe detector with 20% nominal efficiency was placed at 135°. Thin reference standards (54.1  $\mu$ g/cm<sup>2</sup> of MgF<sub>2</sub>, 53.7  $\mu$ g/cm<sup>2</sup> of NaCl and 55  $\mu$ g/cm<sup>2</sup> of Al, deposited on thin Mylar foils) with evaporated 4 nm Au layer were used as targets for cross-section measurements. The following differential cross sections were measured:

<sup>23</sup>Na(p,p' $\gamma$ )<sup>23</sup>Na (E<sub> $\gamma$ </sub> = 440 and 1636 keV) <sup>23</sup>Na(p, $\alpha\gamma$ )<sup>20</sup>Ne (E<sub> $\gamma$ </sub> = 1634 keV) <sup>27</sup>Al(p,p' $\gamma$ )<sup>27</sup>Al (E<sub> $\gamma$ </sub> = 844 and 1014 keV) <sup>27</sup>Al(p, $\alpha\gamma$ )<sup>24</sup>Mg (E<sub> $\gamma$ </sub> = 1369 keV) <sup>25</sup>Mg(p,p' $\gamma$ )<sup>25</sup>Mg (E<sub> $\gamma$ </sub> = 390 and 585 keV)  ${}^{19}F(p,p'\gamma){}^{19}F(E_{\gamma} = 110, 197, 1236 \text{ and } 1349+1357 \text{ keV})$ 

Together with the PIGE spectra, backscattered protons were collected using an SB detector placed at 165° for normalization purposes. Absolute HPGe detector efficiency was measured by placing calibrated sources (<sup>60</sup>Co, <sup>137</sup>Cs, <sup>133</sup>Ba, <sup>152</sup>Eu) at the exact position of the target. Differential cross sections obtained from present measurements were compared with data already existing in the literature.

# 2.8. Measurements of proton induced gamma-ray emission cross sections and yields on Al and Na

#### M. Chiari

The measurement of the proton induced gamma-ray emission cross sections on low-Z nuclei such as Na and Al of specific interest for environmental and cultural heritage applications, were carried out for proton beam energy from 2.5 to 4.1 MeV, including the measurement of the angular distributions of the emitted rays at selected angles, i.e.  $90^{\circ}$ ,  $45^{\circ}$  and  $0^{\circ}$ , using an array of three HPGe detectors coupled to the multi-purpose scattering chamber on the +30° beamline of the Tandetron accelerator at INFN LABEC.

The studied gamma-ray inducing reactions were:  ${}^{27}$ Al(p,p' $\gamma$ ) ${}^{27}$ Al (gamma-ray energies 844 and 1014 keV), and  ${}^{23}$ Na(p,p' $\gamma$ ) ${}^{23}$ Na (gamma-ray energies 441 and 1636 keV) and  ${}^{23}$ Na(p, $\alpha\gamma$ ) ${}^{20}$ Ne (gamma-ray energy 1634 keV).

As a first step, the absolute efficiency of the HPGe detectors placed at 90° and 0° was improved by a factor up to 2 by designing a new target holder, with less absorbing material facing the HPGe detector at 90°, and installing a new Faraday cup/beam stopper with graphite body instead of stainless steel and a thinner Ta cap at the bottom, to reduce the shielding effect for the HPGe detector at 0°. The measurement of the absolute efficiency of the HPGe detectors of the array was carried out using a 152Eu calibration source mounted on the target holder and placed in the exact position of the target under irradiation.

The proton beam energy was calibrated using an aluminum thick target and the resonances at 991.86 keV and 1683.57 keV, respectively in the  $(p,\gamma)$  and  $(p,p'\gamma)$  reactions on <sup>27</sup>Al, and a native aluminium oxide thin target and the resonance at 3470 keV in elastic scattering on <sup>16</sup>O.

The targets employed were thin Al (29  $\mu$ g/cm<sup>2</sup>) and NaF (35  $\mu$ g/cm<sup>2</sup>) films evaporated on thin self-supporting Ag foils; in order to obtain the differential gamma-ray inducing cross-sections, we normalized the results by the Rutherford elastic backscattering of protons from Ag, adopting a procedure not relying on the knowledge of the absolute number of incident protons. The targets were prepared at the IST/ITN in Lisbon and their thickness was characterized by RBS measurements with 2.0 MeV alpha particles at three scattering angles simultaneously.

The results of the measurement of proton induced gamma-ray emission differential cross sections press 90° and 45°, in the journal on Al. at are in NIM В (http://dx.doi.org/10.1016/j.nimb.2014.02.095) and data have been uploaded into IBANDL. Unfortunately, only data from two HPGe detectors were obtained since Al impurities at ppm level in the Ta bottom cap of the Faraday cup made the spectra collected with the HPGe detector placed at 0° for the p+Al PIGE cross section unusable (the yield from the FC alone accounts for half the yield obtained when the Al/Ag target is bombarded). As regards the proton induced gamma-ray emission differential cross sections on Na, data analysis is still in progress.

Finally, the absolute thick target yields for the gamma-ray inducing reactions  ${}^{27}Al(p,p'\gamma){}^{27}Al$  (gamma-ray energies 844 and 1014 keV) and  ${}^{27}Al(p,\alpha\gamma){}^{24}Mg$  (gamma-ray energy 1369 keV) were measured at the three angles of 90°, 45° and 0°, and in the proton beam energy range from 2.5 to 4.1 MeV with a step of 150 keV. Once data analysis will be finalized the values of the thick target yields will be uploaded into IBANDL as well.

#### 2.9. Measurement of gamma production in thin LiF targets at CMAM

#### A. Zucchiatti

The standard beamline at our 5MV coaxial Cockcroft-Walton tandem accelerator has been used to produce cross sections for the reaction channels  ${}^{7}\text{Li}(p,p'\gamma){}^{7}\text{Li}(E_{\gamma} = 478 \text{ keV})$ ,  ${}^{7}\text{Li}(p,n\gamma){}^{7}\text{Be}(E_{\gamma} = 429 \text{ keV})$ ,  ${}^{19}\text{F}(p,p'\gamma){}^{19}\text{F}(E_{\gamma} = 110 \text{ keV})$  and  ${}^{19}\text{F}(p,p'\gamma){}^{19}\text{F}(E_{\gamma} = 197 \text{ keV})$ . The target material was natural LiF; a few target assemblies were used including a carbon backing and a heavy element layer (either Ag or Au) to assure the possibility of normalization to purely Rutherford cross sections.

The gamma rays have been detected by a REGe (Reverse Electron Germanium) detector, 61 mm  $\emptyset$  X 60 mm, featuring a FWHM resolution of 2.0 keV at 1.33 MeV. The absolute efficiency has been measured with a calibrated set of radioactive sources (<sup>152</sup>Eu, <sup>137</sup>Cs, <sup>60</sup>Co) with which we have covered the gamma energy range from 121.78 keV to 1408.01 keV, adequate to interpolating at the energy of the studied reactions gamma rays, with the exception of the 110 keV from <sup>19</sup>F. The charge has been collected in the specifically designed target holder. There the target is electrically connected with a carbon FC, isolated from the ground and kept at +180 V to suppress secondary electrons. The charge is measured by means of an ORTEC 439 Digital Current Integrator. The accelerator energy calibration has been checked by repeatedly measuring the onset of the 991.9 keV resonance of the <sup>27</sup>Al(p, $\gamma$ )<sup>28</sup>Si. The maximum voltage difference between runs was 0.44 kV resulting in less than 1 keV energy difference.

Targets have been characterized either by ERDA-ToF with Cl ions or by RBS with He ions. With ERDA-Tof we have measured one homogeneous target prepared at CMAM and deduced the thickness of the other, by comparing gamma yields. Results are in the following table:

Target	Method	<sup>19</sup> F	<sup>7</sup> Li	<sup>6</sup> Li	Total	Nominal	Diff. %
LiF/Si	γ-comp	10.01	3.41	0.24	13.65	13.67	
LiF/Ag/C	α-RBS	12.17	4.15	0.29	16.61	13.00	+27.7
LiF/Ag/C	γ-comp	14.52	4.95	0.34	19.81	20.00	-4.5
Au/LiF/C	γ-comp	30.69	10.46	0.73	41.88	50.00	-16.3

As shown, there are significant differences between the nominal and measured values; furthermore the ERDA measurement raise doubts about the homogeneity of the thickness across the target (or target roughness). When using the above-measured thicknesses the various series of points, taken in different runs at the CMAM, show clear differences that we have attributed to a systematic error on target thickness, estimated at a maximum of 7% and corrected by renormalizing. In one case even after correction there are clear indications that target material loss has occurred during measurements. The systematic error on target is the major source of uncertainty and we are studying a procedure to reduce it. Of the almost 700 measurements performed, 477 have been analysed so far to produce cross sections for the cited reactions on Li and F. Our measurements confirm the structure of the differential cross section in all the

analysed channels and have been done with an energy grid that has assured the following of even the narrowest resonances in <sup>19</sup>F. The comparison with literature data and with data obtained in parallel by other groups in the CRP, is good up to about 3300 keV proton energy. Above that value we observe a significant spread among the various sets of data. Unfortunately we are not yet in position to propose a validated cross-section curve, due to the systematic error observed in the target thickness. New targets and different characterizations are planned and will be performed during 2014.

#### 2.10. R-matrix calculations for charged-particle induced reactions using SAMMY

#### P. Dimitriou

To provide recommended cross-section data, an evaluation of the measured data involving the critical assessment of the available experimental information and the parameterization of the data within a physical model is required. A powerful and versatile tool that has the potential to meet these needs is the R-matrix computer code SAMMY [1]. The purpose of the code is to analyse time-of-flight cross section data in the resolved and unresolved resonance regions, where the incident particle is either a neutron or a charged particle (p,  $\alpha$ , d, ...). Energy-differential cross sections and angular-distribution data are treated, as are certain forms of energy integrated data.

In the resolved resonance region, theoretical cross sections are generated using the Reich-Moore approximation to R-matrix theory (and extensions thereof). Sophisticated models are used to describe the experimental situation: Data-reduction parameters (e.g. normalization, background, sample thickness) are included. Several options are available for both resolution and Doppler broadening, including a crystal-lattice model for Doppler broadening. Self-shielding and multiple-scattering correction options are available for analysis of capture cross sections. Multiple isotopes and impurities within a sample are handled accurately.

Although it has been extensively used in analyses of neutron-induced cross section data, it has been employed far less often for incident charged particles. An effort to explore and implement all the capabilities available in SAMMY to the analysis of charged-particle-induced cross-section data directly related to IBA has begun.

The code has been used to reproduce the measured cross sections for the elastic scattering and the inelastic scattering of protons by <sup>27</sup>Al, namely the <sup>27</sup>Al(p,p<sub>0</sub>)<sup>27</sup>Al, <sup>27</sup>Al(p,p' $\gamma_{1-0}$ )<sup>27</sup>Al and <sup>27</sup>Al(p,p' $\gamma_{2-0}$ )<sup>27</sup>Al channels, using the resonance parameters derived in R.O. Nelson et al. [2]. The code has been shown to be able to describe the Rutherford contribution of the elastic scattering cross section in combination with the resolved resonances. Work is in progress to use the code to treat both statistical and systematic uncertainties associated with the evaluated data, with the aim to provide uncertainties and their correlations.

## References

 SAMMY-8, Code System for Multilevel R-Matrix Fits to Neutron and Charged-Particle Cross-Section Data Using Bayes' Equations (RSICC, ORNL, USA)
 R.O. Nelson, E.G. Bilpuch, C.R. Westerfeldt, and G.E. Mitchell, Phs. Rev. C 29, 1656 (1984); Phys. Rev. C 30, 755 (1984).

#### 2.11. ERYA (bulk)-finally available and ERYA profile-final adjustments

#### A. Pedro de Jesus

It was announced and shown that the ERYA-bulk code for analysis of in-depth homogeneous samples is now available and may be downloaded from a web site, where a manual is available to explain how to use it. A tutorial on the code's interface and capabilities was shown, namely the capability of calculating simultaneously the mass concentration of an arbitrary number of elements in a homogeneous sample (any thickness), with the additional capability of fitting the sample matrix composition. This may be done by using as an initial estimate either the results from another analytical technique such as PIXE (usually used as a complementary technique) or with prior knowledge of the main chemical composition.

Regarding the development of a routine to perform depth profile measurements, the main aspects of what was already done were presented:

- 1. the routine was developed to be used interactively, as RUMP, or SigmaNRA, by comparing the calculated and experimental results for each concentration distribution given by the user;
- 2. the routine uses a division of the target into layers (as in the case of ERYA bulk) but within each layer the projectiles have an energy distribution and not a single energy value (as in the case of ERYA bulk); this implies that depth together with average energy must be calculated for every layer;
- 3. the energy distribution takes into account Beam Energy Resolution, Beam Energy Straggling and Doppler Broadening;
- 4. in order to implement energy straggling calculations, Landau, Vavilov and Gaussian distributions are used;
- 5. the resonant cross section function may be replaced by an ideal Breit-Wigner function; further efforts to implement the code to use resonance strengths are being developed;
- 6. the concentration may be given for any number of discrete layers or as a depth-dependent continuous function.

This profile routine is already working with a user-friendly interface, which was also presented. Further tests and improvements are being done, including the use of FORTRAN or C to perform the heavy calculations of straggling distributions.

# 2.12. Measurement of excitation yields of low energy prompt $\gamma$ -ray from proton bombardment of Cr-foils with energies ranging between 1.0 and 3.0 MeV

#### A. Goncharov

The goal of this work is measurement of differential cross sections for the production of 378 keV  $\gamma$ -rays from the reactions  ${}^{52}Cr(p,\gamma_1){}^{53}Mn$  and  ${}^{53}Cr(p,n\gamma_1){}^{53}Mn$  for proton energies ranging between 1.0 and 3.0 MeV at the laboratory angle of 90° using foils with thickness  $\sim 1.9 \times 10^{18}$  at/cm<sup>2</sup> (~ 0.23 µm) of  ${}^{nat}Cr$ .

The natural Cr targets on Ta backings were prepared by vacuum deposition technique. The thicknesses of the targets have been measured by back-scattering spectrometry of He and H ions.

Measurements of  $\gamma$  rays were performed by means of a Ge(Li) detector DGDK-80. Calibration of the detector efficiency was carried out with the standard <sup>133</sup>Ba and <sup>152</sup>Eu sources at the geometry used for the cross-section measurements.

All measurements were carried out at the electrostatic accelerator of NSC KIPT ESU-5. The accelerator was calibrated by means of resonances in the  ${}^{27}Al(p,\gamma){}^{28}Si$  reaction.

The average differential cross-section  $d\sigma/d\Omega$  of  $\gamma$ -ray production from the  ${}^{52}Cr(p,\gamma_1){}^{53}Mn$  and  ${}^{53}Cr(p,n\gamma_1){}^{53}Mn$  reactions was determined from the general expression:

$$d\sigma/d\Omega = N_{\gamma} \cos \varphi / 4\pi \varepsilon k N_p f t$$

where

 $N_{\gamma}$  is the number of counts in the full-energy peak; k is the ratio between the live time and the exposure time;  $N_p$  is the number of protons incident upon the target;  $\varepsilon = \varepsilon(E_{\gamma})$  is the efficiency of the detection system; f is the relative content of Cr in target substance (in this case f = I); t is the Cr target thickness (at/cm<sup>2</sup>);  $\varphi$  is the beam incidence angle taking from normal to the target.

The accuracy of the definition of the cross sections varies from 8 to 12%.

#### 3. Methodology

CRP participants have carried out measurements as discussed in the second RCM and presented in Table 8.1. The cross section data files are being uploaded in IBANDL continuously. Pending measurements (Table 8.2) will be completed and submitted to NDS by the end of 2014. From the outset of the CRP, a very ambitious programme for new measurements was put forward (see Table 4.1 in Ref.[1.2]). Since the 1<sup>st</sup> RCM, a total of 74 reactions producing a known  $\gamma$  ray have been measured at various angles, for thin and thick targets within a period of two years. By the end of the CRP in 2014, another 64 reactions will be measured and analysed. From the initial plan, only 34 measurements including thin and thick target yields, will not be completed within the duration of the CRP, mainly due to time limitations. This is already a formidable achievement considering the difficulties involved in planning and performing measurements, many of which can be unpredictable. In addition, the review of the existing literature is almost finished and is in the process of being included in IBANDL. In particular, the nuclear astrophysics compilation NACRE [3.1] was reviewed and cross sections relevant to PIGE were retrieved from it. It was agreed to review also the recently published updated compilation NACRE II [3.2].

Some specific aspects regarding the methodology that were revisited in this meeting are presented in the following sections. The coordinated measurements performed between the  $2^{nd}$  and  $3^{rd}$  RCM meetings were discussed. The importance of thick target benchmark experiments was again emphasized. A working version of the ERYA code was distributed to participants for testing and feedback. A beta version of a program with the capability to analyse depth profiles, ERYA-profiling, was presented.

#### 3.1. Codes for PIGE

As was already pointed out in the first RCM [1.2], the aim of standard-less PIGE could be

achieved if, apart from the differential cross sections compiled in the reference database, the community was also provided with a reliable computer code for use of the database and calculation of the quantities needed by the user.

The ERYA code was distributed and a tutorial was given showing aspects of the interface and the capability of calculating simultaneously the mass concentration of an arbitrary number of elements in a homogeneous sample (any thickness). It was also mentioned that it has the capability of fitting the sample matrix composition. A code for depth profiling analysis featuring several models to take into account energy straggling was also presented.

It was decided that the ERYA bulk analysis code would be tested by participants and feedback would be sent to Adelaide Pedro de Jesus.

#### 3.2. PIGE data in IBANDL database

Several PIGE data from the literature and from new measurements made by the participants have already been uploaded into IBANDL using the R33 format, which has been modified to include additional information specific to PIGE.

Direct uploading of R33 data files into IBANDL is not possible; data files have to be submitted to NDS (EXFOR Compiler V. Semkova). The automatic conversion of EXFOR data files to R33 format is working.

So far, data which can be included in IBANDL are differential and total cross sections, and target yields. Information about angular distributions and resonance strengths can be included in the Comment section of the corresponding R33 file.

Participants discussed the importance of resonance strengths which are essential for PIGE depth profiling and recommend that IBANDL be modified in order to include resonance strengths. It was proposed to create a new data type in addition to EBS, NRA, and PIGE which are already available through the IBANDL interface. This new data type would be named  $\omega\gamma$  and would present tables of resonance strengths and widths, including uncertainties, references, and downloadable ASCII files. These tables could be displayed as in the following example:

Resonance [keV]	ωγ [eV]	Δ[ωγ] [eV]	Г [keV]	ΔΓ [keV]	Reference
992±0.7	2.2	0.3	0.2	0.01	Eur. Phys. Jour. A9 (2000) 479
991±0.1	2.4	0.7	<0.1		NACRE (NPA 656 (1999) 3-183
	3.2	1.2	0.5	0.1	
•••					
405.4±	1.04.10-2	$0.5 \cdot 10^{-2}$			[Ref.]
•••					
292.6±0.3	2.8·10 <sup>-4</sup>	0.51.10-4	0.15	0.05	[Ref.]

Gamma-producing reactions by projectiles heavier than <sup>7</sup>Li, such as <sup>15</sup>N, <sup>18</sup>O and <sup>19</sup>F, are also important for applications, such as hydrogen depth profiling, and should be included in IBANDL.

Regarding the preparation of cross sections data files in R33 format, it was decided that participants should indicate the total systematic uncertainty in the "Sigfactors" string whereas the statistical uncertainties should be placed in the fourth data column called "sigma random error" as is shown in the following example:

COMMENT: Gamma energy 844 keV. The proton energy is known to better than 0.1%. The listed uncertainties in the cross-section values are statistical only: the normalization uncertainty is +/- 7% (see "Sigma scale factor" fields).

Version: R33 Source: M. Chiari et al., accepted for publication in NIMB Name: M. Chiari Address1: Istituto Nazionale Fisica Nucleare Address2: via G. Sansone 1 Address3: I-50019 Sesto Fiorentino (Firenze) Address4: ITALY Address5: chiari@fi.infn.it Address6: SubFile: 27Alppg 844 90.R33 Egamma:844 Serial Number: 0 Reaction: 27Al(p,pg1-0)27Al Distribution: Energy Composition: natural Masses: Zeds: 1,13,1,13 Qvalue: 0.00, 0.00, 0.00, 0.00, 0.00 Theta: 90.00 Sigfactors: 1.00, 0.07

Enfactors: 1.00, 0.00, 0.00, 0.00

Units: mb Data: 2507.250 0.000 0.628 0.022 2517.260 0.000 0.988 0.026

#### 3.3. Coordinated measurements

The coordinated measurements agreed upon in the last RCM were performed and presented at the ECAART-11 Conference, Namur, Belgium, 8 to 13 September 2013.

It was decided to include the results and conclusions of the coordinated measurements in an extended paper — based on the first draft made by A. Pedro de Jesus — which would be submitted for publication in NIM B. The extended paper's title will be "Towards a standard-less PIGE technique" and the paper will address the following issues:

- Motivation of the PIGE CRP: Serious lack of cross-section data.
- Main goal of the IAEA CRP: To fill the gap in PIGE data and measure mainly but not only  $(p,p'\gamma)$  and  $(p,\alpha\gamma)$  reactions.
- A list of priority reactions to be measured was established and the same reactions were measured by more than one laboratory in nearly all cases.
- To assess the experimental methodologies and uncertainties in the measurements performed by the different laboratories, it was decided to perform a collective experimental exercise and measure  ${}^{27}Al (p,p'\gamma){}^{27}Al$ , from 2.5 to 3 MeV, in 10 keV steps.

The paper should emphasize that to achieve a "standard-less PIGE technique" the following

three requirements were indispensable:

- 1. Provision of cross sections;
- 2. Data evaluation in order to provide recommended cross sections to the community;
- 3. Development of software for bulk and profiling analysis.

All three requirements have been addressed by the PIGE CRP.

Further Actions to be taken with regards to the preparation of the paper:

- Contact Alex Gurbich about extending his paragraph on the data evaluation;
- Remove the 992 keV resonance strength;
- Remove the figure correcting the energy and the zoom on the resonance;
- Calculate thick targets yields from every data set with ERYA for pure Al;
- In conclusions emphasize the evaluation leading to recommended values;
- Use the first report to prepare an introduction to the CRP;
- Submit for publication in NIM B;
- Add the RCM reports in references.

#### 3.4. Evaluation

Since the 2<sup>nd</sup> RCM, the SigmaCalc software has been extended to perform calculations of PIGE cross sections. This software has been used to evaluate the cross-section data for the  ${}^{23}$ Na(p,p' $\gamma$ ) ${}^{23}$ Na reaction, as well as the new data for the  ${}^{27}$ Al (p,p' $\gamma$ ) ${}^{27}$ Al reaction mentioned in the previous section. The latter evaluated data were presented at ECAART-11 and will be included in the extended paper as mentioned above.

In addition, the computer code SAMMY was used to perform R-matrix calculations to demonstrate its capability of analyzing charge-particle induced reactions in the resolved resonance region. The code was used to fit the <sup>27</sup>Al(p,p<sub>0</sub>)<sup>27</sup>Al, <sup>27</sup>Al(p,p'\gamma<sub>1-0</sub>)<sup>27</sup>Al, and <sup>27</sup>Al(p,p'\gamma<sub>2-0</sub>)<sup>27</sup>Al reaction channels. The next step would be to treat the statistical and systematic experimental uncertainties using the Bayesian method and produce evaluated data with uncertainties.

## 3.5. Dissemination of CRP results

It was agreed to submit a paper covering the achievements of this CRP to IBA 2015.

#### References

[3.1] NACRE: A Compilation of charged-particle induced thermonuclear reaction rates, Nucl. Phys. A 656, 3-183 (1999).

[3.2] NACRE II: an update of the NACRE compilation of charged-particle-induced thermonuclear reaction rates for nuclei with mass number A<16, Nucl. Phys. A 918, 61-169 (2013).

## 4. Final Technical Document

It was decided to publish the Final Technical Document as an IAEA TECDOC. The content of this document was discussed and defined according to Table 4.1. Sections and chapters were assigned to individual participants as is shown in the table.

The following deadlines for submission of chapters and sections were set:

ChaptersApril 2015Complete first draftJuly 2015

Chapter	Title	Content and Contributing Authors					
Chapter 1	Introduction	Motivation, Objectives, Deliverable	s (P. Dimitriou)				
Chapter 2	Concepts of PIGE (10 pages maximum)	<ul> <li>2.1 PIGE Bulk Analysis (The underlying principles, good practice for analysis.)</li> <li>(A. Pedro de Jesus)</li> <li>2.2 PIGE Profiling (The underlying principles, good practice for analysis.)</li> </ul>					
		(H-W. Becker)					
Chapter 3	PIGE implementation (10 pages maximum)	3.1 A typical/minimal PIGE facility (A. Zucchiatti)					
		3.2 Examples of applications (describing also the facility)	3.2.1 Na bulk analysis (examples and facilities) (I. Bogdanovic, M. Chiari)				
		(nw. beckel)	3.2.2 Hydrogen depth profiling (examples and facilities) (HW. Becker)				
Chapter 4	Cross section	4.1 Methodology	4.1.1 Energy calibration of accelerators				
	measurements (20 pages)	(A. Lagoyannis, J. Raisanen)	4.1.2 Detector efficiency calibration				
			4.1.3 Target Preparation				
			4.1.4 Charge Collection				
			4.1.5 Determination of cross sections				
		4.2 Coordinated measurement (M. Chiari, A. Pedro de Jesus)	Extended version of NIMB paper				
Chapter 5	Cross section data	5.1 Changes in IBANDL (O. Kakuee)					
		5.2 New data - (presented	Li – M. Chiari				
		reaction-by-reaction in figures)	Be – D. Strivay				
		Coordinated by I. Bogdanovic	B – A. Lagoyannis				
			C – H-W. Becker				
			N - A. K1SS				

**Table 4.1** Outline of final technical document to be submitted to IAEA Publishing Department for publication as IAEA TECDOC.

			F – A. Zucchiatti						
			Na – I. Bogdanovic						
			Mg – O. Kakuee						
			Al – A. Pedro de Jesus						
			Si – J. Raisanen						
			P – A. Pedro de Jesus						
			S – A. Lagoyanniss						
			Ti, Cr – A. Goncharov						
		5.3 Compilation of previous	Table to be included in Annex.						
		measurements (O. Kakuee)							
Chapter 6	PIGE Analysis Codes	6.1 ERYA bulk							
	(A. Pedro de Jesus)	6.2 ERYA profiling							
		6.3 Performance Evaluation (Based	on feedback from all participants)						
Chapter 7	Evaluation of PIGE cross	7.1 Methodology							
	sections	7.2 Examples of Evaluation							
	(A. Gurbich)	7.3 Recommended Cross Sections							
Chapter 8	Conclusions and Recommendations (HW. Becker, A. Pedro de Jesus)	<ul> <li>Conclusions:</li> <li>This CRP was very ambitious in its goals, featuring cross section measurements and evaluations. Nevertheless these goals were reached leading to an unprecedented amount of data produced and collected.</li> <li>IBANDL had only a few cases of gamma-producing reaction data; during the CRP much more was added including data existing in the literature.</li> <li>IBANDL has been accommodated to include PIGE Data.</li> <li>New data was produced – measurement of relevant cross sections.</li> <li>Codes were developed for bulk analysis and profiling.</li> <li>The basis for standard-less PIGE was established within the CRP.</li> <li>Comprehensive database readily available to the community.</li> <li>Evaluations were performed showing the potential to establish recommended cross section</li> </ul>							
		<b>Recommendations:</b> Benchmarking. More measurement of important reactions. Modify IBANDL to include resonance strengths and projectiles heavier than <sup>7</sup> Li. Evaluations efforts must be extended and uncertainties must be included in the evalua files. Implement PIGE into existing IBA codes.							

#### 5. Joint session with Physics Section Consultants' Meeting

A joint session with the Physics Section Consultancy Meeting on Improving the Quality of Analytical Data Measured by Ion Beams (from 7-10 April 2014) was held to discuss issues of common interest.

At this joint session the IAEA staff presented the activities of the Nuclear Data and Physics Sections related to Ion Beam Analysis. The new capabilities of the IBANDL interface were demonstrated in detail and were appreciated by all the participants.

A status report of the PIGE CRP was given together with a presentation related to how uncertainties on the data affect PIGE analysis. A summary of the nuclear data needs, as assessed by the Physics Section Consultants, was presented along with some aspects related to assigning uncertainties to evaluated data and benchmarking.

The discussions that followed raised issues on including PIGE analysis into existing IBA codes, including uncertainties on measured and evaluated data, updating stopping powers available on the IAEA website, extending IBANDL to include cross sections at higher energies to cover the needs of new applications where deeper depths must be reached, and improving the models describing screening effects in heavy ion reactions at low energies.

The Accelerator Knowledge Portal hosted at the IAEA web site was presented and participants were invited to visit the portal and provide feedback. The overall impression of the participants was that a great deal of progress had been made in the last few years to compile and produce data as well as analytical codes, under the coordination of the IAEA, and recommended further efforts in the future.

## 6. Action lists

## Table 6.1. Completed Measurements

Isotope	Reaction	γ ray [keV]	Energy range [MeV]	Angle [°]	Initial State, Jπ	Type of Data	Comments	Measured by:
			Mea	surements comp	leted	before the 2nd ]	RCM	
<sup>7</sup> Li	(p,p'y)	478	2-4	130	1/2-	Differential+ Thick target	Detailed-sparse points	Pedro de Jesus
<sup>9</sup> Be	(p,γ)	718	0.5-1.7	130	1+	Differential+ Thick target	Detailed	Pedro de Jesus
<sup>10</sup> B	(p,α'γ)	429	2-4	130	1/2-	Thick target	Sparse points	Pedro de Jesus
<sup>12</sup> C	(p,y)		1.1-2.6	55 and 0		Differential	Detailed	Becker
<sup>14</sup> N	(p,p'y)	2313	4-7	55	0+	Differential	Detailed+sparse points	Raisanen
<sup>14</sup> N	(d,p'y)	1885	0.6-2	55	5/2+	Differential	Detailed+sparse points	Kiss
<sup>14</sup> N	(d,p'y)	2297	0.6-2	55	7/2+	Differential	Detailed+sparse points	Kiss
<sup>14</sup> N	(d,p'y)	8310	0.6-2	55	1/2+	Differential	Detailed+sparse points	Kiss
<sup>19</sup> F	(p,p'y)	110	2-4	130	1/2-	Differential+ Thick target	Detailed	Pedro de Jesus
<sup>19</sup> F	(p,p'y)	197	2-4	130	5/2+	Differential+ Thick target	Detailed	Pedro de Jesus
<sup>19</sup> F	(p,α'γ)	6000- 7000	0.8-4.0	130	3-	Differential+ Thick target	Detailed	Pedro de Jesus
<sup>23</sup> Na	(p,p'y)	440	2-4	130	5/2+	Differential+ Thick target	Detailed	Pedro de Jesus
<sup>23</sup> Na	(p,p'γ) (p,α'γ)	1636 1634	2-4	130	7/2+ 2+	Differential+ Thick target	Detailed	Pedro de Jesus
<sup>23</sup> Na	(p,p'y)	440	1.8-3	135	5/2+	Differential	Detailed	Bogdanovic
<sup>23</sup> Na	(p,p'γ) (p,α'γ)	1636 1634	1.8-3	135	7/2+ 2+	Differential	Detailed	Bogdanovic
<sup>25</sup> Mg	(p,p'y)	390	2-4	130	3/2+	Differential+ Thick target	Detailed	Pedro de Jesus
<sup>25</sup> Mg	(p,p'y)	390	1.8-3	135	3/2+	Differential	Detailed	Bogdanovic
<sup>25</sup> Mg	(p,p'y)	585	2-4	130	1/2+	Differential+ Thick target	Detailed	Pedro de Jesus
<sup>25</sup> Mg	(p,p'y)	585	1.5-2.4	130	1/2+	Differential+ Thick target	Detailed	Pedro de Jesus
<sup>25</sup> Mg	(p,p'y)	974	1.5-2.4	130	3/2+	Differential+ Thick target	Detailed	Pedro de Jesus
<sup>25</sup> Mg	(p,p'y)	585	1.8-3	135	1/2+	Differential	Detailed	Bogdanovic
<sup>27</sup> Al	(p,p'y)	844	1.5-3	130	1/2+	Differential	Detailed	Pedro de Jesus
<sup>27</sup> Al	(p,p'γ)	844	2.5-5	0, 165, 55, 90	1/2+	Differential	Detailed	Lagoyannis
<sup>27</sup> Al	(p,p'γ)	844	1.8-3	135	1/2+	Differential	Detailed	Bogdanovic
<sup>27</sup> Al	(p,p'y)	844	2.5-3.0	135	1/2+	Differential	Detailed	Zucchiatti

Isotope	Reaction	γ ray [keV]	Energy range [MeV]	Angle [°]	Initial State, Jπ	Type of Data	Comments	Measured by:
<sup>27</sup> Al	(p,p'γ)	1014	1.5-4	130	3/2+	Differential	Detailed	Pedro de Jesus
<sup>27</sup> Al	(p,p'γ)	1014	2.5-5	0, 165, 55, 90	3/2+	Differential	Detailed	Lagoyannis
<sup>27</sup> Al	(p,p'γ)	1014	1.8-3	135	3/2+	Differential	Detailed	Bogdanovic
<sup>27</sup> Al	(p,p'γ)	1014	2.5-3	135	3/2+	Differential	Detailed	Zucchiatti
<sup>27</sup> Al	(p,α'γ)	1369	1.5-4	130	2+	Differential	Detailed	Pedro de Jesus
<sup>27</sup> Al	(p,α'γ)	1369	18-3	135	2+	Differential	Detailed	Bogdanovic
<sup>27</sup> Al	(p,α'γ)	1369	2.5-3	135	2+	Differential	Detailed	Zucchiatti
<sup>28</sup> Si	(d,p	1273	0.6-2	55	3/2+	Differential	Detailed	Kiss
<sup>28</sup> Si	(d,p	2028	0.6-2	55	5/2+	Differential	Detailed	Kiss
<sup>28</sup> Si	(p,p'γ)	1779	4-7	55	2+	Differential	Detailed	Raisanen
<sup>29</sup> Si	(p,p'γ)	1274	4-7	55	3/2+	Differential	Detailed	Raisanen
<sup>32</sup> S	(p,p'γ)	2230	3-6	0, 15, 55, 90, 125, 155	2+	Differential	Detailed	Lagoyannis
<sup>48</sup> Ti	(p,y)	62.3/90.6	1-3	90		Differential	Detailed	Goncharov
<sup>nat</sup> Ti	(p,y)	62.3/90.6	1-3	90		Differential	Detailed	Goncharov
<sup>nat</sup> Ti	(p,ny)	62.3/90.6	1-3	90		Differential	Detailed	Goncharov

Isotope	Reaction	γ ray [keV]	Energy range [MeV]	Angle [°]	Initial State, Jπ	Type of Data	Comments	Measured by:
			Measur	ements perforn	ned be	tween 2 <sup>nd</sup> and 3	rd RCM	
$^{10}\mathrm{B}$	(p,p'γ)	718	2-5	0, 55, 90,165 15,40,105,150	1+	Differential+ Thick target	Detailed+sparse points	Lagoyannis
<sup>10</sup> B	(p,α'γ)	429	2-5	0, 55, 90,165 15,40,105,150	1/2-	Differential+ Thick target	Sparse points	Lagoyannis
<sup>12</sup> C	(d,p'y)	3089	0.6-2.0	55	1/2+	Differential	Detailed	Kiss
<sup>23</sup> Na	(p,p'γ)	440	2.5-4	90, 0, 45	5/2+	Differential+	Detailed	Chiari
<sup>23</sup> Na	(p,p'γ) (p,α'γ)	1636 1634	2.5-4	90, 0, 45	7/2+ 2+	Differential+	Detailed	Chiari
<sup>27</sup> Al	(p,p'γ)	844	1-3	90	1/2+	Differential	Detailed+sparse points	Kakuee
<sup>27</sup> Al	(p,p'γ)	844	1-3	90	1/2+	Differential	Detailed+sparse points	Kakuee
<sup>27</sup> Al	(p,p'γ)	844	2.5-4	0,45, 90	1/2+	Differential+ Thick target	Detailed+sparse points	Chiari
<sup>27</sup> Al	(p,p'γ)	844	2.5-3.	55	1/2+	Differential	Detailed	Kiss
<sup>27</sup> Al	(p,p'γ)	844	2.5-4	55	1/2+	Differential	Detailed	Raisanen
<sup>27</sup> Al	(p,p'γ)	844	2.5-3	90	1/2+	Differential	Detailed	Becker
<sup>27</sup> Al	(p,p'γ)	1014	1-3	90	3/2+	Differential+ Thick target	Detailed+sparse points	Kakuee
<sup>27</sup> Al	(p,p'γ)	1014	2.5-4	0,45, 90	3/2+	Differential+ Thick target	Detailed+sparse points	Chiari
<sup>27</sup> Al	(p,γ)	1779	1-3	90	2+	Differential+ Thick target	Detailed+sparse points	Kakuee
<sup>27</sup> Al	(p,α'γ)	1369	1-3	90	2+	Differential+ Thick target	Detailed+sparse points	Kakuee
<sup>27</sup> Al	(p,α'γ)	1369	2.5-4	0,45 and 90	2+	Thick target	sparse points	Chiari
<sup>29</sup> Si	(p,p'γ)	1274	1-3	90	3/2+	Thick target	sparse points	Kakuee
<sup>28</sup> Si	(d, py)	1273,202 8,2426, 4934	0.65-2	55		Differential	Detailed	Kiss
<sup>31</sup> P	(p,p'γ)	1266	1-3	90	3/2+	Thick target	sparse points	Kakuee
<sup>53</sup> Cr	(p,y)	62.3/90.6	1-3	90		Differential	Detailed	Goncharov
<sup>54</sup> Cr	(p,ny)	62.3/90.6	1.5-3	90		Differential	Detailed	Goncharov

Table 6.2. Per	nding Measur	ements
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Isotope	Reaction	γ-ray [keV]	Energy range [MeV]	Angle	Initial State, Jπ	Type of Data	Comments	Assigned to:	Yes/No Deadline
<sup>7</sup> Li	(p,p'y)	478	2-3, 5-7	135	1/2-	Differential+ Thick target	Detailed + sparse points	Zucchiatti	End of 2014 0.8-4.5 MeV
<sup>7</sup> Li	(p,n'γ)	429	2-3, 5-7	135	1/2-	Differential+ Thick target	Detailed + sparse points	Zucchiatti	End of 2014 1-4.5 MeV
<sup>9</sup> Be	(α,η'γ)	4443	2-10	135	2+	Differential+ Thick target	Detailed + sparse points	Strivay	End of 2014
<sup>11</sup> B	(p,p'y)	2124	2.5-5	0, 90,165,15 105,150	1/2-	Differential+ Thick target	Detailed+sparse points	Lagoyannis	Almost done
<sup>14</sup> N	(p,p'y)	2313	3.5-4	0, 45, 90	0+	Thick target	Sparse points	Chiari	End of 2014
<sup>14</sup> N	(p,p'y)	2313	4-10	135	0+	Differential+ Thick target	sparse points	Strivay	End of 2014
<sup>14</sup> N	(d,p'y)	1885	0.6-2	90	5/2+	Differential+ Thick target	Detailed+sparse points	Kakuee	End of 2014
<sup>14</sup> N	(d,p'y)	2297	0.6-2	90	7/2+	Differential+ Thick target	Detailed+sparse points	Kakuee	End of 2014
<sup>14</sup> N	(d,p'y)	8310	0.6-2	90	1/2+	Differential+ Thick target	Detailed+sparse points	Kakuee	End of 2014
<sup>19</sup> F	(p,p'y)	110	2-6	135	1/2-	Differential+ Thick target	Detailed within 30 keV	Zucchiatti	End of 2014 0.8 – 4.5 MeV
<sup>19</sup> F	(p,p'y)	197	2-6	135	5/2+	Differential+ Thick target	Detailed within 30 keV	Zucchiatti	End of 2014 0.8 – 4.5 MeV
<sup>19</sup> F	(p,α'γ)	6000- 7000	2-6	135	3-	Differential+ Thick target	Detailed within 30 keV	Zucchiatti	End of 2014 0.8 – 4.5 MeV
<sup>19</sup> F	(p,p'y)	110	2.5-4	45	1/2-	Differential	Detailed	Chiari	Summer of 2014
<sup>19</sup> F	(p,p'y)	197	2.5-4	45	5/2+	Differential	Detailed	Chiari	Summer of 2014
<sup>23</sup> Na	(p,p'y)	440	1-2.9	90	5/2+	Differential	Detailed	Kakuee	End of 2014
<sup>23</sup> Na	(p,p'γ) (p,α'γ)	1636 1634	1-2.9	90	7/2+ 2+	Differential	Detailed	Kakuee	End of 2014
<sup>23</sup> Na	(p,p'y)	440	2.5-4	90, 0, 45	5/2+	Thick target	Sparse	Chiari	End of 2014
<sup>23</sup> Na	(p,p'γ) (p,α'γ)	1636 1634	2.5-4	90, 0, 45	7/2+ 2+	Thick target	Sparse	Chiari	End of 2014
<sup>23</sup> Na	(p,p'y)	440	2-3	55 (0, 90, 135)	5/2+	Differential	Detailed	Kiss	End of 2014
<sup>23</sup> Na	(p,p'γ) (p,α'γ)	1636 1634	2-3	55 (0, 90, 135)	7/2+ 2+	Differential	Detailed	Kiss	End of 2014
<sup>24</sup> Mg	(p,p'y)	1369	2-6	0, 55, 90,165	2+	Differential	Detailed	Lagoyannis	End of 2014
<sup>24</sup> Mg	(p,p'y)	390	1-3	90	3/2+	Differential	Detailed	Kakuee	End of 2014
<sup>25</sup> Mg	(p,p'y)	390	1-3	90	3/2+	Differential	Detailed	Kakuee	End of 2014
<sup>25</sup> Mg	(p,p'y)	390	2-5.5	0, 55, 90,165	3/2+	Differential	Detailed	Lagoyannis	End of 2014
<sup>25</sup> Mg	(p,p'y)	585	2-5.5	0, 55, 90,165	1/2+	Differential	Detailed	Lagoyannis	End of 2014
<sup>25</sup> Mg	(p,p'y)	974	1-3	90	3/2+	Differential	Detailed	Kakuee	End of 2014
<sup>25</sup> Mg	(p,p'y)	585	1-3	90	1/2+	Differential	Detailed	Kakuee	End of 2014

<sup>26</sup> Mg	(p,γ)	1014	1-3	90	3/2+	Differential	Detailed	Kakuee	End of 2014
<sup>27</sup> Al	(p,p'y)	844	3-10	135	1/2+	Differential+ Thick target	Detailed+sparse points	Strivay	Autumn 2014
<sup>27</sup> Al	(p,p'y)	1014	2.5-3.	55	3/2+	Differential	Detailed	Kiss	Analysis End of 2014
<sup>27</sup> Al	(p,p'y)	1014	3-10	135	3/2+	Differential+ Thick target	Detailed+sparse points	Strivay	Autumn 2014
<sup>27</sup> Al	(p,p'y)	1014	2.5-3	55	3/2+	Differential	Detailed	Raisanen	Analysis End of 2014
<sup>27</sup> Al	(p,p'y)	1014	2.5 <b>-3</b>	90	3/2+	Differential+ Thick target	Detailed+sparse points	Becker	Analysis End of 2014
<sup>27</sup> Al	(p,p'y)	1014	2.5 <b>-3</b>	130	3/2+	Differential+ Thick target	Detailed+sparse points	Pedro de Jesus	Analysis End of 2014
<sup>27</sup> Al	(p,y)	1779	1.5-4	130	2+	Differential+ Thick target	Detailed+sparse points	Pedro de Jesus	End of 2014
<sup>27</sup> Al	(p,α'γ)	1369	2.5-3	55	2+	Differential	Detailed	Kiss	End of 2014
<sup>29</sup> Si	(p,p'y)	1274	1-3	90	3/2+	Differential	Detailed	Kakuee	End of 2014
<sup>29</sup> Si	(p,p'γ)	1274	4-7	55	3/2+	Differential+ Thick target	Detailed+sparse points	Raisanen	Done Analysis Autumn 2014
<sup>nat</sup> Si	(p,p'y)	1274	2.5-4	0,45, 90	3/2+	Thick target	Sparse points	Chiari	End of 2014
<sup>nat</sup> Si	(p,p'y)	1779	2.5-4	0,45, 90	2+	Thick target	Sparse points	Chiari	End of 2014
<sup>28</sup> Si	(p,p'y)	1779	1-3	90	2+	Differential+ Thick target	Detailed+sparse points	Kakuee	End of 2014
<sup>31</sup> P	(p,p'y)	1266	1-3	90	3/2+	Differential	Detailed	Kakuee	End of 2014
<sup>31</sup> P	(p,p'γ)	1266	2-4	130	3/2+	Differential+ Thick target	Detailed+sparse points	Pedro de Jesus	End of 2014
<sup>32</sup> S	(d,p'y)	841	1-2	90	1/2+	Differential+ Thick target	Detailed+sparse points	Kakuee	End of 2014
<sup>35</sup> Cl	(d,p'y)	1165	1-2	90	1+	Differential+ Thick target	Detailed+sparse points	Kakuee	End of 2014

Element/Isotope	Person Responsible
Li	Chiari
В	Lagoyannis
Be	Strivay
<sup>12</sup> C	Becker
Ν	Kiss
F	Zucchiatti
Na	Bogdanovic Radovic
Mg	Kakuee
Al	Pedro de Jesus
Si	Raisanen
Р	Pedro de Jesus
Cl	Pedro de Jesus
S	Lagoyannis
Ti	Goncharov
Cr	Goncharov

Table 6.3. Responsible per Element/Isotope

Table 6.4.	Special	actions
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Action on	Subject	
All concerned	Perform the remaining assigned measurements indicated in Table 6.1 and submit the R33 data files to NDS before the end of 2014.	
All concerned	Use ERYA code and send feedback to Adelaide Pedro de Jesus before the end of 2014.	
Pedro de Jesus	Finish the upgrade of ERYA code in order to handle depth profiling.	
Becker, Lagoyannis	Find out the information of cross sections relevant to PIGE in NACRE II and send them to NDS.	
Responsible Persons (Table 6.3)	Collect data from the literature, compile it in the R33 format and send it to NDS to be included in IBANDL.	
Semkova	On request of participants, digitize data for inclusion in IBANDL and EXFOR.	
Pedro de Jesus and Chiari	Write draft of paper on coordinated measurement to be submitted to NIM B, before the end of July 2014.	
All concerned	Submit contributions to the final technical document, according to specific assignments (see Table 4.1), by 30 April 2015.	
Dimitriou for the CRP	Prepare an abstract on conclusions of the CRP for presentation at the IBA Conference, 14-19 June 2015.	
All concerned	Report errors in IBANDL to NDS.	
Dimitriou	Distribute figure template for the final technical document.	

## 7. Conclusions

The Third Research Coordination Meeting (RCM) on the Development of a Reference Database for Particle-Induced Gamma ray Emission (PIGE) Spectroscopy was held at the IAEA, Vienna, from 7 to 11 April 2014.

Participants presented the work that had been done since the previous RCM. The work plan was reviewed and revised. Deadlines were agreed upon for submission of new data as well as data found in the existing literature. It is expected that with the completion of the work outlined in this report, IBANDL will include a comprehensive compilation of PIGE data. The final version of ERYA code for PIGE bulk analysis was distributed for extensive testing by the participants of the CRP. The ERYA version for PIGE profiling will be finished by the end of 2014. The feasibility of performing theoretically based evaluations was demonstrated for  ${}^{27}$ Al(p,p' $\gamma$ )<sup>27</sup>Al reactions.

The content of the final technical document was discussed, tasks were assigned to the participants and deadlines were set for submitting the chapters to NDS.

## 8. Recommendations

During this final meeting of the CRP, several issues concerning nuclear data needs and implementation of PIGE technique were discussed, leading to the following recommendations:

More measurements of nuclear reactions cross sections, and in particular of angular distributions, are needed to support the evaluation procedure and produce recommended cross sections, in cases where discrepancies are still not resolved.

Evaluation efforts should be extended to include uncertainties in the evaluated files.

Benchmarking experiments are needed to validate the recommended data.

Resonance strengths and widths are essential for PIGE depth profiling and so IBANDL should be modified in order to include information on narrow resonances. Gamma-producing reactions induced by projectiles heavier than <sup>7</sup>Li, such as <sup>15</sup>N, <sup>18</sup>O and <sup>19</sup>F, are also important for applications and should be included in IBANDL.

To support a synergetic use of ion beam analysis techniques, PIGE analysis codes should be incorporated in existing IBA codes.

Clearly a concerted effort is required to address the above mentioned needs of the PIGE community successfully. The participants of this CRP recommend that IAEA NDS take the necessary actions to coordinate this effort.



## 3<sup>rd</sup> Research Coordination Meeting on Development of a Reference Database for PIGE Spectroscopy

IAEA Headquarters, Vienna, Austria 7 – 11 April 2014 Meeting Room M0E27

## ADOPTED AGENDA

## Monday, 7 April

08:30 - 09:30	Registration (IAEA Registration Desk, Gate 1)	
09:30 - 10:15	<b>Opening Session</b> Opening Remarks and Welcome (R.A. Forrest, SH-NDS) Introduction: Objectives of this RCM (P. Dimitriou) Election of Chairman and Rapporteur Discussion and Adoption of the Agenda (Chairman)	
10:15 - 10:45	Coffee break	
10:45 - 12:15	Presentations	
	<ol> <li>Proposal of an interlaboratory PIGE experiment, Pedro de Jesus (~ 30 min)</li> <li>Gamma-ray production cross sections for deuteron induced reactions on C, N and Si, Kiss (~ 30 min)</li> <li>PIGE Data for Material Analysis from Nuclear Astrophysics and other Sources, Becker (~ 30 min)</li> </ol>	
12:15 - 12:30	Administrative matters	
12:30 - 14:00	LUNCH	
14:00 - 17:30	Presentations (cont'd)	
	4) Cross section measurements of the ${}^{10}B(p,p'g){}^{10}B, {}^{10}B(p,ag){}^{7}Be$ and ${}^{11}B(p,p'g){}^{11}B$ reactions at the energy range between 2.5 to 5 MeV, Lagoyannis (~30 min)	
	5) Gamma-ray production cross sections of proton irradiated nitrogen, Raisanen (~30 min)	
	6) Recent PIGE measurements at the VDG Lab in Tehran, Kakuee (~30 min)	
	8) PIGE measurements performed at the Ruđer Bošković Institute, Bogdanović Radović (~30 min)	
	Coffee break as needed	

<u>Tuesday, 8 April</u>	
09:00 - 12:30	Presentations (cont'd)
	<ul> <li>9) Measurements of proton induced gamma-ray emission cross sections and yields on Al and Na, Chiari (~30 min)</li> <li>10) Measurement of gamma production in thin LiF targets at CMAM, Zucchiatti (~30 min)</li> <li>11) Strivay (~10 min)</li> <li>12) R-matrix calculations for charged-particle induced reactions using SAMMY, Dimitriou (20 min)</li> </ul>
	Coffee break as needed
12:30 - 14:00	LUNCH
14:00 - 17:30	Round Table Discussion
	Session on Codes: ERYA (bulk)-finally available and ERYA profile-final adjustments, A. Pedro de Jesus Coffee break as needed
19:00	DINNER at a restaurant in the city

## Wednesday, 9 April

09:00 - 12:30	Round Table Discussion (cont'd)
	Presentation of slides sent by A. Goncharov (by A. Kiss) Coffee break as needed
12:30 - 14:00	LUNCH
14:00 - 17:30	Joint Nuclear Data (NDS) - Physics Section (PS) Session (Room TBA)
	Common session with participants of Physics Section Consultant's Meeting on <b>Improving the Quality of Analytical Data Measured by Ion</b> <b>Beams</b> (from 7 to 10 April 2014 Vienna Austria, PO: Aliz Simon)
	<ul> <li>NDS Programme on IBA applications <ul> <li>Dimitriou (10') + V. Zerkin (5'), NDS IAEA</li> </ul> </li> <li>PS Programme on IBA applications <ul> <li>A. Simon (15'), PS IAEA</li> <li>PIGE CRP: where are we?</li> <li>Massimo Chiari, INFN-Firenze, Italy (10')</li> </ul> </li> <li>From data to PIGE analysis <ul> <li>Adelaide Pedro de Jesus, CFNUL, Portugal (10')</li> </ul> </li> <li>Improving the Quality of Analytical Data Measured by Ion Beams <ul> <li>Nuno Barradas, IST, Portugal (10')</li> </ul> </li> <li>Uncertainty of EBS scattering cross-section function Chris Jeynes, University of Surrey, England (10')</li> </ul>
	<ul> <li>Discussion on</li> <li>✓ IBANDL</li> <li>✓ Standard-less PIGE: codes</li> <li>✓ Joint NDS-PS ICTP/IAEA Workshop</li> <li>✓ Uncertainty of EBS scattering cross-section</li> <li>✓ Future Activities</li> </ul>

Coffee break as needed

## Annex A

## <u>Thursday, 10 April</u>

09:00 - 12:30	Round Table Discussion (cont'd)	
	CRP Final Document	
12:30 - 14:00	LUNCH	Coffee break as needed
14:00 - 17:30	Round Table Discussion (cont'd)	
	CRP Final Document Drafting of the 3 <sup>rd</sup> RCM Summary Report	Coffee break as needed
<u>Friday, 11 April</u>		
09:00 - 12:30	Drafting of the 3 <sup>rd</sup> RCM Summary Report (co	ont'd)
		Coffee break as needed

## 12:30 – 13:00 Closing of the Meeting



## 3rd Research Coordination Meeting on Development of a Reference Database for PIGE Spectroscopy 7-11 April 2014 Vienna, Austria

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## **Presentations - PIGE 3. RCM**

#	Author	Title	Link
1	A.Z. Kiss	Gamma-ray production cross sections for deuteron induced nuclear reactions on C, N and Si	PDF
2	HW. Becker	PIGE Data for Material Analysis from Nuclear Astrophysics and other Sources	PDF
3	M. Chiari	Measurements of proton induced gamma-ray emission cross sections and yields on Al and Na	PDF
4	P. Dimitriou	Charged-particle Cross Sections using SAMMY	PDF
5	A. Goncharov	Measurement of excitation yields of low energy prompt gamma ray from proton bombardment of Cr-foils with energies ranging between 1.0 and 3.0 MeV	PDF
6	O. Kakuee	Recent PIGE measurements at the VDG Lab in Tehran	PDF
7	A. Lagoyannis	Cross section measurements of the ${}^{10}B(p,p'\gamma){}^{10}B$ , ${}^{10}B(p,a\gamma){}^{7}Be$ and ${}^{11}B(p,p'\gamma){}^{11}B$ reactions in the energy range between 2.5 to 5 MeV	PDF
8	I. Bogdanovic	PIGE measurements at the Ruder Boskovic Institute	PDF
9	J. Raisanen	Gamma-ray production cross sections of proton irradiated nitrogen	PDF
10	A. Pedro de Jesus	ERYA - Profiling Gamma-ray Depth Analysis	PDF
11	A. Zucchiatti	Measurement of gamma production in thin LiF targets at CMAM	PDF

## Presentations - Joint Session of Nuclear Data and Physics Section, Wednesday, 9 April, 14:00-17:00

#	Author	Title	Link
1	P. Dimitriou	IBA activities at the Nuclear Data Section	<u>PDF</u>
2	M. Chiari	PIGE CRP: where are we?	<u>PDF</u>
3	A. Simon	Improving the Quality of Analytical Data Measured	<u>PDF</u>
4	N. Barradas	Nuclear Data Needs for IBA	<u>PDF</u>
5	C. Jeynes	The Uncertainty of EBS Scattering Cross-Section Functions	<u>PDF</u>
6	A. Pedro de Jesus	From Cross Section Data to PIGE Bulk Analysis	<u>PDF</u>

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