IAEA
International Atomic Energy Agency

INDC(NDS)-0589
Distr. IBA

INDC International Nuclear Data Committee

Summary Report

1st Research Coordination Meeting

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

IAEA Headquarters
Vienna, Austria

16-20 May 2011

Prepared by

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Lisboa, Portugal

July 2011

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Produced by the IAEA in Austria

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Abstract

The First 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 16-20 May 2011. A summary of the participants' presentations is given as well as background information, objectives and recommendations concerning approach and methodology. The extension of the IBANDL database format to include PIGE data was discussed. The different tasks to achieve the CRP objectives were assigned to participants. A list of priority measurements was produced and the individual sets of measurements assigned to participants.

July 2011

TABLE OF CONTENTS

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 μm) by measurement of characteristic prompt γ-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, with better resolution than other Ion Beam Analysis (IBA) techniques, was soon recognized. The basic physical processes underlying PIGE are now well understood, but the reliability of analytical results cannot be taken for granted due to insufficient knowledge of the physical data.

Compositions and structures are inferred from measured quantities such as γ-ray spectra or excitation curves, via physical models incorporating the sample structure and the basic physical processes, and quantities giving rise to the observed spectra or excitation curves. The primary quantities required are the stopping power and the cross sections of the interactions involved. Whilst work remains to be done on accurate stopping powers, the field is largely catered for by the considerable body of work of Ziegler and co-workers, embodied in the SRIM computer code [1].

The case is quite different for cross sections for nuclear reactions with γ-rays in the exit channel. Although a considerable body of published data exists in the nuclear physics literature, there is no up-to-date, comprehensive compilation specifically dedicated to the IBA community. A number of PIGE cross-section data have already been uploaded to IBANDL (http://www-nds.iaea.org/ibandl) by members of the IBA community. In doing so, the IBA community has shown that there is an overwhelming need for compilation, assessment and evaluation of PIGE data. However, a preliminary survey of this 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.

This state of affairs has been a preoccupation of the IBA community for many years. However, to date a concerted effort to improve the situation has not taken shape for the lack of resources and coordination. As a result of this situation the users of PIGE are forced to implement a semi-quantitative approach. On the basis of experience gathered in developing IBANDL [2], which has virtually become the main source of the charged particle cross-section data for IBA, it is clear that the IAEA could play a unique and critical role in meeting those needs.

1.2. Overall objective

To create a data library for Ion Beam Analysis that contains reliable and usable data on charged particle γ-ray emission cross sections that will be made freely available to the user community.

1.3. Specific research objectives

To attain this goal a four-pronged approach will be 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 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 will be made available on the NDS Web server 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 in about four years. Three Research Coordination Meetings (RCMs) are planned, this first RCM to determine the detailed work plan and to assign tasks to participants. The aim of the second RCM, which is envisaged to take place in the last quarter of 2012, will be to monitor the progress made. The final RCM near the end of the project will serve to review results and prepare the documentation related to the project.

The first RCM was held at the Agency headquarters in Vienna from 16 to 21 May 2011. The meeting was opened with a welcome address by Meera Venkatesh, Director of the Division of Physical and Chemical Sciences (NAPC). After short presentations by the participants, the project officer, Daniel Abriola, outlined the main objective of the meeting as to establish the course of action, related to measurements, evaluation of existing data, evaluation of the data format and database design, in order to fulfil the final goal of obtaining a reference database for Particle Induced Gamma-ray Emission (PIGE) Spectroscopy. Alexander Gurbich was elected chairman and Adelaide Pedro de Jesus agreed to serve as rapporteur for the meeting. The RCM 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 the work to be done, the scope, and the assignment of tasks. 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.

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[2] IAEA Report INDC(NDS)-0555, Summary Report Third Research Coordination Meeting on Development of a Reference Data Base for Ion Beam Analysis, IAEA Headquarters, Vienna, Austria 27 – 30 April 2009, December 2009.

2. Participants' Presentations

A summary of presentations is given here. The participants' full presentations can be found at http://www-nds.iaea.org/pige/#i.

2.1. The role of nuclear reaction induced alignment for PIGE, Pedro de Jesus

The presentation started with an overview of the CFNUL/ITN Ion Beam Laboratory in Lisbon/Portugal and the applied work being done there.

The presentation focused on the physical conditions and equations expressing the alignment of the final state from which the γ-ray is emitted, leading to an angular distribution of this radiation. The alignment condition, i.e. the population of the substate M_1 is equal to the population of the substate $-M_1$, implies that the angular distribution will include only even terms (and even Legendre polynomials) and also that states with $J_1 = 0$ or ½ will not be aligned, leading to an isotropic distribution. Assuming that the angular distribution will be dominated by the first two terms, that is proportional to $\cos^2\theta$, then the angles 55° and 125° are neutral angles – the total cross section may be obtained from measurements at these angles as if the distribution were isotropic.

Table 1 below presents information for several cases on the angular momentum of the final state from which the γ-ray is emitted, showing that, theoretically, there is the possibility of several γ-lines used for PIGE to be anisotropic. This may cause discrepancies among different measurements made at different angles.

In the literature, there is scarce information on angular distributions; they have mostly been measured in the 1950s and 1960s, with low resolution detectors and only for a few projectile energy conditions. As the population parameters of the substates depend on the specific process by which the state $|J_1M_1>$ is formed, they will depend on projectile energy and on resonances in the specific compound nucleus state.

The considerations above were derived assuming an undefined intermediate compound nucleus state; for a specific compound nucleus state expressions given in the presentation may no longer apply. Although, as alignment conditions are expected to prevail, only even Legendre polynomials will appear in the angular distribution, leading to a main dependence on $\cos^2\theta$.

Concluding, it was emphasized that, in order to obtain accurate cross section values for PIGE, angular distribution of γ-rays must be measured.

Table 1. Initial state Jπ and γ-ray energies relevant to PIGE.

Isotope	Reaction	γ-ray	Initial State, $J_1\pi$
^{7}Li	(p,p´γ)	478 keV	1/2-
^{9}Be	(p,γ)	718 keV	1+
^{10}B	(p,p´γ)	718 keV	1+
^{10}B	(p,αγ)	429 keV	1/2-
^{19}F	(p,p´γ)	110 keV	1/2-
^{19}F	(p,p´γ)	197 keV	5/2+
^{23}Na	(p,p´γ)	440 keV	5/2+
^{23}Na	(p,p´γ)	1636 keV	7/2+
^{24}Mg	(p,p´γ)	1369 keV	2+
^{25}Mg	(p,p´γ)	585 keV	1/2+
^{27}Al	(p,p´γ)	844 keV	1/2+
^{27}Al	(p,p´γ)	1014 keV	3/2+
^{28}Si	(p,p´γ)	1779 keV	2+

2.2. The PIGE technique at ATOMKI and its applications in archaeometry, Kiss

The talk was divided into three parts: In the first part the Section of Ion Beam Physics of ATOMKI was introduced, both its previous activity in γ-ray spectrometry and its present day instrumentation. The second part dealt with questions related to the planned work in the context of this CRP. The third part showed some results achieved at ATOMKI with regard to the analysis of cultural heritage where the PIGE technique played a role.

The Section of Ion Beam Physics was originally based on a home-made 5 MV Van de Graaff (VdG) electrostatic accelerator. The accelerator was put into operation in 1971 and, in the beginning, it supplied ion beams exclusively for nuclear physics. Gamma-ray spectrometry was one of the methods used from the beginning and achieved results – among others – in the field of radiative capture in cooperation with the University of Helsinki (see e.g. [1, 2]). At present, the Section is divided into two groups: the Nuclear Astrophysics Group and the Laboratory of Ion Beam Applications. The Nuclear Astrophysics Group works in a field of close international cooperation (Bochum, LUNA, etc.) and performs nuclear reaction cross section measurements important for nuclear astrophysics. Part of the γ-ray spectroscopy is using the beam of this VdG machine [3, 4].

The Laboratory of Ion Beam Applications of ATOMKI is devoted to applications of atomic and nuclear physics in different fields such as environmental research, biomedicine, geology, materials and surface science (including ion beam induced damage investigations and proton beam lithography) and cultural heritage research. The work is performed in the frame of various projects and collaborations and contributes to higher education, as well.

Concerning previous activities of the Section in the field of particle induced γ-ray emission technique (PIGE), the most important works are the following: Thick target γ-ray yields for p-PIGE. The work is an extension of the work done in Helsinki up to 4.2 MeV proton energy for elements: Li – Sc (except Ne, Ar) [5]. A similar measurement was performed on thick target γ-ray yields for d-PIGE (in collaboration with LRMF, Paris) in the deuteron energy interval: 0.7-3.4 MeV [6]. Gamma-ray production cross sections were determined in the deuteron energy range of 0.6-2 MeV for the most dominant γ-lines of Li, Be, B, O and F [7]. Ge(Li), HpGe detectors and, in some measurements, a Clover-BGO detector system were used [8]. The absolute full-energy peak efficiency calibration of the detector system was done using proton-capture nuclear reactions and radioactive sources [9].

Instrumentation: The main facility is the 5 MV electrostatic accelerator. The available ions for analysis are H^+, D^+, $^4He^+$. The assortment of ions and their energy range (0.6-3.8 MeV) provided by the accelerator makes it possible to apply most of the ion beam analytical techniques: PIXE, PIGE, RBS, STIM, ERDA. The accelerator is provided with four beam lines. One of them serves for investigations with the PIXE technique. The second beam line has a turntable for 2 shielded gamma detectors for gamma spectroscopy, especially for p- and d-PIGE analysis and for nuclear astrophysics. The most frequently used one is the beam line equipped with an Oxford-type scanning nuclear microprobe [10] (1.5 μm x 1.5 μm beam size, an HPT XZY-stage two-axis goniometer), and devoted to the micro-PIXE (and PIGE, RBS, NRA & ERDA) analysis of minute samples with high lateral resolution. Various γ-ray detectors (HPGe 40% (ORTEC), HPGe 20% (CANBERRA), Clover-Ge-BGO 120%, NaI(Tl)) are available for PIGE analysis and depth profile measurements for light elements. A laboratory equipped with a Leybold UINIVEX 350 vacuum coating system serves for sample preparation.

Planned experimental work: On the basis of previous experience both in p-PIGE and d-PIGE, ATOMKI will take part in cross section measurements mainly related to the analysis of the most important elements for interdisciplinary applications. In the case of deuteron induced reactions, thin target carbon and nitrogen γ-ray cross section measurements would be important. The experimental determination of the "best" practical usable gamma detection angle (with respect to the beam direction) would be interesting especially in the case of resonant reactions. A new target chamber is planned on the gamma spectroscopy beam line, allowing accurate measurement of beam current, and easily variable detector-target distance, as well as detection angle to the beam direction and with a possibility to measure RBS simultaneously.

Application of PIGE in the study of archaeological samples included the study of obsidian glasses [11], classification of late Roman glass seals [12], investigation of classical ring-stones and their imitations [13] and investigation of incrusted pottery [14]. From the recent results obtained in the frame of the FP7 project CHARISMA the study of archaeological glass seals [15] and some other results were mentioned.

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2.3. Depth profiling with low energy nuclear resonances, Becker

Nuclear resonances at low energies, e.g. below 500 keV in (p,γ) or (p,αγ) reactions, can be a viable tool for depth profiling of isotopes in thin layers and thin layer systems. Although the resonance strengths are usually smaller than at higher energies, the depth resolution is better, due to the larger stopping power. Moreover, the resonances are narrow, isolated and well above the non-resonant background which is also preferable for depth profiling purposes [1]. Probably the best known case is the resonance at E_p= 429 keV in the $^{15}N(p,\alpha\gamma)^{12}C$ reaction, which is mostly used in the inverse kinematics with a ^{15}N beam to profile hydrogen.
Other than, for example, in the case of RBS, the energy resolution of the detector in such measurements is only necessary to identify the γ-ray of interest, but is not relevant for the depth resolution. The depth resolution is given by the width of the resonance together with the beam energy resolution and the energy spread caused by the Doppler broadening due to the thermal motion of the sample atoms. The latter one can be estimated, for example, for protons with an energy of 400 keV on a silicon sample at room temperature to be some 70 eV. Since most low energy resonances have an energy width smaller than that, depth resolutions of 1 nm and better can be achieved with proton beams having a good energy resolution.
The method has been employed and proven to be useful in various applications ranging from the investigation of semiconductor layers to diffusion studies in minerals. Since the method is isotopic sensitive, it also offers the opportunity for isotopic tracing studies.
There are several resonances in light nuclei which can be employed for such purposes. For material analysis applications it is necessary to know besides the resonance energy either the maximal cross section and width of the resonance or, for resonances having a width smaller than accessible by a measurement, the resonance strength. This is essentially the integral over the resonance curve which determines the γ-ray yield in a depth profiling measurement. Furthermore, angular distributions of the emitted γ-rays and the non-resonant cross section need to be known to estimate their influence on the depth profiles in a particular study.
Looking in the material analysis literature it might appear that there is only little information concerning low energy resonances and yield curves. However, extensive studies of nuclear reactions at low energies have been done in the field of nuclear astrophysics, where a good knowledge of cross sections and resonance parameters are crucial for the calculation of stellar reaction rates. Therefore it is proposed for a future data base for material analysis to collect and assess the available data and incorporate them in a form best suited for the needs in the analysis of depth profiles.

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2.4. PIGE research activities at the Van de Graaff Laboratory in Tehran, Kakuee

The Van de Graaff Laboratory (VDG lab) of Nuclear Science and Technology Research Institute (NSTRI) in Tehran has a long history of applying various kinds of IBA methods such as PIXE, microPIXE, RBS, RBS-Channeling, ERD and NRA to characterize different categories of samples from environmental science, materials science, life science, archaeology and other disciplines. Moreover, the Laboratory has been involved in fundamental research to collect basic data required for IBA methods [1-5]. The 3MV Van de Graaff electrostatic accelerator is used to produce energetic ion beams of H^+, D^+ and He^+ up to 3 MeV. Accurate analysis of various samples is being carried out in seven beamlines equipped either with modern facilities such as microbeam system (manufactured by Oxford Microbeam Co.) and RBS-channeling system (manufactured by HV Co.), or with home-made complementary reaction chambers and equipment. The publications of VDG lab indicate its contribution and activities to solve the problems facing the IBA community.

Measurement of low-Z elements, especially in external PIXE analysis of archaeological samples, is one of the big challenges in VDG lab, since the low energy X-rays strongly attenuate in air. To overcome this limitation, Proton Induced Gamma-ray Emission (PIGE) could be a great opportunity.

In this presentation, the thick target excitation function of γ-ray production yield for some light elements including Na, Mg, Al and Si is reported. The γ-ray emission in PIGE is the consequence of one or more charged-particle reactions of inelastic collisions (p,p´γ), pickup (p,γ) and rearrangements reactions. After discussing all open nuclear reaction channels for γ-ray production in the energy range of interest, the γ-ray yields of a thick target bombarded by a proton beam of energy E_0 are calculated and reported using the following relation [6]:

$$Y(E_0) = \varepsilon_{abs}(E_\gamma) \,.\, N_p \,.\, f_m \,.\, f_i \,.\, N_{av} \,.\, A^{-1} \,.\, \int_0^{E0} \sigma(E) \,/\, \varepsilon(E)\, dE$$

Where $\varepsilon_{abs}(E_\gamma)$ is the absolute efficiency of the detection system, E_γ is the emitted γ-ray energy, N_p is the number of incident protons, f_m is the mass fraction (concentration), A^{-1} is the inverse of the atomic mass of the element, f_i is the abundance of isotope i, N_{av} is Avogadro's number, $\sigma(E)$ is the nuclear reaction cross section and $\varepsilon(E)$ is the stopping cross section of the sample in units of energy area per mass.

By applying the published resonance strengths and widths at different energy levels and using the respective target stopping cross sections, the thick target excitation yields were calculated for Na, Mg, Al and Si. The thick target γ-ray yields of these elements for the γ-lines of significance were also measured using HPGe detector for the proton beams of 1.5 up to 2.6 MeV with an energy step of 100 keV.

As an example, the measured thick target γ-ray yields of Mg by proton beams ($1.5<E_p(MeV)<2.6$) for the γ-lines of significance and the calculated excitation function for the 585 keV γ-line of Mg as well as the Mg γ-ray spectrum at E_p=2.5 MeV are shown in Fig. 1.

In this work, details of the reactions potentially applicable for PIGE analysis of Na, Mg, Al and Si were outlined. Also, the thick target excitation functions of these elements for the γ-lines of

significance were calculated based on the published resonance strengths and widths. The thick target γ-ray production yields of the same elements were measured for the proton beams of 1.5 up to 2.6 MeV with an energy step of 100 keV. Such data are basically required for quantitative measurement of the elemental concentration by PIGE analysis.

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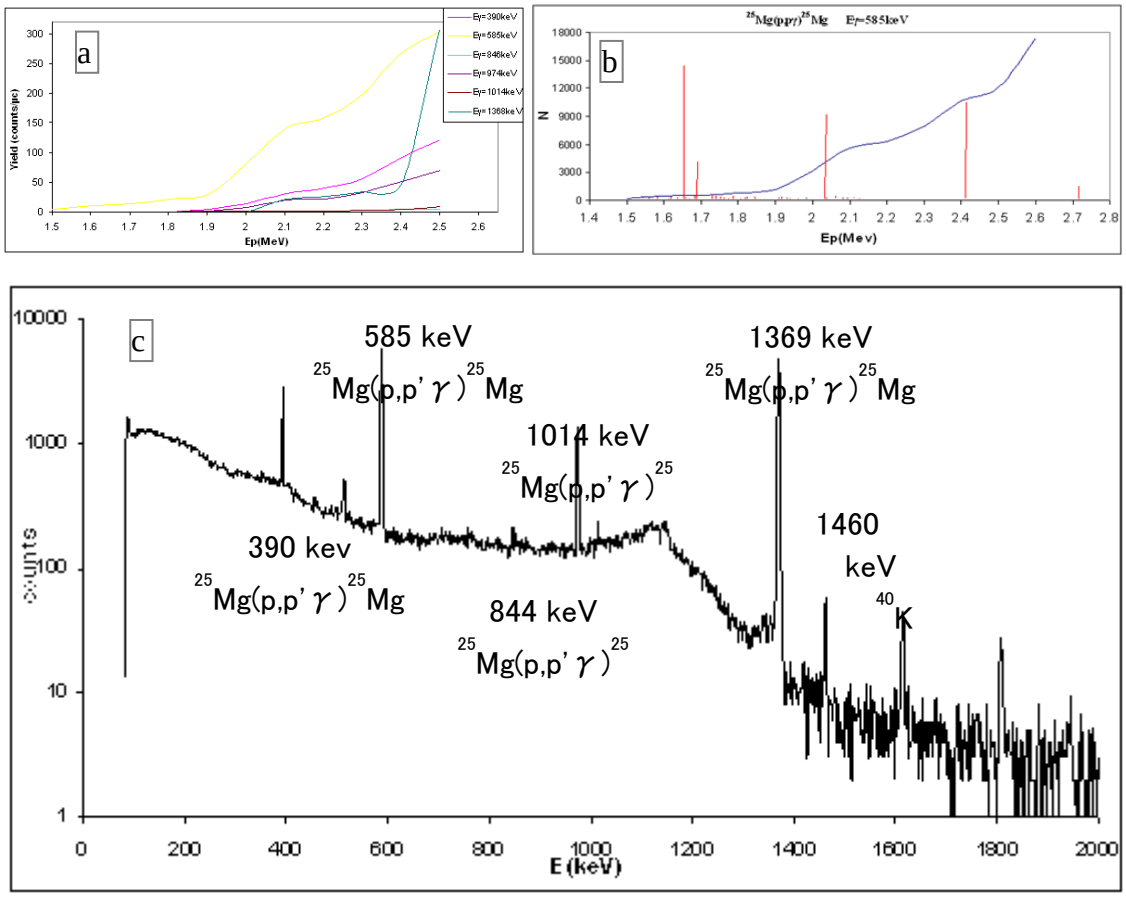

Fig.1 a) Measured thick target γ-ray yields of Mg by proton beams ($1.5<E_p(MeV)<2.6$) for the γ-lines of significance,
b) calculated excitation function for the 585 keV γ-line of Mg,
c) typical γ-ray spectrum of Mg at E_p=2.5 MeV.

2.5. PIGE studies at Helsinki University, Raisanen

1. General description of the organization and available facilities

In the presentation the organizational structure of the Helsinki University, Department of Physics is described. The Department comprises five divisions: General Division, Divisions of Materials Physics, Atmospheric Physics, Elementary Particle Physics and Geophysics and Astronomy. The Division involved in this CRP consists of the following laboratories: Microtomography, Electronic Structures, Electronics, Medical Physics, Simulations, Nanomaterials and Ion Beam Analysis.

The work at the Ion Beam Analysis laboratory can be summarized as ion beam related research and training of students. The studied processes involve ion implantation, charged-particle induced defects in materials, sputtering and ion-matter interactions (such as stopping powers, cross sections). The facilities comprise two accelerators, a 5 MV tandem accelerator with five beam lines and a 500 kV accelerator/implanter with two beam lines. The following ion beam based techniques are used for material analyses and characterization: ERD (Elastic Recoil Detection Analysis), PIXE (Particle Induced X-Ray Emission), RBS (Rutherford Backscattering Spectrometry, also combined with ion channelling), NRB (Nuclear Resonance Broadening), NRA (Nuclear Reaction Analysis), DSA (Doppler Shift Attenuation), PIGE (Particle Induced Gamma-Ray Emission) and AMS (Accelerator Mass Spectrometry). The facility for proton induced point defect production and silicon particle detector irradiation at low temperatures is described in some detail in the full presentation. The facility is equipped with a He-cryostat and a thermal resistor rendering sample temperatures between 10K and room temperature. The movable sample holder enables on-line positron annihilation spectroscopy and particle detector IV/CV –measurements at fixed temperature. The incorporated instrumentation for in-situ charge carrier lifetime testing in semiconductors is briefly described, followed by the introduction of the facilities available for cluster- and ion beam based nanostructure preparation.

2. Particle Induced Gamma-ray Emission studies

The laboratory has long-standing experience in depth profiling employing nuclear resonance reactions on the light elements. For example the following stable isotopes have been profiled: ^{1}H, ^{13}C, ^{15}N, ^{19}F, ^{22}Ne, ^{23}Na, ^{24,26}Mg, ^{27}Al, ^{30}Si, ^{31}P, ^{34}S, ^{37}Cl and ^{40}Ar. The applications mainly concerned range determinations related to ion implantation and studies of solid state diffusion. Related to bulk sample elemental analysis by PIGE, the measured thick-target γ-ray yields are compiled (Table 1). All measurements have been carried out systematically at the laboratory angle of 55 degrees.

Table 1. Measured thick-target γ-ray yields.

Studied elements [Z-values]	**Particle energy [MeV]**
Protons	
3-9, 11-14	1.0, 1.7 and 2.4
≥ 31	1.7 and 2.4
3-9, 11-21	2.4 – 4.2 (relative values)
3-9, 11-82	7 and 9 (relative neutron yields included)
^{4}*He -ions*	
3-9, 11-14	2.4
22-30	5 and 10
^{7}*Li -ions*	
≥3-82	12 and 18
^{12}*C,* ^{14}*N and* ^{16}*O -ions*	
3-30	22 and 28 ^{12}C
3-9	28 ^{14}N
3-9	28 and 33 ^{16}O

With bulk samples, very low concentrations are often of interest and therefore minimal system background achievement has been of prime importance. In choosing the construction and lining materials for the experimental set-ups, the measured thick target γ-ray yields have been taken advantage of. In the full presentation, typical examples of the use of PIGE in elemental analyses of the light elements are mentioned briefly. These range from lithium analysis via particle-gamma reactions including a sensitivity comparison with particle-particle reactions in caries research studies carried out in collaboration with dentists for Ca, P, Mg and F determination in teeth. The so-called rule of thumb for stopping power correction has been tested aiming at sample concentration determinations by using pure element thick target γ-ray yields.

As a more detailed example, the development of a rapid and sensitive procedure for carbon, nitrogen and oxygen detection using (p,p´γ) reactions (all experiments using an external beam) can be mentioned here. These are the major structural elements of biomedical and organic samples. The applications also include oxygen determination from high-T_C superconductors. The method is the most sensitive and practical for the simultaneous analysis of C, N and O with about 7.5 MeV protons. A typical γ-ray spectrum obtained from a bone sample is provided in Fig. 1 where the strong γ-ray peaks for carbon, nitrogen and oxygen can be noted. It has been shown that absolute concentration values for carbon, nitrogen and oxygen can be achieved using organic compounds as standards (when proper standards are not available), utilizing the known compound stoichiometry. In the appendix of this presentation appropriate references are provided.

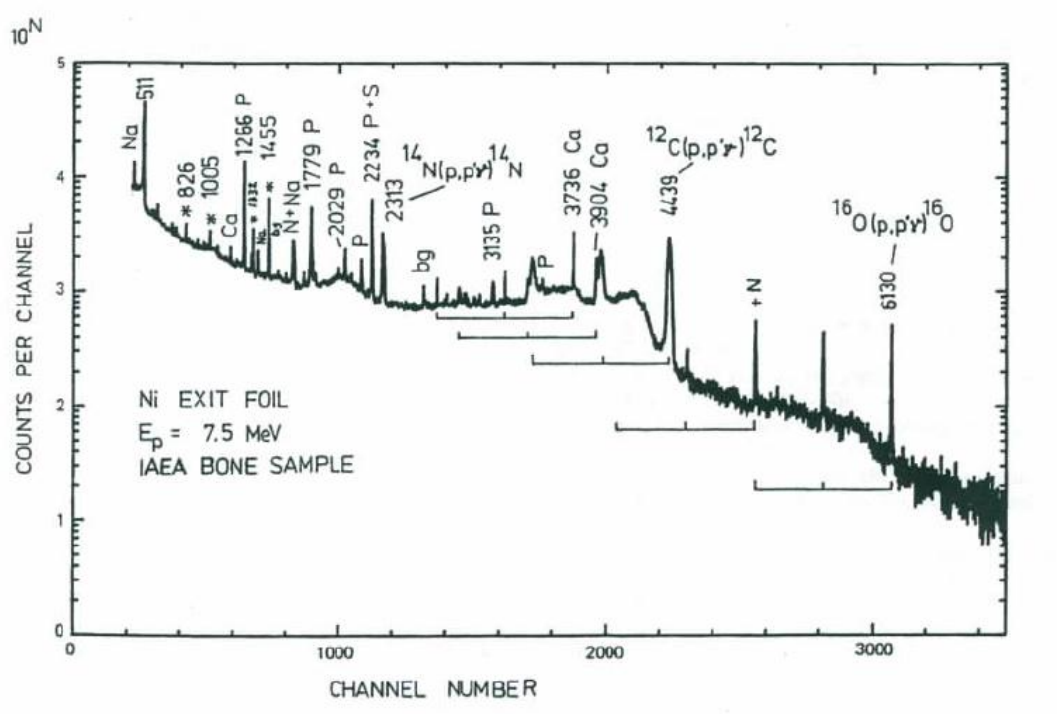

Fig. 1. A spectrum from a bone sample obtained by 7.5 MeV proton bombardment. The measurement time has been 30 minutes and the γ-ray peaks due to the nickel exit foil are marked by the asterisks.

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2.6. Working with PIGE at the INFN/LABEC Laboratory in Florence: cross-section measurements and analytical applications, Chiari

First, the presentation provided a general overview of the LABEC laboratory at INFN in Florence and of the routine PIGE measurements for non-destructive analysis of low-Z elements (Na, Mg, Al, Si,…), performed in the field of cultural heritage and atmospheric aerosol studies.
The LABEC facility consists of a 3 MV HVEE Tandetron, three independent ion sources and seven beam lines, one for Accelerator Mass Spectrometry and six for Ion Beam Analysis. On three of the IBA beam lines, dedicated external beam facilities are installed.
In the PIGE analysis of cultural heritage objects (i.e. infinitely thick targets), the unknown concentrations are typically deduced by comparing the γ-ray yields with those of thick standards of similar composition. Differences in stopping powers of the unknown sample and of the standard are thus critical. Discussed are examples concerning the crucial use of PIGE as a complementary technique to PIXE in the analysis of Na or Al in such samples where crusts and

patinas or varnish layers [1] strongly absorb the low energy X-rays.
As concerns the study of atmospheric aerosols, PIGE measurements can be used to correct the underestimation of PIXE in quantifying the concentration of the lighter elements, like Na, Mg, Al and Si, due to X-ray self-absorption inside aerosol particles (dimensions up to few micrometers). Unknown concentrations are deduced by comparing the γ-ray yields of the irradiated aerosol sample with those of a thin elemental standard. Choosing the proper beam energy is indeed crucial, since the PIGE cross sections have to be constant over the beam energy loss in the sample [2].
Examples considering the use of PIGE to analyse Al in mineral dust aerosols collected in-flight over the Sahel desert (for climate change study) [3] and in mineral dust particles archived in Antarctic ice cores (for paleoclimate research studies) [4, 5] are described.
The presentation continued showing the results of cross-section measurements of proton induced γ-ray emission reactions on ^{7}Li, ^{19}F and ^{23}Na for beam energies in the 2.2 - 5.5 MeV range [6, 7], carried out in recent years in collaboration with the Centre for Micro Analysis of Materials (CMAM), a research centre of the Universidad Autónoma de Madrid (UAM) in Spain. The list of the studied nuclear reactions and γ-ray energies is the following:

^{7}Li(p,n´γ)^{7}Be	429 keV
^{7}Li(p,p´γ)^{7}Li	478 keV
^{19}F(p,p´γ)^{19}F	110, 197, 1236, 1349, 1357 keV
^{19}F(p,α´γ)^{16}O	6.13, 6.92, 7.12 MeV
^{23}Na(p,p´γ)^{23}Na	440, 1636 keV
^{23}Na(p,α´γ)^{20}Ne	1634 keV

Then, the foreseen activity of LABEC in the present CRP is described and discussed. The objective of the proposed research is mainly experimental, focusing on a systematic investigation of the proton induced γ-ray emission differential cross sections on low-Z nuclei such as B, Na, Al and Si of specific interest for environmental and cultural heritage applications, for proton beam energy from 2.5 to 5 MeV, including - when possible – the measurement of the angular distributions of the emitted γ-rays. To accomplish such a project, the experimental apparatus that will be used is the multi-purpose scattering chamber installed at LABEC on the +30° beam line. The scattering chamber is equipped with a HPGe detector for PIGE (~25% relative efficiency at 1.33 MeV, placed in fixed position, at 45°), several charged particle detectors for EBS/ERDA (165°, 150°, 120° and 45° scattering angles) that can be used to measure the elastic (and inelastic) scattering of the beam particles at backward angles for cross-section normalization, and two X-ray detectors, SDD and Si(Li), for PIXE. The scattering chamber is also equipped with a remote controlled multi-sample target holder. For the measurement of the γ-ray angular distributions, an array of up to 5 HPGe detectors (~25% relative efficiency at 1.33 MeV), at adjustable angular positions from the beam axis and distances from the target, will be mounted outside the scattering chamber. To collect and analyze the data a portable acquisition system, based on the VME bus and an Apple Macintosh front–end, will be used; the system permits to acquire data from up to 8 detectors (energy and time information) in multiplex or multiparametric mode and can be easily extended to support more detectors.

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2.7. Past and planned PIGE applications at the Ruđer Bošković Institute in Zagreb, Bogdanović Radović

At the beginning, the accelerator facility at the Institut Ruđer Bošković was presented. The facility consists of two electrostatic accelerators, 1 MV Tandetron and 6 MV EN Tandem Van de Graaff accelerator and eight beam lines dedicated to different Ion Beam Analysis and nuclear physics experiments as can be seen from the layout shown in Fig. 1.

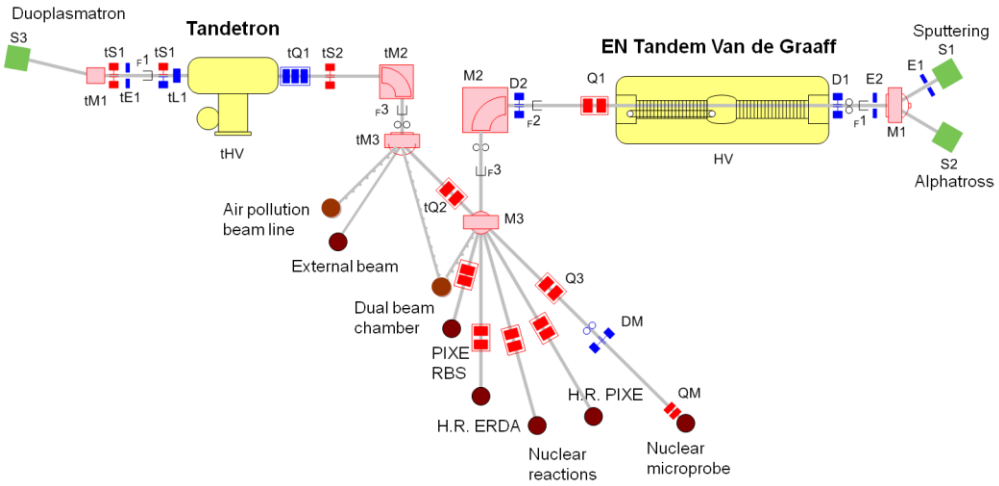

Fig. 1: Layout of the accelarator facility at the Institut Ruđer Bošković

Past PIGE and NRA applications

In the past PIGE was mostly used together with X-ray spectrometries PIXE and XRF for characterisation of coal and coal ash samples [1, 2].
Thick Thick target yields were measured for selected elements:

$^{19}F(p,p'\gamma)^{19}F$	E_γ = 197 keV	E_p = 2.3 – 3.3 MeV
$^{23}Na(p,p'\gamma)^{23}Na$	E_γ = 440 keV	E_p = 2.3 – 3.5 MeV
$^{23}Na(p,\alpha\gamma)^{23}Na$	E_γ = 1634 keV	E_p = 2.3 – 3.5 MeV
$^{28}Si(p,p'\gamma)^{28}Si$	E_γ = 1779 keV	E_p = 2.8 – 5.0 MeV.

External and in-vacuum microbeam, PIGE was used for determination of lateral distributions of Li and F in gel polymer samples to study distribution of Li ions inside the gel polymer as well as homogeneity of F which is one of the constituents in the gel polymer. Together with PIGE, the PIXE method was used for in-vacuum studies of gel polymer interfaces with Li-anode and spinel ($LiMn_2O_4$)-cathode to study correlation between Li, Mn and F in the interface region [3, 4].
In-vacuum microbeam NRA was used together with PIXE to study boron content and distribution in multilayer films designed for optical applications. For that purpose, 0.9 MeV protons were focused to micrometer dimensions and $^{11}B(p,\alpha)^{8}Be$ reaction was applied.
For determination of O in WO_x films, (d,p) reaction was used. Correlation between pressure and oxygen content was established.

Planned PIGE activities

In the future it is planned to use PIGE technique together with other IBA techniques (RBS, PIXE and PESA) at the new beam line that will be used for air pollution monitoring (IAEA TC project CRO8008). PIGE will be applied for determination of light elements Li, F, B, Mg, Na and Al. As the new beam line is attached on the 1 MV Tandetron accelerator, it is important to measure PIGE differential cross sections for those light elements and proton energies around 2 MeV in order to determine what is the applicability of using the PIGE method with proton energies around 2 MeV.

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2.8. PIGE Activities at the Demokritos Accelerator, Lagoyannis

The Institute of Nuclear Physics at the NCSR "Demokritos" hosts a 5.5 MV Tandem Van der Graaff accelerator built in 1973. The accelerator is equipped with two ion sources for the production of negative ions: a duoplasmatron for proton and deuteron production and a cesium sputter source for heavier ions such as lithium, carbon, oxygen etc. The accelerator activities are concentrated in the following research fields: Basic research studies which include nuclear astrophysics, neutron physics and light ion reactions, as well as applied research such as the characterization of materials for interdisciplinary purposes such as microelectronics, archaeometry, etc. Among the five experimental beam lines that are currently in use, there are two that are entirely devoted to ion beam analysis techniques: a reaction chamber suitable for RBS, NRA, PIGE and channeling studies and an external beam equipped with two Si(Li) detectors for PIXE, one high purity germanium detector for PIGE and a surface barrier one for RBS and NRA studies. Recently, one of the existing beam lines was upgraded with the addition of a goniometric table capable of hosting up to four high purity germanium detectors. This setup, as it will be described later on, is suitable for gamma ray emission cross section measurements.
According to our experience with PIGE studies, there are some key features that need to be taken into account when conducting cross section measurements such as:

- The preparation and characterization of suitable targets
- The beam's charge measurement
- The detection apparatus
- The analyzing software

In order to produce reliable cross sections for PIGE analysis, the issue of proper target preparation must be addressed. A suitable target should be thin enough, to enable the scanning of thin resonances which are commonly found in light element reactions with protons. It should also be thermally and chemically stable so as to avoid disintegration during the irradiation procedure. An enhanced feature of the ideal target would be its possibility to act as a reference for the beam current. Such a target, which was successfully used in previous cross section measurements, could be a threefold "sandwich" – like a target consisting of a thin carbon foil as substrate, the actual target as a second layer and a very thin gold layer on top. The layer of gold in front of the target ensures the thermal, mechanical and chemical stability of the target and acts

as a reference for the accumulated charge through a simultaneous RBS measurement. The Tandem Laboratory is equipped with an evaporator which has both a thermal source and an electron gun for target production. As most of the targets that are used in PIGE measurements are homemade, their accurate characterization is an absolute requirement. This is mainly achieved in our laboratory with the use of XRF and other analytical techniques, such as PIXE, RBS and charged particle NRA.

One of the most interesting and often cumbersome challenges involved in all ion beam analysis techniques is the measurement of the beam current. This fact is especially true when electrically insulating samples need to be analyzed. The commonly used technique in order to solve this problem is the use of sophisticated Faraday cups with the aid of suppression voltages and bending magnets. Some efforts have been made in the past in order to determine the accumulated charge with sample–independent techniques. One of these focuses on the use of beam choppers at the entrance of the reaction chamber. In our case, for the measurement of the beam charge, we use a microcontroller–based ion beam chopper with enhanced reproducibility and minimal electronics. In addition to that, our experimental setup is equipped with a surface barrier detector mounted at 150^{o} with respect to the target. It detects the backscattered beam particles from the target's gold coating, thus enabling a second, independent of the first, measurement of the current.

The last and most important aspect, in our opinion, that has to be taken into account is a powerful detector setup. A motorized goniometric table has recently been installed at the Tandem laboratory of I.N.P. On it there are 4 high purity germanium detectors having, on average, a relative efficiency of 100%. The detectors are initially placed at 0^{o}, 55^{o}, 90^{o} and 165^{o} with respect to the beam. The electronically controlled goniometric table can move the detectors with high angular accuracy, thus facilitating the measurement of angular distributions. All the detector electronics are of the NIM standard, while the upgrade of an event-by-event acquisition system (CAMAC based) is under progress.

The experimental procedure to be followed during the measurements can be summarized as follows:

- Preparation/characterization of the targets
- Energy and efficiency calibration of the germanium detectors using point sources
- Q x Ω calculation for the Si detector using RBS spectra from gold
- Determination of Q using the chopper and the RBS technique
- Machine calibration using either $^{27}Al(p,\gamma)$ or threshold reactions
- Peak analysis using two different algorithms to account for the bias error
- Data validation using thick targets and appropriate software

The proposed measurements aim at providing reliable cross section data for some of the light elements commonly detected with the PIGE technique, namely ^{32}S, $^{10,11}B$ and ^{13}C which will eventually allow the determination of the concentration profiles of the specific isotopes without the need for standards.

The ^{32}S isotope (95% in natural sulphur) is related to a number of important processes and reactions on materials: Corrosion, passivation, deterioration of metallic, ceramic and stone surfaces. The $^{32}S(p,p'\gamma)^{32}S$ nuclear reaction can be used as an alternative to the $^{32}S(d,p)^{33}S$ reaction, previously studied by our group. This nuclear reaction has, at projectile energies of 3.379 and 3.716 MeV, two distinct and narrow resonances, offering the possibility of determination of the depth distribution of sulphur in near-surface layers of metallic materials of

several micrometers of thickness, by measuring the intensity of the emitted 2.230 MeV γ-ray. The broad resonances at 4.77 and 5.10 MeV observed in the past have also been used for the analysis of sulphur on atmospheric aerosol samples collected on filters. Thus, the aim of this work is to determine the excitation function of the $^{32}S(p,p'\gamma)^{32}S$ nuclear reaction in the projectile energy region between 3.0 and 7.0 MeV.

In addition, boron is a highly regarded technological element and has numerous applications in various fields. It is widely used in the semiconductor industry as a dopant for Si and Ge substrates, and it is also an essential ingredient of hard coatings on the walls of thermonuclear plants. Thus, the accurate quantitative determination of boron depth profiles in heavy and light matrices or substrates is of great importance. The ^{10}B isotope (19.9% of natural boron) has been studied in the past through the $^{10}B(p,\alpha\gamma)^{7}Be$ and the $^{10}B(p,p'\gamma)^{10}B$ reactions that emit a 429 keV and a 718 keV γ–ray, respectively. Data exist in the literature but they are rather discrepant, with differences up to 30%. Moreover, current IBA applications require the availability of differential cross section data up to $E_{p,lab}$~5 MeV. As far as the predominant ^{11}B isotope (80.1% in natural boron) is concerned, to the authors' best knowledge, there is only one recent reference work for the $^{11}B(p,p'\gamma)^{11}B$ reaction up to $E_{p,lab}$ = 3.8 MeV [1]. It is evident from the above that the boron case requires further investigation. The experimental differential cross sections which will be obtained from the present work will be tested against a thick polished natural boron compound target, with the use of an appropriate computer code.

Finally, stable isotope ratios such as $^{13}C/^{12}C$ play an important role in many areas including environmental sciences due to differential uptake and energy applications. The extremely low natural abundance of ^{13}C (1.1% in natural carbon) makes its high resolution depth profiling detection extremely challenging for all other IBA techniques. Proton induced gamma emission (PIGE) studies, however, can implement the strong and narrow resonance for the detection of ^{13}C at E_p = 1748 keV (Γ = 0.075 keV). Because of the angular dependence of the emitted γ-rays, selected partial differential cross-section data will be measured (e.g. 55^o, 125^o, 90^o) for the beam energy range between 1000 – 5000 keV.

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2.9. The Center for Microanalysis of Materials, Muñoz-Martin

The presentation gave a general overview of the Center for Micro Analysis of Materials, introducing its capabilities with regard to its participation in the CRP.

The Centre for Micro Analysis of Materials (CMAM) is a research centre of the Universidad Autónoma de Madrid (UAM). The building that hosts the laboratories is located in at the Cantoblanco Campus in Madrid, 15 km away from the city center.

At the Campus of Cantoblanco there are not only research institutes and faculties from the University, but also a large number of research institutes from the Spanish National Research Council (CSIC). In 2009, UAM and CSIC together were ranked among the International Campus of Excellence (CEI) in Spain, the main research areas of CEI being: Nanoscience and Advanced Materials, Biology and Biomedicine and Theoretical Physics and Mathematics. This environment is determining the activity of CMAM, which is now considered a research facility of the Campus. The activity of CMAM is based on the following main points: Advanced Materials, Energy, Health, Cultural Heritage and Cooperation.

To fulfill its activities, the Center relies on a staff formed by 10 scientists and 3 PhD students, with the support of 8 technicians for the maintenance and development of the infrastructure, and 2 administrative assistants.

The experimental equipment of the Center consists of a 5MV ion accelerator, its beam lines,

dedicated to various application areas and several ancillary equipments (micro-analytical techniques, sample preparation laboratory, etc).

The accelerator, built by HVEE, is of the tandem type, with a Cockcroft-Walton system for generating the high voltage. It is provided with two ion sources: a plasma source for gaseous substances and a sputtering source for obtaining practically any element of the periodic table from a solid target. Presently, beamtime is roughly divided into one third for protons, one third for alpha particles, and the remaining to heavier ions, the latter part being constantly increasing.

At CMAM, there are seven beamlines, three under development, namely an implantation beamline, an internal microbeam and an UHV setup for surface science, and four fully operative:

- Standard beamline. It is a multipurpose beamline, equipped with two particle detectors, one at a fixed position and another one movable. The last one has also the possibility of inserting, in front of it, thin foils or defining slits. A high sensitivity optical camera and a far infrared (thermal) one complete the setup. This beamline is mainly used for classical IBA techniques (RBS, RBS/c, ERDA, NRA) and irradiation of small area samples. When a HPGe detector is installed, PIGE experiments can be carried out. The Standard Beamline has already been used for measuring differential cross sections of gamma production in Na, F and Li with protons, and for profiling Na in ancient roman glasses using PIGE.
- External microbeam. Mainly used for IBA in art objects and archaeology, the beamline provides an external beam focused to a spot size in the order of 50μm. Two Si(Li) detectors for X-rays, one implanted Si detector for charged particles, and the possibility of installing two (HPGe and $BrLa_3$) gamma detectors , make up the detection setup of the beamline. A remotely controlled positioning table and a local He atmosphere complete the beamline. At the external microbeam, PIGE has been used, for example, for the detection of beryllium treatment of natural sapphires, using the $^{9}Be(\alpha,n\gamma)^{12}C$.
- Nuclear Physics Beamline. The Nuclear Physics beamline at the CMAM is in operation as a result of the collaboration with the Institute for the Structure of Matter (IEM), CSIC. The beamline is at the -30º port of the first switching magnet of the accelerator and is equipped with two sets of slits for defining beam size and shape. It is compatible with high vacuum conditions and it is specifically designed for easily connecting a large variety of experimental set-ups at its end. It makes the beamline a really versatile one, being possible to carry out nuclear reaction experiments, characterization of new detector systems, etc, taking advantage of the high stability and accuracy of CMAM ion accelerator.
- Time of Flight (ToF) beamline. It has a scattering chamber with a Time of Flight telescope, placed at 40º from the beam. When bombarding with heavy ions, recoiled particles are collected in the telescope, measuring in coincidence both energy and time of flight for each one. In this way it is possible to distinguish the mass of the detected particle.

  At the end of ToF beamline, a new high vacuum chamber has been installed. It is electrically isolated, so as to use it as a Faraday Cup. Inside, a sample positioning system allows for easy sample exchange. Two gamma ray detectors (HPGe and $LaBr_3$) are placed at +/-135 degrees from the beam. The acquisition electronics allows recording of data in list mode, registering as well the monitored current during the irradiation. This setup is still under development, and it is intended to be used for the gamma measurements of the CRP.

The participation of CMAM in the CRP can be summarized with the following key points:

- Taking advantage of the 5MV tandem accelerator, exploring cross sections at higher energies,
- Focusing in Li, Be and F reactions, for their application in studying fusion reactors materials, gemstones, environmental sciences, etc.,
- The use of proton and alpha beams.

2.10. PIGE activities at the University of Liège/Belgium, Strivay

The "Institut de Physique Nucléaire, Atomique et de Spectroscopie" (IPNAS) is specialized in ion beam analysis and their applications to various fields (biology, thin films, polymers, archaeometry, etc. The IPNAS has three accelerators, two van de Graaff (2 and 2.5 MV) and one cyclotron that can produce proton, deuteron and helium beams from 3 to 20 MeV.
Two beam lines of the 2.5 MV are dedicated to ion beam analysis in vacuum, one for routine RBS analysis, one for multi-analysis (RBS, PIXE, PIGE).

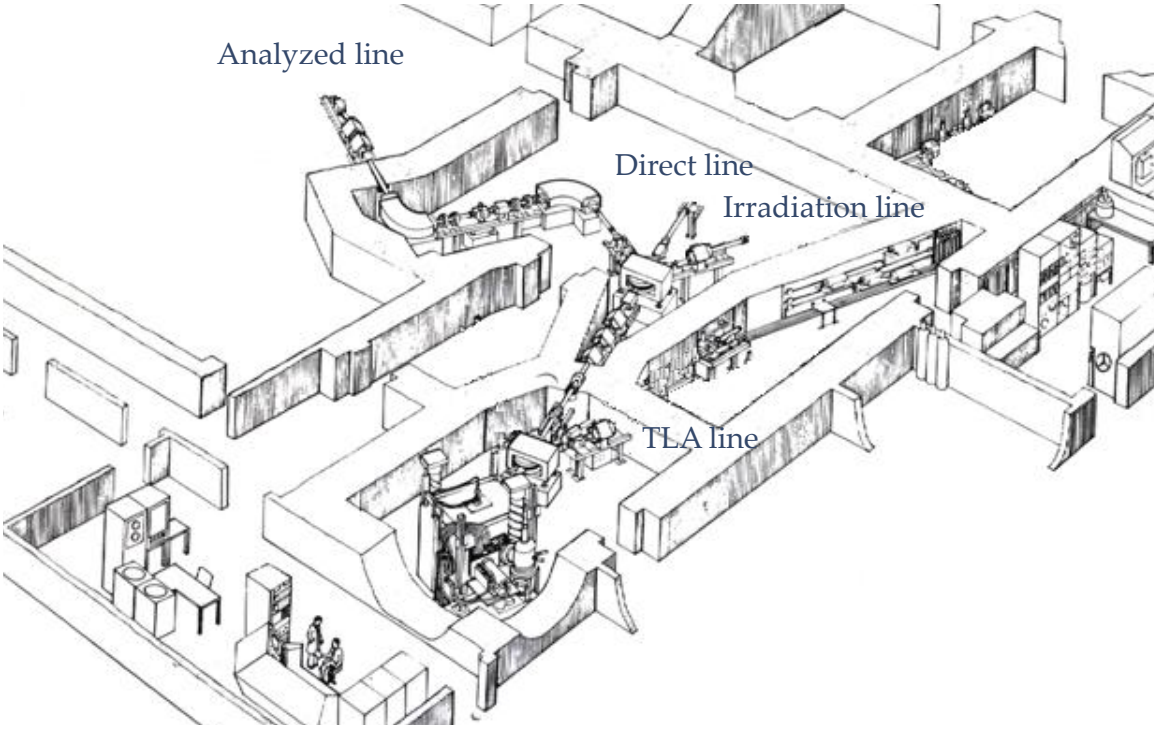

Fig. 1. Cyclotron beam lines

Three extracted beam lines are installed on the cyclotron and are used for:

- thin layer analysis technique for mechanical parts;
- atmospheric ion beam analysis (PIXE-PIGE-IBIL) with broad energy dispersion (50keV at 3MeV);
- atmospheric ion beam analysis (PIXE-PIGE-IBIL-RBS) with good energy resolution (2 keV at 3 MeV).

Two vacuum chambers are installed on the cyclotron beam lines for:

- cross-section measurements of charge particle retrodiffusion and of X-ray production by charged particles;
- charged-particle irradiation of electronic systems.

The main applications of IBA in cultural heritage research have been highlighted and, more precisely, the differential PIXE-PIGE system.
The main PIGE activities in Liège have been described, namely the use of Na and Be detection in connection with cultural heritage objects.
The new energy calibration system that will be installed on the cyclotron has been described. It consists of a time-of-flight (TOF) system that will give the beam energy with sufficient precision.
We are planning to use the new vacuum chamber on the cyclotron to measure particle induced γ-ray production cross sections.

2.11. Measurement of excitation yields of low energy prompt γ-ray from proton bombardment of ^{48}Ti foil, Goncharov (presented by Gurbich)

The PIGE technique can be used for determination of Ti in the strengthened by fine dispersed TiO_2 ferritic steels which are developing for fast reactors. PIGE measurements can be simultaneously performed with PIXE measurements using a HPGe detector. In comparison with the PIXE technique, the PIGE one is characterized by larger depth of analysis in steels. That is only one of reasons why the experimental cross-section values of $^{48}Ti(p,\gamma)^{49}V$, $^{48}Ti(p,\gamma)^{49}V+^{49}Ti(p,n\gamma)^{49}V$ reactions are necessary for PIGE database.

In the present work, differential cross sections for the production of 62.3 and 90.6 keV γ-rays from the reactions $^{48}Ti(p,\gamma)^{49}V$ for proton energies ranging between 1.0 and 1.6 MeV at the laboratory angle of 90^0 have been measured.

The measurements were carried out by means of NSC KIPT Van de Graaff accelerator using the Ti target with 97.8 % enrichment of the ^{48}Ti isotope on Ta backing. The correct value of the Ti target thickness was determined from RBS spectrometry data. In our case it was equal to 3.7×10^{18} at/cm^2 ±5%.

A typical spectrum of low-energy γ-ray from the ^{48}Ti target is presented in Fig. 1.

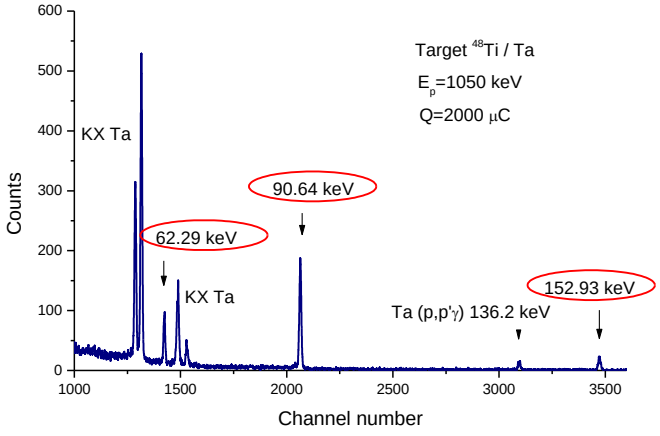

Fig. 1. Typical spectrum of low-energy γ-rays from the ^{48}Ti.

The averaging differential cross section $d\sigma_\gamma/d\Omega$ of γ-ray production from the ^{48}Ti(p,γ)^{49}V reaction was determined from the general expression:

$$N_\gamma = kN_p(d\sigma/d\Omega)\Omega_e ft/\cos\varphi$$

N_γ 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.
$\Omega_e=\Omega_e(E\gamma)$ is the effective solid angle of the detector.
f is the relative content of ^{48}Ti in Ti target substance.
t is the Ti target thickness (at/cm^2).
φ is the beam incidence angle taken from the normal to the target.

The preliminary results of the measured differential cross sections for the production of 62.3 and 90.6 keV γ-rays from the reactions ^{48}Ti(p,γ)^{49}V, $\theta_{lab}=90^0$ are presented on Fig. 2.

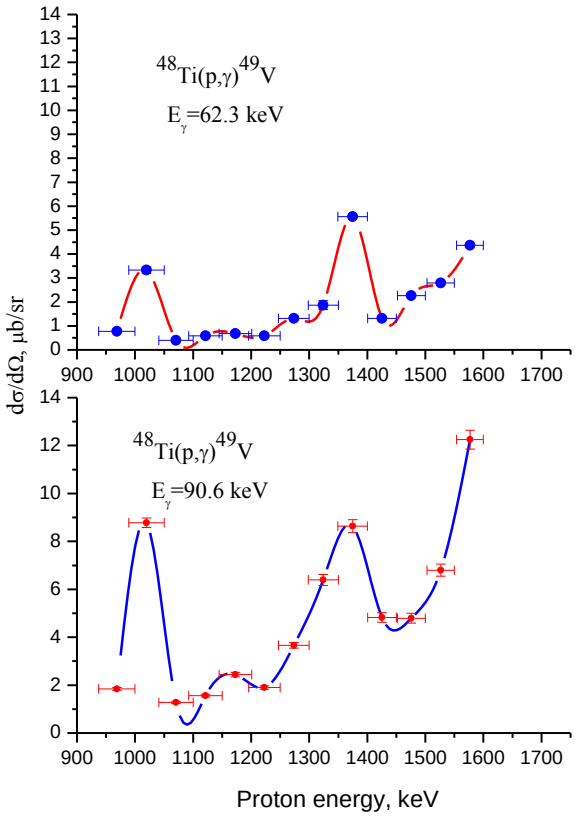

Fig 2. Preliminary results of the differential cross sections for the production of 62.3 and 90.6 keV γ-rays from the reactions ^{48}Ti(p,γ)^{49}V, $\theta_{lab} = 90^0$.

2.12. PIGE activity at IPPE, Gurbich

PIGE was employed for the analysis of carbon, sodium, aluminium, and chromium resonances. The excitation functions for the corresponding reactions were measured in the vicinity of resonances favourable for analytical applications. The oxygen analysis using gammas from direct non-resonant radiative capture was undertaken. PIGE was used for the analysis of various samples including semiconductor structures and nuclear reactor materials.

Hydrogen analysis using resonance $^{1}H(^{19}F,\alpha\gamma)^{16}O$ reaction was used to study hydrogen penetration into coating layers on the surface of zirconium pipes. Propagation of the spectrometer efficiency calibration on the high energy region was made using cascade gamma quanta from the resonance $^{27}Al(p,\gamma)^{28}Si$ reaction with known gamma ray branching. Tickonov's regularization method was applied to resolve the ill-posed problem of the determination of concentration on depth distribution.

Pulsed incident beam was used to substantially enhance the sensitivity of the PIGE analysis due to suppression of the background gamma-radiation. The advantages of the method were demonstrated in the case of detection of trace amounts of sodium in oxidized silicon samples.

3. Methodology

The participants agreed that new measurements are fundamental for the successful development of this CRP. Accordingly, each participant will take on a certain number of reactions to be measured. In doing so, he or she will research the excisting scientific literature and assess the previous data identifying possible discrepant data. In order to achieve a consistent set of measurements a certain methodology was agreed which will be discussed in this section. In order to compare the results and identify possible sources of discrepancies and systematic errors among the different institutions, round robin measurements will be important. In addition, the importance of thick target bechmark experiments was recognized. The participants also agreed that, in the long run, once the database is assembled a practical and user-friendly code would be needed for the final user in order to implement the standardless PIGE method.

3.1. Basic code for PIGE

The aim of standardless PIGE, could be achieved if, besides the differential cross sections compiled in the reference database subject of the present CRP, the community is provided with a reliable computer code for use of the database and calculation of the quantities needed by the user. In particular, the code should calculate the material composition in the case of bulk analysis and the layer composition in the case of depth analysis. To date no such code is freely available to the community. In order to establish the first steps towards the production of such a code, the ERYA code which was developed in CFNUL, Universidade de Lisboa, will be provided to the PIGE community to enable members to use the reference database for PIGE in an effective and user-friendly way for analytical applications. The code will be used to simulate experimental results. Even though up to now only bulk analysis is implemented, new developments will include depth analysis capabilities. Simultaneously, a comprehensive manual should be prepared in order to make the code useful to the community.

3.2. PIGE data in IBANDL database

The database for the PIGE data will be IBANDL, the R33 format being modified to include additional information specific to PIGE. The data to be included will be differential cross sections and thick target yields. IBANDL will be modified to be able to deal with both kinds of data. It is recommended that, if a cross section is known to be isotropic, the cross section would be presented as a total cross section. The IBANDL interface should be able to re-scale those data to plot them together with anisotropic data at different angles. A lighter version of ERYA (written in Fortran) could be called by IBANDL to perform calculations of target yields using the differential cross section data. Concerning γ-ray spectra, it was decided to include the corresponding graphs only in the CRP final report and not in the IBANDL database.

3.3. Energy calibration of accelerators

Several methods were discussed, mainly: thick or thin target resonances of well-known nuclear reactions and elastic and inelastic proton scattering.

In relation to resonances for proton energies below 2 MeV, several are well known, as the 991.9 ± 0.1 keV, 1664.4 ± 0.2 keV and 1683.6 ± 0.1 keV resonances of $^{27}Al(p,\gamma)^{28}Si$ and the Mg(p,p) 1483 keV± 2 keV, which participants recognized to be particularly useful. For energies around and above 2 MeV, the 1931 keV resonance of $^{23}Na(p,p'\gamma)^{23}Na$ and the 2413, 2914 and 3660 keV resonances of $^{24}Mg(p,p'\gamma)^{24}Mg$ were suggested. Also, participants were urged to use other points also cited in Marion, Rev. Mod. Phys. 38, 1966, p. 660.

At higher accelerator energies, where thin well defined resonances are scarce, a measurement of elastic and inelastic proton scattering may be used in order to obtain a calibration constant with a moderate accuracy. When a thin (compared with the beam energy spread) target containing an isotope with well separated low energy excited states (for example ^{56}Fe, 91% of natural abundance) is bombarded with protons at two different accelerator energies the information contained in the measured spectra is sufficient in order to find both a spectrometer channel width and the energy calibration constant (see also D.M. Scott, B.M. Paine "Accelerator energy calibration using non-resonant nuclear reactions" in NIM 218 (1983) 154).

Participants recognized the importance of a proper accelerator energy calibration for the accuracy of cross-section measurements and (as may be seen below) some concerted measurements were proposed.

3.4. Target preparation

Target preparation was also found to be a difficult problem. For the aluminium target that will be used for the round robin inter comparison, it was suggested to use aluminium oxide targets obtained by oxidation of aluminium foil followed by acid etching leaving some nm film of aluminium oxide, with a gold film for normalization. An alternative could be Al evaporated on thin self supporting Ag. The targets should be deposited on a high atomic number self-supporting film for normalization purposes of thickness around 40-50 $\mu g/cm^2$. For detailed measurements, thin targets of about 10-20 $\mu g/cm^2$ were suggested. The following targets were accepted for the measurements:

- $LiWO_3$, which is stable and suitable for thin or thick targets (evaporated on Ag film);
- B evaporated on Ag films;
- B_4C;
- Be evaporated on Cu or Ag (silver is better for normalization purposes);
- for P targets the possibility of using some kind of phosphate will be investigated;
- thin silicon nitride targets are available and should be used;

- for Na, NaCl was suggested again deposited on a Ag film;
- Mg evaporated on Ta is fine for thick targets;
- TiS evaporated on C and covered with Ta.

A list of instructions for target preparation will be delivered to the participants. Every effort will be made to share targets among participants.

3.5. Absolute cross-sections measurements

The cross section may be derived from the following expression

$$\sigma_\gamma(E_0,\theta) = \frac{Y_\gamma(E_0,\theta)}{N_p N_T \varepsilon_{abs}(E_\gamma)} \qquad (1)$$

where $Y_\gamma(E_0,\theta)$ is the measured γ-ray yield (i.e. the area of the γ-ray peak) at projectile energy E_0 and γ-ray detection angle θ, N_p is the number of incident projectiles, N_T is the number of target nuclei per square centimetre and $\varepsilon_{abs}(E_\gamma)$ is the absolute efficiency of the γ-ray detector correspondent to the E_γ energy γ-ray line.

For absolute cross-section measurements, several key factors have to be taken into account such as detector efficiency measurement, cross-section normalization and the different sources of uncertainty.

3.5.1. Detector efficiency determination

The accurate absolute detector efficiency determination is very important, because it is directly reflected in the quality of the extracted cross-section data.
It was agreed to use calibration sources (^{152}Eu, ^{133}Ba, ^{56}Co) at the exact position of the target and, if possible, Monte Carlo simulation to determine the absolute photopeak efficiency of the γ-ray detectors for energies below 3.5 MeV. In order to interpolate and extrapolate from the experimental calibration points, the following fit to the data will be used (beyond the maximum of the efficiency curve):

$$\varepsilon(\gamma) = a + \frac{b}{E} + \frac{c}{E^2} + \frac{d}{E^3}. \qquad (2)$$

Simulation and the cascade method (using a resonant capture reaction such as ^{27}Al(p,γ)^{28}Si at Ep=767keV) will be employed to determine efficiencies at energies higher than those provided by the sources (see e.g. Elekes *et al.* NIM A 503 (2003) 580.)

3.5.2. Cross-section normalization

In addition to the gamma rays, it is recommended to measure the elastic (and inelastic) scattering of the beam particles at backward angles. The use of a high-Z element such as Au or Ag, as part of the target, to use for normalization to Rutherford scattering is advised. Then, in relation to the expression given above for the cross section, the product $N_p N_T$ may be derived from

$$N_p N_T = \frac{Y_S(E_0,\beta) r}{d\sigma_{Ruth}(E_0,\beta)/d\Omega \times \Omega\varepsilon} \qquad (3)$$

where $Y_S(E_0,\beta)$ is the measured scattered projectile yield for the high-Z element on the target (i.e. the area of the scattered projectile peak) measured at projectile energy E_0 and particle detection angle β, $d\sigma_{Ruth}(E_0,\beta)/d\Omega$ is the Rutherford cross section for the high-Z element at

projectile energy E_0 and particle detection angle β, ε is the intrinsic efficiency of the particle detector (usually ~100%), Ω is the solid angle of particle detection (assumed to be small) and *r* is the stoichiometric ratio from the analysed light element to the heavy-Z element. In case of a large solid angle the product $d\sigma_{Ruth}(E_0, \beta) / d\Omega \times \Omega$ should be replaced by

$$\int_{\Omega} d\sigma_{Ruth}(E_0, \beta) / d\Omega \qquad (4)$$

3.5.3. Assignment of uncertainties

The participants agreed that it is important to maintain an accurate uncertainty budget. The systematic and statistic uncertainties have to be recognized and provided in a tabular form. In the cross-section graphs only the statistical uncertainties should be plotted as uncertainty bars.

3.6. Thick target measurements

The measurement of the γ-ray yields from thick targets is useful both for extracting resonance parameters and for bulk analysis relative to standards. Even though the main purpose of the CRP is to produce a reference database that makes the use of standards unnecessary, the need of an intermediate time interval where both thick target yields and cross-section data are made available for current analytical applications is recognized until the CRP aim of standardless PIGE is reached. However, once the PIGE code is fully developed, the thick target yields will be easily calculated from the differential cross sections according to

$$Y_{\gamma}(E_0, \theta) = \varepsilon_{abs}(E_{\gamma}) \cdot N_p \cdot f_m \cdot f_i \cdot N_{Av} \cdot A^{-1} \cdot \int_0^{E_0} \sigma(E_0, \theta) / S(E)\, dE, \qquad (5)$$

where f_m is the mass fraction of the analysed element, f_i is the abundance of the isotope producing the γ-radiation, N_{Av} is the Avogrado number, A is the atomic mass of the element and *S(E)* is the stopping power of the projectile in the target in energy per areal mass units and the other quantities which have been defined above. Note that

$$f_m \cdot f_i \cdot N_{Av} \cdot A^{-1} = N_T . \qquad (6)$$

From resonant thick target yields, the following formula can be used to extract the resonance parameters.

$$Y = \frac{N_T}{2} \frac{\sigma_R \Gamma}{dE/dx} \left(\frac{\pi}{2} + \tan^{-1} \frac{E - E_R}{\Gamma / 2} \right) \qquad (7)$$

where σ_R is a cross section at resonance energy E_R and Γ is a resonance width. In this case Γ includes, apart from the resonance width, the convolution of beam energy resolution, Doppler broadening of the gamma peak and the effect of contamination on the target surface.

To determine the elemental concentration of thick targets for bulk analysis, unknown concentration is typically deduced by comparing the γ-ray yields with those of thick standards of similar composition. Therefore, it is crucial to compare the γ-ray yields, taking into account the different stopping powers in the different matrices, namely the sample and the standard matrix. Such stopping powers are usually calculated not at the incident beam energy, but at an energy that corresponds to a production of half the yield ($E_{1/2}$). This value can be easily derived from the provided thick-target yield.

3.7. Inter-laboratory comparisons

For thin-target measurements it was decided that, in order to assess systematic problems of experimental facilities, everyone will measure the $^{27}Al(p,p'\gamma)^{27}Al$, $E\gamma$ = 844 keV (isotropic line) excitation function from 2.5 MeV to 3 MeV at 10 keV energy steps.
For thick target measurements it is suggested that every participant use the target that is routinely employed in their laboratory for accelerator energy calibration. The suggested energy points are between 0.95 and 1.1 MeV with the energy step small enough to reproduce the $^{27}Al(p,\gamma)^{28}Si$ resonance at 991 keV proton energy. The gamma line of 1.779 MeV will be used.

3.8. Benchmark test measurements

The participants agreed that thick target benchmark measurements to test the available differential cross section measurements will be discussed and implemented in the 2nd RCM.

3.9. Evaluation

Evaluation consists of generally established steps such as data compilation followed by critical analysis, and assigning on this basis statistical weight to each of the data sets, parameterization of the data in the framework of some nuclear model, and analysis of the revealed inconsistencies between theoretical calculations and experimental data. In order to meet the needs of the IBA community, a certain number of charged-particle cross sections were evaluated and the SigmaCalc software was developed for the IBA scientists to perform the calculations of the required smooth curves $d\sigma(E)/d\Omega$ at any angle. Similar evaluation efforts will be applied to extend such an approach for the PIGE data.

3.10. Miscellaneous

In relation to assessment of the existing data, it was decided that people assigned to measure a specific reaction will also take care of the assessment of previous published data. The references and maybe numerical data, if available, will be sent to Daniel Abriola at IAEA/NDS. Data in graphical format will be digitized by Valentina Semkova (EXFOR group) from IAEA/NDS.

Cross section measurements should be carried out at different angles in order to get the γ-ray angular distributions. It was agreed that, whenever possible, the angular distributions of emitted particles will also be measured.

Discussion took place about the kind of data needed for depth profiling and participants came to the conclusion that compilation and evaluation of existing data must be done first and decisions about additional measurements should be postponed to next year's meeting. Hans-Werner Becker and Anastasios Lagoyannis will take care of that assessment in relation to the most used resonances, as for instance, $^{7}Li(p,\gamma)$, $^{15}N(p,\alpha\gamma)$, $^{19}F(p,\alpha\gamma)$, $^{27}Al(p,\gamma)$, ^{28}Si (p,γ) and $^{52}Cr(p,\gamma)$, $^{12}C(p,\gamma)$ and $^{18}O(p,\gamma)$ and $^{18}O(p,\alpha\gamma)$.

4. Action lists

Table 1. Measurements for bulk analysis

Isotope	Reaction	γ-ray [keV]	Energy range [MeV]	Angle	Initial State, Jπ	Type of Data	Comments	Measured by:
^{7}Li	(p,p´γ)	478	2-4	130	1/2-	Differential+ Thick target	Sparse points	Pedro de Jesus
^{7}Li	(p,p´γ)	478	2-10	135	1/2-	Differential+ Thick target	Detailed + sparse points	Martin
^{7}Li	(p,n´γ)	429	2-10	135	1/2-	Differential+ Thick target	Detailed + sparse points	Martin
^{9}Be	(p,γ)	718			1+		Measured by Pedro de Jesus	
^{9}Be	(α,n´γ)	4443	2-10	135	2+	Differential+ Thick target	Detailed + sparse points	Martin/Strivay
^{10}B	(p,p´γ)	718	1.0-3.8	55,90	1+	Differential+ Thick target	Detailed+sparse points	Kiss
^{10}B	(p,p´γ)	718	3-5	45, others?	1+	Differential+ Thick target	Detailed+sparse points	Chiari
^{10}B	(p,p´γ)	718	3-5	0, 15, 55, 90	1+	Differential+ Thick target	Detailed+sparse points	Lagoyannis
^{10}B	(p,α´γ)	429	2-4	130	1/2-	Differential+ Thick target	Sparse points	Pedro de Jesus
^{10}B	(p,α´γ)	429	3-5	45, others	1/2-	Differential+ Thick target	Detailed+sparse points	Chiari
^{10}B	(p,α´γ)	429	1.0-3.8	55, 90	1/2-	Differential+ Thick target	Detailed+sparse points	Kiss
^{10}B	(p,α´γ)	429	1.0-3.8	0, 15, 55, 90	1/2-	Differential+ Thick target	Detailed+sparse points	Lagoyannis
^{11}B	(p,p´γ)	2124	3-5	45, others	½-	Differential+ Thick target	Detailed+sparse points	Chiari
^{11}B	(p,p´γ)	2124	2.8-3.8	55, 90	½-	Differential+ Thick target	Detailed+sparse points	Kiss
^{11}B	(p,p´γ)	2124	2.8-3.8	0, 15, 55, 90	½-	Differential+ Thick target	Detailed+sparse points	Lagoyannis
^{12}C	(d,p´γ)	3089	2.8-3.8	55	½+	Differential+ Thick target	Detailed+sparse points	Kiss
^{14}N	(p,p´γ)	2313	3.5-5	45	0+	Differential+ Thick target	Detailed+sparse points	Chiari
^{14}N	(p,p´γ)	2313	4-10	135	0+	Differential+ Thick target	Detailed+sparse points	Martin/Strivay
^{14}N	(p,p´γ)	2313	4-7	90	0+	Differential+ Thick target	Detailed+sparse points	Raisanen
^{14}N	(d,p´γ)	1885	0.6-2	55	5/2+	Differential+ Thick target	Detailed+sparse points	Kiss
^{14}N	(d,p´γ)	2297	0.6-2	55	7/2+	Differential+ Thick target	Detailed+sparse points	Kiss
^{14}N	(d,p´γ)	8310	0.6-2	55	1/2+	Differential+ Thick target	Detailed+sparse points	Kiss
^{14}N	(d,p´γ)	1885	0.6-2	90	5/2+	Differential+ Thick target	Detailed+sparse points	Kakuee

Isotope	Reaction	γ-ray [keV]	Energy range [MeV]	Angle	Initial State, Jπ	Type of Data	Comments	Measured by:
^{14}N	(d,p´γ)	2297	0.6-2	90	7/2+	Differential+ Thick target	Detailed+sparse points	Kakuee
^{14}N	(d,p´γ)	8310	0.6-2	90	1/2+	Differential+ Thick target	Detailed+sparse points	Kakuee
^{19}F	(p,p´γ)	110	2-4	130	1/2-	Differential+ Thick target	Detailed (in progress)	Pedro de Jesus
^{19}F	(p,p´γ)	197	2-4	130	5/2+	Differential+ Thick target	Detailed (in progress)	Pedro de Jesus
^{19}F	(p,α´γ)	6000-7000	0.8-4.0	130	3-	Differential+ Thick target	Detailed (in progress)	Pedro de Jesus
^{19}F	(p,p´γ)	110	2-10	135	1/2-	Differential+ Thick target	Detailed	Martin/Strivay
^{19}F	(p,p´γ)	197	2-10	135	5/2+	Differential+ Thick target	Detailed	Martin/Strivay
^{19}F	(p,α´γ)	6000-7000	2-10	135	3-	Differential+ Thick target	Detailed	Martin/Strivay
^{23}Na	(p,p´γ)	440	2-4	130	5/2+	Differential+ Thick target	Detailed	Pedro de Jesus
^{23}Na	(p,p´γ) (p,α´γ)	1636 1634	2-4	130	7/2+ 2+		Detailed	Pedro de Jesus
^{23}Na	(p,p´γ)	440	1-2.9	90	5/2+		Detailed	Kakuee
^{23}Na	(p,p´γ) (p,α´γ)	1636 1634	1-2.9	90	7/2+ 2+		Detailed	Kakuee
^{23}Na	(p,p´γ)	440	3-5	90, 0, 135, 55	5/2+		Detailed	Chiari
^{23}Na	(p,p´γ) (p,α´γ)	1636 1634	3-5	90, 0, 135, 55	7/2+ 2+		Detailed	Chiari
^{23}Na	(p,p´γ)	440	1-4	135	5/2+		Detailed	Bogdanovic
^{23}Na	(p,p´γ) (p,α´γ)	1636 1634	1-4	135	7/2+ 2+		Detailed	Bogdanovic
^{23}Na	(p,p´γ)	440	1-3.8	55 (0, 90, 135)	5/2+		Detailed	Kiss
^{23}Na	(p,p´γ) (p,α´γ)	1636 1634	1-3.8	55 (0, 90, 135)	7/2+ 2+		Detailed	Kiss
^{23}Na	(p,p´γ)	440	4-10	135, 90, 55	5/2+		Detailed	Martin/Strivay
^{23}Na	(p,p´γ) (p,α´γ)	1636 1634	4-10	135, 90, 55	7/2+ 2+		Detailed	Martin/Strivay
^{24}Mg	(p,p´γ)	1369	2-6	0, 15, 55, 90	2+		Detailed	Lagoyannis
^{25}Mg	(p,p´γ)	390	2-4	130	3/2+		Detailed (in progress)	Pedro de Jesus
^{25}Mg	(p,p´γ)	390	1-3	90	3/2+		Detailed	Kakuee
^{25}Mg	(p,p´γ)	390	2-5.5	0, 15, 55, 90	3/2+		Detailed	Lagoyannis

Isotope	Reaction	γ-ray [keV]	Energy range [MeV]	Angle	Initial State, Jπ	Type of Data	Comments	Measured by:
^{25}Mg	(p,p´γ)	390	1.5-4	135	3/2+		Detailed	Bogdanovic
^{25}Mg	(p,p´γ)	585	2-4	130	1/2+		Detailed (in progress)	Pedro de Jesus
^{25}Mg	(p,p´γ)	585	1.5-2.4	130	1/2+		Detailed (in progress)	Pedro de Jesus
^{25}Mg	(p,p´γ)	974	1.5-2.4	130	3/2+		Detailed (in progress)	Pedro de Jesus
^{25}Mg	(p,p´γ)	585	2-5.5	0, 15, 55, 90	1/2+		Detailed	Lagoyannis
^{25}Mg	(p,p´γ)	585	1.5-4	135	1/2+		Detailed	Bogdanovic
^{25}Mg	(p,p´γ)	974	1-3	90	3/2+		Detailed	Kakuee
^{25}Mg	(p,p´γ)	585	1-3	90	1/2+		Detailed	Kakuee
^{26}Mg	(p,γ)	1014	1-3	90	3/2+		Detailed	Kakuee
^{27}Al	(p,p´γ)	844	1.5-4	130	1/2+		Detailed+sparse	Pedro de Jesus
^{27}Al	(p,p´γ)	844	1-3	90	1/2+		Detailed+sparse	Kakuee
^{27}Al	(p,p´γ)	844	2.5-5	45, others	1/2+		Detailed+sparse	Chiari
^{27}Al	(p,p´γ)	844	2.5-5	0, 15, 55, 90	1/2+		Detailed+sparse	Lagoyannis
^{27}Al	(p,p´γ)	844	1.5-3.8	55	1/2+		Detailed+sparse	Kiss
^{27}Al	(p,p´γ)	844	1.5-4	135	1/2+		Detailed+sparse	Bogdanovic
^{27}Al	(p,p´γ)	844	3-10	135	1/2+		Detailed+sparse	Martin/Strivay
^{27}Al	(p,p´γ)	844	2-6	90	1/2+		Detailed+sparse	Raisanen
^{27}Al	(p,p´γ)	844	2-6	90	1/2+		Detailed+sparse	Becker
^{27}Al	(p,p´γ)	1014	1.5-4	130	3/2+		Detailed+sparse	Pedro de Jesus
^{27}Al	(p,p´γ)	1014	1-3	90	3/2+		Detailed+sparse	Kakuee
^{27}Al	(p,p´γ)	1014	2.5-5	45, others	3/2+		Detailed+sparse	Chiari
^{27}Al	(p,p´γ)	1014	2.5-5	0, 15, 55, 90	3/2+		Detailed+sparse	Lagoyannis
^{27}Al	(p,p´γ)	1014	1.5-3.8	55	3/2+		Detailed+sparse	Kiss
^{27}Al	(p,p´γ)	1014	1.5-4	135	3/2+		Detailed+sparse	Bogdanovic
^{27}Al	(p,p´γ)	1014	3-10	135	3/2+		Detailed+sparse	Martin/Strivay
^{27}Al	(p,p´γ)	1014	2-6	90	3/2+		Detailed+sparse	Raisanen
^{27}Al	(p,p´γ)	1014	2-6	90	3/2+		Detailed+sparse	Becker

Isotope	Reaction	γ-ray [keV]	Energy range [MeV]	Angle	Initial State, Jπ	Type of Data	Comments	Measured by:
^{27}Al	(p,γ)	1779	1.5-4	130	2+		Detailed+sparse	Pedro de Jesus
^{27}Al	(p,γ)	1779	1-3	90	2+		Detailed+sparse	Kakuee
^{27}Al	(p,γ)	1779	2.5-5	45, others	2+		Detailed+sparse	Chiari
^{27}Al	(p,γ)	1779	2.5-5	0, 15, 55, 90	2+		Detailed+sparse	Lagoyannis
^{27}Al	(p,γ)	1779	1.5-3.8	55	2+		Detailed+sparse	Kiss
^{27}Al	(p,γ)	1779	1.5-4	135	2+		Detailed+sparse	Bogdanovic
^{27}Al	(p,γ)	1779	3-10	135	2+		Detailed+sparse	Martin/Strivay
^{27}Al	(p,γ)	1779	2-6	90	2+		Detailed+sparse	Raisanen
^{27}Al	(p,γ)	1779	2-6	90	2+		Detailed+sparse	Becker
^{27}Al	(p,α´γ)	1369	1.5-4	130	2+		Detailed+sparse	Pedro de Jesus
^{27}Al	(p,α´γ)	1369	1-3	90	2+		Detailed+sparse	Kakuee
^{27}Al	(p,α´γ)	1369	2.5-5	45, others	2+		Detailed+sparse	Chiari
^{27}Al	(p,α´γ)	1369	2.5-5	0, 15, 55, 90	2+		Detailed+sparse	Lagoyannis
^{27}Al	(p,α´γ)	1369	1.5-3.8	55	2+		Detailed+sparse	Kiss
^{27}Al	(p,α´γ)	1369	1.5-4	135	2+		Detailed+sparse	Bogdanovic
^{27}Al	(p,α´γ)	1369	3-10	135	2+		Detailed+sparse	Martin/Strivay
^{27}Al	(p,α´γ)	1369	2-6	90	2+		Detailed+sparse	Raisanen
^{27}Al	(p,α´γ)	1369	2-6	90	2+		Detailed+sparse	Becker
^{29}Si	(p,p´γ)	1274	1-3	90	3/2+			Kakuee
^{29}Si	(p,p´γ)	1274	2-6	90	3/2+			Raisanen
^{29}Si	(p,p´γ)	1274	2.5-5	45	3/2+			Chiari
^{28}Si	(p,p´γ)	1779	2.5-5	45	2+			Chiari
^{28}Si	(p,p´γ)	1779	1-3	90	2+			Kakuee
^{31}P	(p,p´γ)	1266	1-3	90	3/2+			Kakuee
^{31}P	(p,p´γ)	1266	1-4	130	3/2+			Pedro de Jesus
^{32}S	(p,p´γ)	2230	3-6	0, 15, 55, 90	2+			Lagoyannis
^{32}S	(d,p´γ)	841	1-2	90	1/2+			Kakuee

Isotope	Reaction	γ-ray [keV]	Energy range [MeV]	Angle	Initial State, Jπ	Type of Data	Comments	Measured by:
^{35}Cl	(p,p´γ)	1219			1/2+			
^{35}Cl	(p,p´γ)	2230			2+			
^{35}Cl	(d,p´γ)	1165	1-2	90	1+			Kakuee
^{48}Ti	(p,γ)	62.3/90.6	1-3					Goncharov
^{nat}Ti	(p,γ)	62.3/90.6	1-3					Goncharov
^{nat}Ti	(p,nγ)	62.3/90.6	1.5-3					Goncharov

Table 2. Special actions

Action on	**Subject**
All concerned	Submit assessment of those reactions assigned in Table 1 paying attention in retrieving angular distributions wherever available
All concerned	Perform the efficiency calibration of the γ-ray detector and present them in the 2nd RCM
Semkova	On request of participants, digitize data for inclusion in IBANDL and EXFOR
All concerned	Perform over the period of the CRP the assigned measurements indicated in Table 1.
All concerned	Production and distribution of targets
All concerned	For inter-laboratory comparison make both the thin and thick aluminium measurements
Gurbich	Study the feasibility of producing evaluations for PIGE including the problem of an isotropy in the angular distribution
Gurbich	Make the necessary changes in IBANDL and in the R33-format to accommodate PIGE data
Pedro de Jesus	Complete and distribute the ERYA-code to the participants including a comprehensive manual in English
Pedro de Jesus	In a second step upgrade the ERYA-code in order to handle depth profiling
Becker, Lagoyannis	Find out the information of cross sections relevant to PIGE in the astrophysics community resources and input them in IBANDL

5. Conclusions

The First 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 16-20 May 2011.

Right from the beginning, there was a consensus among meeting participants' about the need for an extension of the IBANDL format and update of its interface to include PIGE data. Regarding the production of new experimental data for IBANDL, participants discussed and agreed the proper methodology to perform PIGE crosssection measurements, and also agreed on a list of priority measurements to be carried out. Concrete recommendations were made concerning accelerator calibration, target preparation and γ-ray detector efficiency calibration. Each participant responsible for a set of measurements will also review the scientific literature in search of previous data, will assess those data and submit them for inclusion in IBANDL. The need of a computer code to allow the final user to profit from the PIGE database was highlighted. Until the next meeting, foreseen for the last quarter of 2012, the CRP webpage will serve as forum for communication and information of each participant's progress with their individual assignments.

Annex A

International Atomic Energy Agency

1st Research Coordination Meeting on
Development of a Reference Database for PIGE Spectroscopy

IAEA Headquarters, Vienna, Austria
16-20 May 2011
Meeting Room A2774

Adopted AGENDA
Monday, 16 May

08:30 – 09:30 **Registration (IAEA Registration Desk, Gate 1)**

09:30 – 10:15 **Opening Session**

Opening Remarks and Welcome (M. Venkatesh, DIR-NAPC)
Introduction: Objectives of this RCM (D. Abriola)
Election of Chairman and Rapporteur
Discussion and Adoption of the Agenda (Chairman)

10:15 – 10:45 *Coffee break*

10:45 – 12:15 **Presentations**

1) The role of nuclear-reaction induced alignment for PIGE, Pedro de Jesus (~ 30 min)
2) The PIGE technique at ATOMKI: applications in archaeometry, Kiss (~ 30 min)
3) Depth profiling with low-energy nuclear resonances, Becker (~ 30 min)

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

Coffee break as needed

12:30 – 14:00 *LUNCH*

14:00 – 17:30 **Presentations cont'd**

4) PIGE activities in Van de Graaff Laboratory in Tehran, Kakuee (~ 10 min)
6) Gamma-ray yield measurements at the University of Helsinki, Raisanen (~ 30 min)
7) Chiari (30 min)

Round table discussion

Coffee break as needed

Tuesday, 17 May

09:00 – 12:30 **Presentations cont'd**

8) Past and planned PIGE applications at the Ruđer Bošković Institute in Zagreb, Bogdanović Radović (30 min)
9) PIGE activities at the Demokritos accelerator, Lagoyannis (30 min)
10) The Center for Microanalysis of Materials, Munoz (30 min)
11) Strivay (30 min)
12) Measurement of excitation yields of low energy prompt γ-ray from proton bombardment of ^{48}Ti foil Goncharov (presented by Gurbich, 30 min)
13) Gurbich (45 min)

Round table discussion

Coffee break as needed

12:30 – 14:00 *LUNCH*

14:00 – 17:30 **Methodology (discussion)**

1) Codes and database format

Coffee break as needed

19:00 *DINNER at a restaurant in the city*
("Gasthaus Am Nordpol", see separate information)

Wednesday, 18 May

09:00 – 12:30 **Methodology (discussion cont'd)**

2) Detector efficiecy calibration
3) Accellerator energy callibration

Coffee break as needed

12:30 – 14:00 *LUNCH*

14:00 – 17:30 **Methodology (discussion cont'd)**

4) Target preparation

Coffee break as needed

Thursday, 19 May

09:00 – 12:30 **List of priority measurements (discussion)**

Coffee break as needed

12:30 – 14:00 *LUNCH*

14:00 – 17:30 **Drafting of the List of Actions**

Friday, 20 May

09:00 – 12:30 **Drafting of the 1st RCM Summary Report**

Coffee break as needed

12:30 – 14:00 *LUNCH*

14:00 – 16:00 **Closing of the Meeting**

Annex B

1st Research Coordination Meeting on
"Development of a Reference Database for PIGE Spectroscopy"
IAEA, Vienna, Austria
16 to 20 May 2011

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