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Working Material

Report of the Consultants' Meeting on

Preparation of Table of Contents Relevant to an Education and Training Handbook on Nuclear Science Experiments using Accelerators and Research Reactors

17-18 December 2009

IAEA, Vienna, Austria

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1. BACKGROUND AND OBJECTIVES

Background

The enhancement of nuclear science education and training in all Member States, but in particular in the developing countries, is of interest to the IAEA since many of these countries are building up and expanding their scientific infrastructures but are lacking in sufficient numbers of well-educated and qualified nuclear specialists and technologists. This may arise from amongst other things:

- a lack of candidates with sufficient educational backgrounds in nuclear science who would qualify to receive specialized training
- a lack of institutions available for training nuclear science specialists
- a lack of lecturers in nuclear-related fields, and
- a lack of suitable educational and teaching resources

A related concern is the potential loss of valuable knowledge, accumulated over many decades, due to ageing of the workforce.

An imperative for Member States is to develop and conduct suitable graduate and post-graduate academic programmes of study and project work to attain a prerequisite level of knowledge, abilities and skills in their subject area. In nearly all academic programmes, experimental work is an essential and integral component to help develop graduates' general and subject-specific skills. Experimental work can mean practical work in a conventional laboratory, computer simulations, paper exercises, etc.

In this context, available or newly planned research reactors and particle accelerators should be seen as extremely important and indispensible components in today's nuclear science and technology curricula. Research reactors can demonstrate nuclear science and technology based on nuclear fission and neutrons and particle accelerators can demonstrate nuclear science and technology based on charged particle induced nuclear and atomic reactions. The extent and level of education and training offered by research reactor / particle accelerator facilities can be tailored to suit the interests of the academic department.

Objectives

In view of the above, research reactor and particle accelerator facilities have high potential for educating, training and qualifying scientists, engineers and technicians in nuclear science and technology. The utility of these facilities however depends on factors such as power level, operational characteristics, safety and security regulations, accessibility, etc.

A consultancy meeting is being held to outline the table of contents relevant to an **education and training handbook on nuclear physics experiments using particle accelerators and research reactors.**

The specific objectives of the consultancy meeting are:

- Provide a list and short description of nuclear physics experiments using research reactors

- Provide a list and short description of nuclear physics experiments using particle accelerators
- Critically examine and outline complementarities between research reactors and particle accelerators by comparing the nuclear physics experiments that they are capable of supporting
- Prepare a draft table of contents relevant to the education and training handbook on nuclear physics experiments using particle accelerators and research reactors

2. WORK DONE AND RESULTS ACHIEVED

The consultancy meeting was attended by 7 participants, from Austria, Germany, Ghana, Jordan, Slovenia, South Africa and USA. The meeting commenced with introductory remarks and brief presentations by Mr N. Dytlewski and Mr D. Ridikas, the IAEA Scientific Secretaries of the meeting, Physics Section, NAPC on the specific objectives of the meeting within the ongoing IAEA projects relevant to the Research Reactors and Particle Accelerators. Individual presentations by the experts then followed.

The individual presentations given by the experts provided a background for the detailed discussions that are summarized below. Focusing on the main objectives of the meeting, a number of key questions were addressed and reported.

The Annexes of this report are organized as follows: 1) future work plan, 2) research reactor-based physics experiments 3) accelerator-based physics experiments, 4) Radioactive source-based physics experiments, 5) meeting agenda and 4) list of participants. Copies of all presentations, other relevant documentation and administrative information were distributed at the end of the meeting to all participants and may be obtained from the Scientific Secretaries on request. The full meeting report as a working document is also available upon request from the Scientific Secretaries.

2.1. Discussion and draft list of nuclear physics experiments using particle accelerators

Note: general introduction to accelerators and their applications should be given before detailed description of accelerator-based experiments.

Ion stopping

- **Stopping of light ions in different thin foils using second scattering foil and detector.** To evaluate energy loss in a foil of known thickness. Thickness can be evaluated with precise weighing and measurement of the foil area. The results of measurements will be compared with SRIM simulations. Equipment required: sample holder to handle several targets at once; particle detector positioned at 10 degree forward angle; fixed scattering Al foil positioned behind the foil of interest. Software: SRIM, SIMNRA (optional)

Ion scattering

- **Rutherford scattering of (He (Li)) ions from thin Ta (Ni) foil) for a few scattering angles**. Measurement of angular dependence of RBS signal. Comparison of the results with predictions from the Rutherford formula (simulation with RUMP, SIMNRA or other appropriate software). Make sure that this is done in the Rutherford regime. Equipment required: SSB or similar detector, experimental chamber with easily changeable detector angle. Software: RUMP or SIMNRA or similar.

- **Non-Rutherford scattering cross-section (protons on thin C foil) for few proton energies close to the (p, p) resonance energy.** Measurement of energy dependence of backscattering signal. Comparison of the results with predictions from IBANDL data base. Equipment required: SSB or similar detector, experimental chamber with detector at backward angle. Software: RUMP or SIMNRA or similar.

- **Quantum interference in Rutherford cross-section (C-12 ions on thin C foil).** Measurements need to be performed for a reasonable number of scattering angles. Carbon beam 4-6 MeV. Comparison of the results with predictions from the Rutherford formula (simulation with RUMP, SIMNRA or other appropriate software). Describe and interpret the deviations from RBS predictions. Equipment required: SSB or similar detector, experimental chamber with easily changeable detector angle. Software: RUMP or SIMNRA or similar.

- **Calibration of SSB detector using Th-228 or Am-241 sources.** Equipment required: SSB or similar detector, experimental chamber; alpha source (one of the above)

- **Heavy element layer on Si.** Measurement of simple RBS spectra. Comparison of the results with theory predictions and simulations. Determination of the areal density of heavy element layer. Equipment required: SSB or similar detector, experimental chamber with detector at backward angle. Software: RUMP or SIMNRA or similar.

- **Comparison between Rutherford and non-Rutherford Back-scattering.** Low-Z targets (C, Al, Si) targets irradiated with a) ^{4}He beam, and b) proton beam. Simulation of the obtained spectra using appropriate cross-section data base. Equipment required: SSB or similar detector, experimental chamber with detector at backward angle. Software: RUMP or SIMNRA or similar.

- **Two-component (i.e. Ta_xN_y on non-crystalline substrate Si) layer stoichiometry determination in thin film (ion dose determination).** Equipment required: SSB or similar detector, experimental chamber with detector at backward angle. Software: RUMP or SIMNRA or similar.

ERDA

- **Hydrogen concentration in thin film using ^{4}He beam.** Equipment required: SSB or similar detector at 30° forward angle with foil absorbing the primary particles. Standard reference material: Kapton. Software: SIMNRA or similar.

Ion-Photon methods

- **PIXE Efficiency characteristics of X-ray detector.** Equipment required: X-ray detector (Si(Li), SDD, HPGe), experimental chamber with precise charge integration available, set of thin targets with known composition (e.g. thin metal foils). Software: AXIL, GUPIX, GUPIXWIN

- **PIXE on metal alloy** (Sum of concentrations 100%). Equipment required: X-ray detector (Si(Li), SDD, HPGe), experimental chamber with precise charge integration available, few pure metal targets or SRMs. Software: AXIL, GUPIX, GUPIXWIN.

- **In-air PIXE with Argon normalisation.** Equipment required: X-ray detector (Si(Li), SDD, HPGe), external proton beam, unknown target of simple composition; few pure metal targets or SRMs. Software: AXIL, GUPIX, GUPIXWIN.

- **Secondary fluorescence spectroscopy.** Pure metal target (e.g. Cu) to stop primary proton beam. Collimated secondary fluorescence is directed on unknown target. Equipment required: X-ray detector (Si(Li), SDD, HPGe), unknown target of simple composition.

- **Calibration of the detector for PIGE measurements.** Equipment required: Gamma-ray detector (NaI or HPGe detector); set of gamma sources i.e. ^{137}Cs, ^{60}Co, ^{22}Na.

- **Proton-gamma calibration of accelerator by using thin Fluorine target.** Equipment required: Gamma-ray detector (NaI or HPGe detector), thin and thick fluorine-containing target (i.e. CaF_2) or Al, proton beam

- **Proton-Induced Gamma-ray Emission (PIGE).** Gamma-ray spectrometry of Al(p, p´γ) and Na(p, p´γ) reactions and nuclear energy levels and transitions. Equipment required: Gamma-ray detector (NaI or HPGe detector), proton beam (3 MeV or higher), charge integrator, thick Al and Na containing targets, Reference materials: pure Al thin foils, NIST SRM 620 (soda lime glass, containing known amount of Na).

Nuclear Reaction Analysis (NRA)

- **Boron determination in material using ^{11}B(p, α)^{8}Be reaction.** Determination of Boron areal density in thin film or semiconductor material. Equipment required: proton beam, stopping foil, charge particle detector at backward angle. Analysis software: SIMNRA or equivalent

- **^{7}Li(p, 2α)** (1951 Nobel prize: Cockcroft andWalton experiment demonstrating transmutation of atomic nuclei). Equipment required: thin Li target, proton beam, SSB detectors.

Digital data acquisition

- **Set up a Pulse Height Analysis on RBS detector (Gamma detector)** using classic analog modules and an equivalent digital acquisition system (performance of high count rate using DSP is much better, less pulse pileup). Equipment required: SSB or similar detector, (pre-amp., spec. amp., ADC) for analog setup and digital acquisition unit. Software: RUMP or SIMNRA or similar.

2.2. Discussion and draft list of nuclear physics experiments using research reactors

Note: general introduction to research reactors and their applications should be given before detailed description of RR-based experiments.

a) nuclear physics

1. **NAA-type experiment:** Prediction of the irradiation conditions – determination of exposure time based on reactor power, sample material and expected activity (minimum detectable activity). Sample preparation. Sample irradiation. Spectroscopy and spectral analysis. Determination of concentrations.

2. **neutron attenuation experiment:** Using a beam port or a neutron source. Properly tailored beam (attenuation materials, collimation, filters, detectors, low background).

3. **delayed neutron experiment:** Refer to NAA (point 1) using fissile material. Optimized neutron detectors. Decay spectra analysis.

4. **neutron spectral measurements** (Bonner sphere, monochromator, beam filters, TOF, velocity selector, activation foils + unfolding).

b) use of neutron beams

1. **Powder Diffraction:** Use of monochromatic, collimated neutron beam. Preparation of diffraction geometry by using rotation stages for the sample and the detector. Calculation of the position of diffraction peaks for standard powder sample. Measurement of the diffraction spectrum by counting tube and comparison with the calculated values.

2. **Triple-Axis Spectroscopy**: Using of diffraction geometry (see Powder Diffraction) with implementation of analyzing part in front of the detector (counting tube). Measurement of neutron inelastic scattering spectrum from a standard sample.

3. **Small Angle Neutron Scattering:** Choosing of an appropriate beam line with available long beam path. Monochromatisation and collimation of the neutron beam. Detecting of the small-angular scattering signal in transmission geometry by position sensitive detector. Measurement of particle-size distribution in standard sample.

4. **Time-of-Flight Spectroscopy:** Installation of system of disk choppers in front of the sample which provides a defined pulsed beam structure. Using of array of detectors

around the sample position. Measurement of inelastic neutron scattering signal from a standard sample.

5. **Reflectometry:** Use of high-collimated, monochromated neutron beam. Preparation of reflection geometry by positioning of sample and detector in a dedicated reflecting arrangement. Investigation of the structure of thin layer sample.

6. **Neutron imaging:** Beam line preparation by use of different collimation ratios (L/D) and recording of the beam profile by position sensitive neutron detector. Calculation of attenuation coefficients and experimental measurement of neutron transmission of different materials. Imaging of test objects providing information about spatial and time resolution of the instrument. Visualization of various technical objects.

7. **Autoradiography:** Choosing of high-intensive beam line position ($>10^8$ n/cm^{2}s). Calculating of appropriate exposure time. Exposure of flat samples (paintings, borated histological slices, circuit boards etc.) on neutron beam. Using of appropriate sample holder for fixation of layers of x-ray films (imaging plates) in front of the sample after its neutron exposition. Processing and analyzing of X-ray films (or imaging plates).

Example of the courses offered by the annual neutron school, where most of these experiments are performed for education and training purposes can be found at:
http://www.helmholtz-berlin.de/events/neutronschool/ (January 2010)

c) reactor physics

1. **Thermal, epithermal and fast neutron flux measurement:** Thin Au, Ni and/or Fe foils are irradiated in the research reactor (RR) core at an appropriate power (corresponding to a convenient neutron flux level) radially and vertically. Both bare and Cd-covered foils are utilized. Using the Cd-difference approach the radial and axial neutron flux distribution is determined.

2. **Influence of void coefficient on reactor power:** At low (e.g., 10 W) RR power a small container with different air volumes is pulled axially through the core while the reactor is in the automatic operation mode. The influence of volume and position in the core on reactivity is determined.

3. **Critical experiment:** Fuel elements are removed from the RR core and consecutively re-loaded, the neutron count rate is measured after each step. At each step measurements are performed with all control rods up and then down. Criticality is reached with all control rods up after reloading of a certain number of fuel elements.

4. **Control rod calibration:** One control rod is calibrated by removing it stepwise from the critical core and measuring the resulting reactor period. Using the in-hour equation the respective reactivity value is determined.

5. **Reactivity values of fuel elements in different core positions (execution of this experiment will depend on the regulatory aspects of a given facility)**: While the RR is on automatic control at low power (e.g., 10 W), a fuel element is removed from chosen internal and external core positions. The loss of reactivity is compensated by the movement of the regulating rod. From the rod position difference and using the

rod calibration curve the reactivity value of the fuel element in different core positions can be determined.

6. **Reactor power calibration and fuel temperature coefficient of reactivity:** The reactor is operated at low power (e.g., 10 W), rod positions, water- and fuel temperature is noted, then the RR power is raised to 100 kW again the values are noted. From the difference in rod position and fuel temperature the fuel temperature coefficient can be determined. Then RR is operated for 90 min only with convection cooling and the increase of water temperature is monitored. Comparing the temperature increase with the value from a previous e calibration the thermal reactor power can be determined.

7. **Reactor moderator temperature coefficient:** While operating the RR at low power (e.g., 10-100 W) secondary cooling is disrupted resulting in increasing the primary water temperature. This temperature increase is related to observed changes in the control rod position.

8. **Reactor power coefficient measurement (dependent on reactor type):** the RR is operated at low power (10-100 W). A small rod jerk is performed to observe the resulting increase in RR power and the eventual decrease and shutdown.

9. **Demonstration of a prompt critical power excursion (dependent on reactor type):** Due to the strong negative temperature coefficient of reactivity TRIGA reactors allow prompt critical excursion to 1000 times the normal power mode without any damage to the core. This is demonstrated using a pneumatic rod which is removed promptly from the critical core, typical power levels of 250 to 300 MW are reached for a time period of about 40 ms.

10. **Control rod Calibration in the subcritical range:** The safety rod will be calibrated in the subcritical range by cross-calibration using the reactivity data of the regulating rod. In this case the safety rod is lifted in small steps from the zero position and the count rate increase is measured with a fission chamber.

11. **Xenon build up effect (dependent on reactor power):** Operate the reactor at high power until Xe reaches its steady state condition; then lower the power and operate it in auto mode and observe the control rod position.

d) reactor instrumentation and control

1. **Introduction to typical research reactor instrumentation**: An introduction to the instrumentation of a given reactor is provided. A reactor start up exercise is performed (Check list, Check in, Check out, etc.).

2. **Calibration of the nuclear channels**: The nuclear and temperature channels are calibrated according to given procedures, alarm and scram settings are verified.

3. **Measurement of control rod drop times:** The control rod drop times are checked according to given procedures, the individual rod drop time is measured from different rod positions.

4. **A compensated ionisation chamber** (CIC) is used to determine the optimal compensation voltage and to measure the A-V characteristics at different power levels.

5. **Fission chambers**: A fission chamber is used to set the discriminator between gamma- and neutron signal and to determine the range of neutrons outside the core (flux monitoring outside the reflector).

6. **Self-powered neutron detectors**: A self powered neutron detectors is exposed in the core centre, where its activation and decay is monitored. This allows determining the type of emitter material.

7. **NPP Simulator Program:** Using an IAEA simulator program for different type of power reactors a cold start up is carried out, followed by power changes and selected incident simulation.

e) other experiments

1. Safeguards mock-up inspection: …
2. Demonstration fuel handling: …
3. Gamma-spectrometry with various fuel samples: …
4. Verification of the radiation level during reactor operation. Using various radiation detectors the radiation field at different reactor areas are verified.

2.3. Proposed structure of a typical nuclear physics experiment

The following structure to describe a typical nuclear physics experiment based either on RR or Particle Accelerator was proposed and will be developed in detail for the future Handbook:

1. Introduction
2. Theoretical - physics background
3. Application of the experiment
4. Experimental outline/procedure
5. Necessary equipment
6. Data collection/recording templates
7. Data evaluation, analysis, interpretation of results
8. Safety and radiation protection instructions
9. List of References

Equally, the guidance for the trainee on how to prepare a scientific publication based on the performed experiment should be provided. This should include: a) abstract, b) introduction, c) methodology, d) results and discussion, and e) conclusions.

2.4. Work-plan for the future actions

The following table sets out a draft work plan of actions that should be taken in order to implement the recommendations in a timely fashion.

Activity	Coordination	Commencement date	Delivery date
Consultants' Contracts (3+3 months) with the following role: focal point, informed editor, facilitator, etc.	IAEA	May 2010	End of the contract(s)
Consultancy Meeting	IAEA	May-June	End of meeting
Consultancy Meeting	IAEA	November-December	End of meeting
Preliminary inputs for RR related experiments	This Meeting Experts + IAEA	February 2010	May 2010
Preliminary inputs for Accelerator related experiments	This Meeting Experts + IAEA	February 2010	May 2010

3. CONCLUSIONS AND RECOMMENDATIONS

There was unanimous agreement during the meeting that there are significant needs to develop the Handbook Relevant to the Education and Training on Nuclear Physics Experiments using Accelerators and Research Reactors. Indeed, hands-on experiments and practical exercises (under supervision of experienced staff) accompanied by corresponding modelling were considered as indispensable part of the modern nuclear education and training curricula.

The meeting participants adopted the following concrete recommendations, satisfying the stated objectives of the meeting:

- There is a need for the above proposed document both for the developed and developing Member States. Therefore, the Agency's activities already planned for the biennium 2010-2011 were endorsed and strongly supported.

- Preparation of the Manual for RR and Accelerator supported nuclear physics experiments (as drafted above) is strongly recommended and should be implemented

- This manual should be the guidance document for the trainers as well as for the trainees. This can be extended and/or adopted to the educational objectives of the specific training programme.

- Support of regional/international nuclear education and training initiatives (e.g. schools, workshops, conferences) should be encouraged and continued. Dedicated funding possibilities should be created when necessary and continuously ensured.

- Complementary aspect in the techniques, instrumentation and domain of application in the case of research reactors and accelerators was clearly indicated.

- Links with on going international activities, relevant to nuclear education and training, should be utilised and further developed (e.g. ENEN, ENS, ENSA, AONSA, ANS, WNU, etc.); when available web links should be provided including informative examples where these experiments could be performed.

ANNEX I. RESEARCH REACTORS: TYPICAL EXPERIMENTS FOR VARIOUS EDUCATION & TRAINING PURPOSES

Source: "Survey of RRs" by H. Böck & M. Villa, Atominstitut, Austria

http://www.reak.bme.hu/Wigner_Course/WignerManuals/Bratislava/Research_Reactors_I.htm

It would difficult to give an outline of the training programmes run on research reactors without taking into account the trainees involved (students, physicists, operating personnel, etc.) or mentioning the possibilities and limitations offered by each type of reactor (power, accessibility, flexibility, etc.). The following classification is proposed.

Training of students and physicists

Most of the RRs allow training to be given in the following areas:

- nuclear radiation measurement and application such as activity, dose, half-life, energy, reaction with materials, activation analysis and statistics, etc.
- reactor theory, neutron transport by using spectrometers, neutron choppers, foil activation dosimeters, etc.
- reactor kinetics, reactor dynamics
- reactor operation and control by using an associated computer to simulate the reactor operation and control
- criticality and power increase of the reactor
- relative and absolute flux measurements
- reactivity measurements
- control rod calibration
- temperature coefficient measurements
- poisoning effect measurement
- spectrum measurement
- void coefficient determination
- radiation protection and shield measurement
- neutron radiography
- activation analysis
- radioisotope determination

Training of operating personnel

For this type of trainees the emphasis is placed on procedures and operations involved in reactor operation and safety, in particular:

- fuel loading and unloading
- approach to criticality
- effects of prompt and delayed neutrons
- poisoning effects (xenon, samarium)
- temperature effects
- reactivity effects
- load variations
- instrumentation and calibration

- flux and power measurements
- reactor kinetics and dynamics
- radiation protection
- radiochemistry.

Training for research: related applications

Low power reactors can also be used for a whole series of related applications, involving the field of basic or applied research such as:

- archaeometry
- biological applications
- chemical applications
- earth sciences
- environmental sciences
- medical applications
- metallurgy
- industrial applications

ANNEX II. PARTICLE ACCELERATORS: TYPICAL EXPERIMENTS PERFORMED FOR VARIOUS EDUCATION & TRAINING PURPOSES

- The Van de Graff Nuclear Physics Laboratory. Complete Nuclear Physics Course of 30 Experiments (High Voltage Engineering Corporation (1965))
- Accelerator Nuclear Physics. Fundamental Experiments with a Van de Graff Accelerator (High Voltage Engineering Corporation; First edition (1970))

ANNEX III. RADIOACTIVE SOURCES: TYPICAL EXPERIMENTS PERFORMED FOR VARIOUS EDUCATION & TRAINING PURPOSES

Experiments in Nuclear Science Laboratory Manual, Introduction to Theory and Basic Applications: Methods and Electronics for detection of Alpha, Beta, Gamma, X-Ray, and Neutron Radiation (4th Edition, Revised)

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ANNEX IV. MEETING AGENDA

Consultants' Meeting on Preparation of Table of Contents Relevant to an Educational and Training Handbook on Nuclear Physics Experiments using Accelerators and Research Reactors

17-18 December 2009, IAEA, Vienna, Austria

Thursday, 17 December 2009

08:30-09:00	**Registration, Gate 1**
09:00-09:30	**Welcome & Opening Remarks** ***Mr Nick Dytlewski*** & ***Mr Danas Ridikas*** *(IAEA Scientific Secretary, Physics Section, NAPC)* Self introduction of the participants, Discussion & Administrative Arrangements
09:30-10:00	***Mr Nick Dytlewski*** & ***Mr Danas Ridikas,*** IAEA Objectives of the Meeting
10:00-10:30	**Mr Wojciech Przybylowicz,** iThemba LABS, South Africa
10:30-11:00	Coffee break
11:00-11:30	**Mr Primoz Pelicon,** Jozef Stefan Institute, Slovenia
11:30-12:00	**Mr G.K. Banini,** GAEC, Ghana
12:00-13:30	Lunch break
13:30-14:00	**Mr Helmuth Böck,** Atominstitut, Austria
14:00-14:30	**Mr Nikolay Kardjilov,** HZB, Germany
14:30-15:00	Coffee break
15:00-15:30	**Mr Ayman I. Hawari,** North Carolina State University, USA
15:30-16:00	**Mr Ned Xoubi,** JAEC, Jordan
16:00-17:00	**All; summary discussion**

Friday, 18 December 2009

09:00-12:30	**All; discussion and drafting of** • a list and short description of nuclear physics experiments using research reactors • a list and short description of nuclear physics experiments using accelerators
12:00-13:30	Lunch break
13:30-15:00	**All; discussion on** • Preparation of a draft table of contents relevant to the educational and training handbook on nuclear physics experiments using particle accelerators and research reactors
15:00-15:30	Coffee break
15:30-17:00	**All** • Formulation of conclusions and recommendations • Drafting of the meeting report • Closing of the meeting

ANNEX V. LIST OF PARTICIPANTS

Consultants' Meeting on Preparation of Table of Contents Relevant to an Educational and Training Handbook on Nuclear Physics Experiments using Accelerators and Research Reactors

17-18 December 2009, IAEA, Vienna, Austria

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