WPEC meeting
8/9 April 2005
Antwerp, Belgium

WPEC action (ref. Item 5 of Summary Record), May 2004:
Summary of ND measurements, 2004 (generally beyond direct WPEC contacts)

1. Beta decay and decay heat

Concern has been expressed following the adoption of average β and γ energies taken from TAGS (total absorption gamma-ray spectrometry) for decay-heat calculations (Yoshida *et al.*, 2004). As a consequence of these difficulties, experimental efforts are being made to resolve the current uncertainties in the β-strength distributions of some of the most relevant decay-heat radionuclides and to address other uncertain features of nuclear structure (Algora *et al.*, 2002 and 2004).

A proposal was submitted in 2004 to irradiate samples for beta decay studies at the University of Jyvaskyla, Finland. Experiment I77 was approved and performed to quantify beta-decay data for reactor decay-heat calculations, focusing on identifying the possible source of the known gamma discrepancy in the 300-3000 secs cooling period (7 – 12 December 2004, at the IGISOL facility of the University of Jyvaskyla). Resulting data are in the process of analysis.

Yoshida, T. *et al.*, 2004. Impact of total absorption γ-ray spectroscopy on FP decay heat calculations, Private communication, Musashi Institute of Technology, Japan.
Algora, A. *et al.*, 2002. β-decay data for reactor decay-heat calculations: confirmation of a possible source of the γ discrepancy in the 300-3000 secs cooling period, Private communication, IFIC-University of Valencia, Spain.
Algora, A. *et al.*, 2004. Beta-decay studies using total absorption spectroscopy, *Eur. Phys. J.* **A20**, 199-202.

2. Neutron capture cross section measurements

The neutron cross sections of the $^{109}Ag(n, \gamma)^{110m}Ag$, $^{186}W(n, \gamma)^{187}W$ and $^{158}Gd(n, \gamma)^{159}Gd$ reactions have been measured at 55 and 144 keV by the activation method by means of filtered neutron beams at the Dalat research reactor (Vuong Huu Tan *et al.*, 2004). The cross sections were determined relative to the standard capture cross sections of ^{197}Au using highly pure metallic foils of Ag, W, Gd and Au, and a high-efficiency HPGe detector was used for the gamma-ray measurements.

Vuong Huu Tan *et al.*, 2004. Neutron capture cross section measurements of ^{109}Ag, ^{186}W and ^{158}Gd on filtered neutron beams of 55 and 144 keV, IAEA report INDC(VN)-011, December 2004, IAEA, Vienna, Austria.

3. Charge changing interactions of ultra-relativistic Pb nuclei

Experimental and theoretical results have been obtained on charge loss ($-27 \leq \Delta Z \leq -1$), charge pickup ($\Delta Z = +1$), and total charge changing cross sections for 158A GeV ^{208}Pb ions on CH_2, C, Al, Cu, Sn and Au targets (Scheidenberger *et al.*, 2004). Calculations based on the revisited abrasion-ablation model for hadronic interactions and the relativistic electromagnetic dissociation (RELDIS) model for electromagnetic interactions describe the data in a satisfactory way. The decay of excited nuclear systems created in both types of interaction is described by the statistical multi-fragmentation model, which includes evaporation, fission and multi-fragmentation channels. At very high projectile energy, the excitation energy of residual nuclei may be estimated on average of the order of 40 MeV per removed nucleon, with a significant increase in comparison with fragmentation of heavy ions of intermediate energy (~1A GeV).

Scheidenberger, C. *et al*., 2004. Charge-changing interactions of ultrarelativistic Pb nuclei, *Phys. Rev.* **C70**, 014902.

4. Measurements of neutron cross sections at the n_TOF facility at CERN

2004 saw the conclusion of a campaign of neutron cross section measurements at the neutron time-of-flight (n_TOF) facility at CERN (spallation induced by the 20 GeV proton beam of the CERN PS accelerator). 135 researchers from 37 institutes where involved in the n_TOF Collaboration. The purpose of the experimental campaign was to determine with unprecedented accuracy neutron cross sections of isotopes of interest to nuclear astrophysics (capture) and for accelerator driven systems associated with nuclear waste transmutation (capture, fission, (n, 2n) and (n, 3n)).

Preliminary results on experimental methods and cross section measurements were presented at the 8th International Symposium on Nuclei in the Cosmos, 19-23 July 2004, Vancouver, Canada, and at the International Conference on Nuclear Data for Science and Technology, 26 September – 1 October 2004, Santa Fe, New Mexico, USA.

5. Neutron capture cross section of ^{135}Cs

The neutron capture cross section of the unstable ^{135}Cs isotope was measured relative to that of gold by means of the activation method (Patronis *et al*., 2004). The neutron capture cross sections were determined at E_n = 30 and 500 keV, and were used to normalize the theoretically derived cross-section shape. Based on these data, statistical model calculations were performed to obtain the capture cross sections of the short-lived ^{134}Cs and ^{136}Cs isotopes as well.

Patronis, N. *et al*., 2004. Neutron capture studies on unstable ^{135}Cs for nucleosynthesis and transmutation, *Phys. Rev.* **C69**, 025803.

6. Neutron capture cross sections of ^{208}Pb and ^{209}Bi

Stellar cross sections of importance with respect to the termination of the *s*-process reaction chain were determined for ^{208}Pb (n, γ) ^{209}Pb and ^{209}Bi (n, γ) ^{210}Bi ^{g} , yielding kT = 30 keV values of $\langle\sigma v\rangle/v_T = 0.31 \pm 0.2$ mb and 2.54 ± 0.14 mb, respectively (Ratzel *et al*., 2004). The measurements were carried out by activation of Pb and Bi samples in a quasi-stellar neutron spectrum using gold as a cross section standard. With this technique, the uncertainties reported in previous work were considerably reduced.

Ratzel, U. *et al*., 2004. Nucleosynthesis at the termination point of the s process, *Phys. Rev.* **C70**, 065803.

7. Coulomb and nuclear break-up of the halo nucleus ^{11}Be

Break-up reactions of the one-neutron halo nucleus ^{11}Be on Pb and C targets at about 70 MeV/nucleon were investigated at RIKEN (Fukuda *et al*., 2004). The relative energy spectra as well as the angular distributions of the ^{10}Be + n centre-of-mass system were extracted both for Pb and C targets.

Fukuda, N. *et al*., 2004. Coulomb and nuclear breakup of a halo nucleus ^{11}Be, *Phys. Rev.* **C70**, 054606.

8. Stellar He burning of ^{18}O: low-energy resonances

^{22}Ne(α, n) reaction is the main neutron source for neutron capture photosynthesis (s process) in massive stars. ^{22}Ne is produced by the reaction sequence ^{14}N(α, γ)^{18}F(β^+)^{18}O(α, γ)^{22}Ne. While the first reaction is well understood, α capture on ^{18}O is highly uncertain. At the temperatures of stellar He burning, the reaction rate is determined by two resonances at α energies of 566 and 470 keV – resonance strengths of 0.71 ± 0.17 and 0.48 ± 0.16 μeV have been determined for the 566- and 470-keV resonances, respectively (Dababneh *et al*., 2003).

Dababneh, S. *et al*., 2003. Stellar He burning of ^{18}O: a measurement of low-energy resonances and their astrophysical implications, *Phys. Rev.* **C68**, 025801.

9. ^{95}Mo(n, α) cross section from 1 eV to 500 keV

^{95}Mo(n, α) cross section has been measured in the energy range from 1 eV to 500 keV at ORELA, Oak Ridge (Rapp *et al*., 2003). This work is part of a series of such studies involving staff from the Forschungszentrum Karlsruhe.

Rapp, W. *et al*., 2003. ^{95}Mo(n, α) cross section from 1 eV to 500 keV: a test of the α + nucleus optical potential used in calculating reaction rates for explosive nucleosynthesis, *Phys. Rev.* **C68**, 015802.

10. Neutron capture cross section of ^{139}La

The neutron capture cross section of 139La has been measured relative to that of ^{197}Au by means of the activation method. New value for kT = 300 keV of 31.6 ± 0.8 mb is 18% lower than the previously recommended value of 38.4 ± 2.7 mb, and considerably less uncertain (O'Brien *et al*., 2003).

O'Brien, S. *et al*., 2003. Neutron capture cross section of ^{139}La, *Phys. Rev.* **C68**, 035801.

11. Fundamental studies on isomeric cross sections

The formation of the isomeric pair $^{52m,\,52g}$Mn has been investigated in four nuclear reactions: ^{52}Cr(p, n), ^{52}Cr(^{3}He, t), ^{54}Fe(d, α) and ^{54}Fe(^{3}He, αp). Further details of these and other on-going studies can be found in Klein *et al*. (2000) and Zaman *et al*. (2003).

Klein, A.T.J. *et al*., 2000. Investigation of ^{50}Cr(d, n)^{51}Mn and nat-Cr(p, x)^{51}Mn processes with respect to the production of the positron emitter ^{51}Mn, *Radiochim. Acta* **88**, 253.

Zaman, M.R. *et al*., 2003. Production of ^{55}Co via the ^{54}Fe(d, α)-process and excitation functions of ^{54}Fe(d, t)^{53}Fe and ^{54}Fe(d, α)^{52m}Mn reactions from threshold up to 13.8 MeV, *Radiochim. Acta* **91**, 105.

12. Nuclear reaction cross-section data for medical applications

Various studies have been made to determine the cross sections and yields of the positron emitters ^{76}Br, ^{124}I and ^{82}Sr(^{82}Rb), along with ^{103}Pd, ^{140}Nd, ^{169}Y and ^{192}Ir. Proton therapy related activation cross sections have also been studied with respect to the formation of short-lived β^+ emitters in human tissue and long-lived activation products in collimator materials (Qaim *et al*., private communication, 2004).

13. Alpha-particle emission probabilities in the decay of ^{235}U

Measured as a collaborative programme involving NPL/CIEMAT/IRMM/University of Extramadura (EUROMET, project 591). Work has been completed, and a draft of the final paper has been prepared. A new set of P(α) values for 13 alpha emissions has been determined with improved uncertainties (compared to previous measurements of 1975).

Basic and integral nuclear data: note on experimental activities in India

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A summary is given of some of the past and on-going experimental activities in the field of basic and integral nuclear data within India.

1. Basic nuclear physics experiments

Basic physics experiments are performed using the FOTIA accelerator in BARC, the Pelletron accelerator in TIFR, the cyclotron at VECC, Kolkata, and the 15UD Pelletron accelerator at the Nuclear Science Centre (NSC), New Delhi, especially for physics studies of heavy ion fusion reactions. These facilities form part of the regular basic nuclear physics research activities in India, and are excluded in this summary report. The interested reader may consult the websites [1-7] of individual laboratories for more information.

2. Fission yield measurements

The combination of world class radiochemical laboratories, research reactors (APSARA, CIRUS and DHRUVA), well-equipped radiation detection and measurement systems, other associated facilities and a large team of well-trained manpower, BARC has become a recognized leader in experimental fission yield measurements (mainly absolute yields). BARC has performed experiments on the neutron-induced fission of several actinides using radiochemical techniques and a new approach know as "track-etch-cum gamma spectrometry" involving a combination of high resolution gamma spectrometry and solid state nuclear track detectors (SSNTD).

Absolute fission product yield measurements have been carried out for fission in thorium foils irradiated in the thermal spectrum of the APSARA reactor. The fission product yields were also measured for ^{233}U in thermal and epithermal spectra. The epithermal data were obtained by means of cadmium-covered foils.

A new approach based on the recoil catcher technique coupled to track-etch-cum gamma-ray spectrometry has been developed to determine the absolute yields of fission products in the low-energy fission of actinides. The technique is particularly suitable for determining absolute fission yields in the fission of highly alpha active and sparingly available actinide isotopes. This technique has been employed to study the spontaneous fission of ^{244}Cm; absolute yields of 21 fission products in 20 mass chains have been determined. The total number of fissions occurring in the target was estimated after registering the fission tracks on a Lexan solid state track detector, and the number of fission product atoms was analyzed by gamma-ray spectrometry after their collection on the Lexan catcher using the recoil catcher technique. Resulting fission yields show very good agreement with literature data, indicating the sensitivity and accuracy of the present technique. Interested readers may consult references [8-10].

3. 14-MeV neutron activation measurements

Aligargh Muslim University: Cockcroft-Walton accelerator for the generation of fast neutrons (no longer in operation). Energy and flux of incident neutrons were measured by recording the energy and angular distribution of alpha particles emitted in the reactions T(d, n)^{4}He. Most of the measurements were made in the forward hemisphere; mean neutron energy was found to be 14.8 ± 0.5 MeV. Furthermore, the calibration of the energy of the neutrons was undertaken by means of the emulsion technique. Approximately14 MeV neutrons were used to measure the cross sections for (n, p), (n, α) and (n, 2n) reactions using the activation technique. Reaction cross-sections for more than 100 reactions have been measured, and efforts are underway [11] in collaboration with Reactor Physics Design Division, BARC, Mumbai to compile all of these old experimental cross-sections for neutrons as well as charged particles, in the standard EXFOR format. These files will be submitted to the EXFOR-NRDC compilation effort, so that the raw experimental data may be made available to any user through the international nuclear data compilation centres (e.g., IAEA Nuclear Data Section, Vienna).

4. Integral shielding experiments

Many integral experiments on shielding have been performed using the APSARA facility (Dravid and Indira [12]), and are not repeated here. These experiments are designed to validate shielding data and methods at an integral level for fast reactor applications.

5. Integral reactor irradiation experiments

We have a continuous programme of irradiating thorium in research reactors. For instance, thoria rods have been irradiated in the graphite/reflector annulus of the CIRUS reactor. Several advanced fuels have also been irradiated in the in-pile loops and further such work is in the pipeline. A 30-kW research reactor (KAMINI) is in operation that uses plate-type ^{233}U-Al alloy fuel.

Thorium bundles irradiated in the 220-MWe PHWRs (KAPS) are undergoing PIE and chemical analysis. Preliminary experimental results from the chemical analysis have been obtained. Samples were taken from one of the irradiated ThO_2 bundles, and have been analyzed experimentally by alpha spectrometry for ^{232}U and by thermal ionization mass spectrometry for ^{233}U, ^{234}U, ^{235}U and ^{236}U by two different groups [13-14] at BARC.

Measurements of ^{233}U breeding rates are planned at the PURNIMA laboratory using the recently installed 400-kV, 14-MeV-T (d, n) neutron generator [15].

Ref. [16] provides a clear perspective of the Indian scene and integral approach to experimental validation of nuclear data with respect to our needs for nuclear data for the thorium fuel cycle. Detailed experiments involving integral parameter measurements are being planned [15] in the proposed experimental critical facility for AHWR.

6. Measurement of neutron total cross sections by n-TOF technique

Proposals are being evolved to undertake neutron-chopper studies based on neutron time-of-flight measurements with our 100MW DHRUVA reactor facility.

Neutron Time-of-Flight (TOF) technology is already familiar to basic nuclear physicists in India. For instance, energy analyses by n-TOF is being performed by Nuclear Physics Division at the Pelletron laboratory, Tata Institute of Fundamental Research, to characterize the neutron output for heavy ion fusion reaction experiments. Proposals are also being made in India to build a 100-kW electron LINAC based neutron source.

Ganesan, Koparde and Kumar (University of Rajasthan, Jaipur) have collaborated with Prof. Kim and his team at the Institute of High Energy Physics, Kyungpook National University, Daegu, South Korea during 2003/04 in the measurement and analysis of the neutron total cross sections of tantalum and bismuth.

India is also hoping to join Phase 2 of the CERN n_TOF collaboration.

7. Concluding remarks

Some of the past and on-going experimental activities in basic and integral nuclear data have been summarized. Indian nuclear data activities have the generic perspective to encompass a user-oriented approach, starting from data files distributed by the IAEA. This perspective is now changing: India sponsors mirroring of the international IAEA-NDS nuclear data site (http://www-nds.indcentre.org.in) at BARC. India also recognizes that own measurements, critical evaluations of basic nuclear data and associated uncertainties, and knowledge management should be rigorously initiated, pursued, sustained, and well supported.

REFERENCES

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2. Bhabha Atomic Research Centre: http://www.barc.ernet.in
3. Indira Gandhi Centre for Atomic Research: http://www.igcar.ernet.in
4. Centre for Advanced Technology: http://www.cat.gov.in
5. Variable Energy Cyclotron: http://www.veccal.ernet.in
6. Institute of Plasma Research: http://www.plasma.ernet.in
7. Significant work is also carried out at the Nuclear Science Centre, New Delhi on heavy ion induced reactions and accelerator development; visit the website of the Nuclear Science Centre for more details: http://www.nsc.ernet.in/ann_report/
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16. S. Ganesan, New reactor concepts and new nuclear data needed to develop them, invited paper presented at the International Conference on Nuclear Data for Science and Technology (ND2004), 26 September – 1 October 2004, Santa Fe, NM, USA.