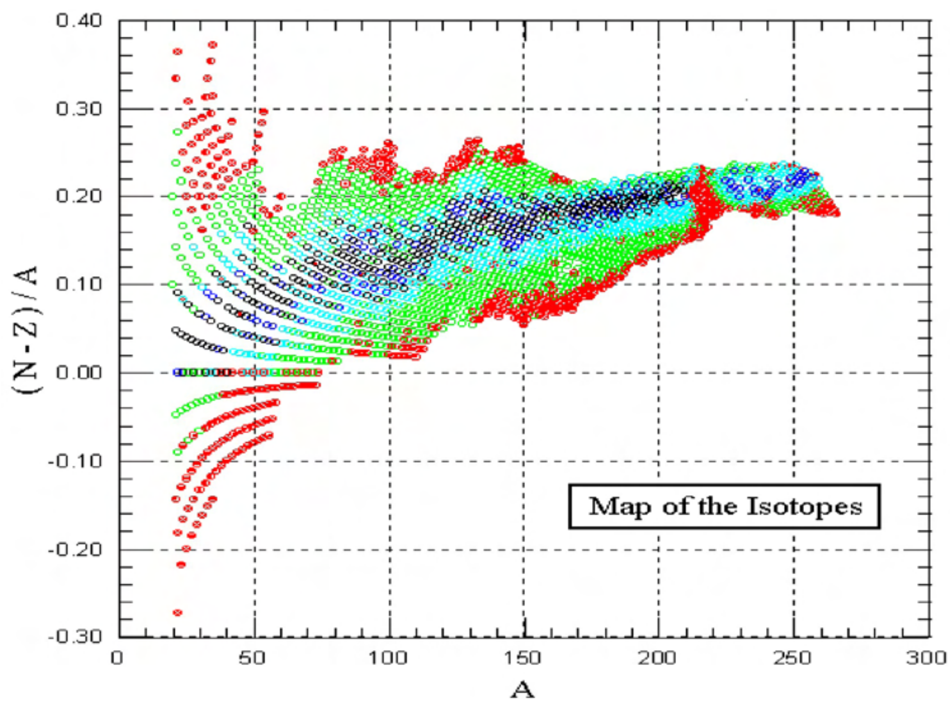
ANL/NDM-168

Report on the Workshop "Decay Spectroscopy at CARIBU: Advanced Fuel Cycle Applications, Nuclear Structure and Astrophysics"

14-16 April 2011, Argonne National Laboratory, USA

Nuclear Data and Measurements Series



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Report on the Workshop "Decay Spectroscopy at CARIBU: Advanced Fuel Cycle Applications, Nuclear Structure and Astrophysics", 14-16 April 2011, Argonne National Laboratory, USA

Nuclear Data and Measurements Series

by M.P. Carpenter[1], P. Chowdhury[2], J.A. Clark[1], F.G. Kondev[3], C.J. Lister[1], A.L. Nichols[4] and D. Seweryniak[1]

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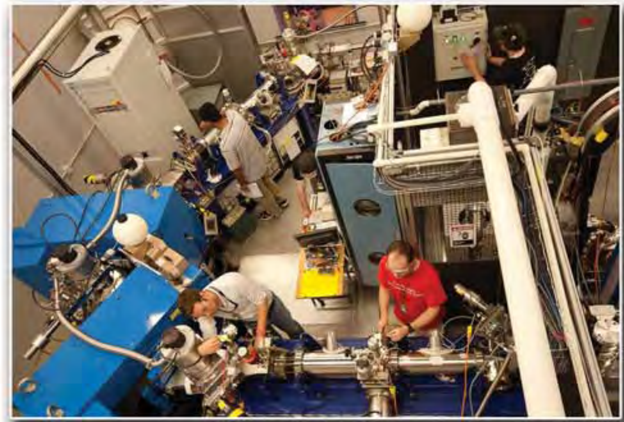
July 2011

Workshop on "Decay Spectroscopy at CARIBU: Advanced Fuel Cycle Applications, Nuclear Structure and Astrophysics"

Argonne
NATIONAL LABORATORY



A workshop on "Decay Spectroscopy at CARIBU: Advanced Fuel Cycle Applications, Nuclear Structure and Astrophysics" will be held at Argonne National Laboratory on **April 14-16, 2011**.

The aim of the workshop is to discuss opportunities for decay studies at the Californium Rare Isotope Breeder Upgrade (CARIBU) of the ATLAS facility with emphasis on advanced fuel cycle (AFC) applications, nuclear structure and astrophysics research. The workshop will consist of review and contributed talks. Presentations by members of the local groups, outlining the status of relevant in-house projects and available equipment, will also be organized. Time will also be set aside to discuss and develop working collaborations for future decay studies at CARIBU.

Topics of interest include:

- Decay data of relevance to AFC applications with emphasis on reactor decay heat
- Discrete high-resolution gamma-ray spectroscopy following radioactive decay and related topics
- Calorimetric studies of neutron-rich fission fragments using Total Absorption Gamma-ray Spectrometry (TAGS) technique
- Beta-delayed neutron emissions and related topics
- Decay data needs for nuclear astrophysics

Workshop Organizers

Dr. Michael Carpenter, Argonne National Laboratory
Prof. Partha Chowdhury, University of Massachusetts Lowell
Dr. Jason Clark, Argonne National Laboratory
Dr. Filip Kondev, Argonne National Laboratory
Dr. Kim Lister, Argonne National Laboratory
Dr. Dariusz Seweryniak, Argonne National Laboratory

Please visit the Workshop web site for additional information about registration, program, lodging and transportation to Argonne.

http://www.ne.anl.gov/capabilities/nd/AFC-Apr11/

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Workshop on "Decay Spectroscopy at CARIBU:
Advanced Fuel Cycle Applications, Nuclear Structure and Astrophysics"
April 14-16, 2011, Argonne National Laboratory
Physics Division, Building 203 Auditorium, Argonne, Illinois

Never miss important updates of this file: download the original pdf at http://www.ne.anl.gov/capabilities/nd/AFC-Apr11/

Program

Thursday, April 14th, 2011

8:00-9:00		Registration
9:00-9:15	R. V. F. Janssens	Welcome
9:15-9:30	K. Lister/F. G. Kondev	Workshop Plans & Goals

Session I

Chair	*P. Garrett*	
9:30-10:00	R. N. Hill (ANL)	Role of Decay Heat in Advanced Fuel Cycles
10:00-10:30	J. Tain (IFIC-U. Valencia)	Total Absorption Spectroscopy Technique and Applications
10:30-11:00		Coffee Break
Chair	*K. Nollett*	
11:00-11:30	P. Möller (LANL)	Nuclear Structure of Neutron-Rich Nuclei in the Fission Product Region - A Theoretical Perspective
11:30-12:00	F. A. Montes (MSU)	Understanding the *r*-Process
12:00-12:30	R. A. Surman (Union College)	Nuclear Data and *r*-Process Nucleosynthesis
12:30-1:30 A&B		Lunch (on your own) at the Cafeteria - Seating in Dining Rooms

Session II

Chair	*A. M. Bruce*	
1:30-2:00	K. Lister (ANL)	Nuclear Structure Opportunities
2:00-2:20	G. Savard (ANL)	CARIBU Status & Schedule
2:20-2:40	R. C. Pardo (ANL)	CARIBU and ATLAS
2:40-3:00	N. D. Scielzo (LLNL)	Decay Correlations & BPT
3:00-3:30		Coffee Break
Chair	*P. Chowdhury*	
3:30-3:50	D. Seweryniak (ANL)	Decay Station
3:50-4:10	M. P. Carpenter (ANL)	Digital Gammasphere
4:10-4:30	J. A. Clark (ANL)	First Measurements with the Canadian Penning Trap at CARIBU
4:30-4:50	P. Mueller (ANL)	Laser Spectroscopy at CARIBU
4:50-5:10	B. B. Back (ANL)	HELIOS
5:10-5:30	TBD	EXO Experiment
5:30-6:30	J. A. Clark & S. Zhu	Tour of CARIBU & ATLAS
7:00-10:00		Dinner at the Guest House

Friday, April 15th, 2011

Session III		
Chair	*W. B. Walters*	
9:00-9:30	A. L. Nichols (U. Surrey)	Power Reactor Decay-Heat Calculations: Identifying Fission Products to Benefit from Study by Means of Total Absorption Gamma-Ray Spectroscopy (TAGS)
9:30-10:00	A. Algora (IFIC-U. Valencia)	Beta-Delayed Neutrons - Physics and Detection
10:00-10:30	K. P. Rykaczewski (ORNL)	Decay Spectroscopy of Fission Products for Nuclear Fuel Cycle at the HRIBF
10:30-11:00		Coffee Break
11:00-12:00	B. Rubio (U. Valencia)	Physics Colloquium
12:00-1:30		Lunch (on your own) at the Cafeteria
Session IV		*Presentation by Participants*
Chair	*G. J. Lane*	
1:30-1:55	P. Garrett (U. Guelph)	The Decay Spectroscopy Program with the 8 π Spectrometer at TRIUMF: Lessons Learned and Future Plans
1:55-2:20	W. B. Walters (U. Maryland)	Radioactivity Studies at TRISTAN and ISOLDE: from Ag to Pr
2:20-2:40	V. R. Werner (Yale U.)	Decay Studies at Yale University
2:40-3:00	F. G. Kondev (ANL)	Shape-Changes and Isomers in Neutron-Rich Zr-Mo-Ru Nuclei
3:00-3:30		Coffee Break & Workshop Picture
Session V		*Presentation by Participants*
Chair	*G. S. Hackman*	
3:30-3:50	W. A. Schier (U. Mass. Lowell)	Neutron-Induced Fission Product Studies at 0.17 to 50000 s after Fission - A Review of Past Practices
3:50-4:10	M. P. Karny (U. Warsaw)	Modular Total Absorption Spectrometer (MTAS) for Decay Heat Studies of Fission Products
4:10-4:30	R. B. Firestone (LBNL)	Measurements of $^{117-121}Xe$, $^{117-124}Cs$, and $^{123,124}Ba$ EC Decays with the LBNL Total Absorption Spectrometer
4:30-4:50	T. Kawano (LANL)	Beta-Delayed Gamma Emission by Combining the Statistical Model with Nuclear Structure Data
4:50-5:10	M. L. Smith (ANU)	Development of a Monte-Carlo Model for the Argonne Total Absorption Gamma-Ray Spectrometer
5:10-5:30	A. M. Bruce (U. Brighton)	Lessons from the RISING Decay Campaign
5:30-5:50	M. Madurga (U. Tenn.)	Recent Results from the Low Energy Radioactive Ion Beam Spectroscopy Station
5:50-6:10	S. L. Tabor (Florida State U.)	Beta-Gamma Spectroscopy Experience with Fragmentation and ISOL Beams
After 6:10		Dinner on your own. Please check the Workshop Web Site for a list of local restaurants.

Saturday, April 16th, 2011

Session VI		*Presentation by Participants*
Chair	*S. L. Tabor*	
9:00-9:20	S. P. Lalkovski (U. Sofia)	Single-Particle States and Transition Probabilities Around ^{132}Sn
9:20-9:40	A. Y. Deo (U. Mass. Lowell)	Isomer Studies Using CPT at CARIBU
9:40-10:00	B. M. Bucher (U. Notre Dame)	Decay Spectroscopy of Neutron-Rich Nuclides Near A $\sim$ 110
10:00-10:20	G. J. Lane (ANU)	Research Possibilities with CARIBU Beams and Associated Measurement Methods
10:20-11:00		Coffee Break
11:00-12:00		*The Practicalities of CARIBU Decay Spectroscopy Studies*
Chair	*K. Lister*	
	R. V. F. Janssens	PAC & Scheduling
		The Beam Setup
	K. Lister & F. G. Kondev	Collaborations & Conclusions

1 Introduction

The primary aims of the CARIBU workshop were to stimulate interest in, and discuss the opportunities for, nuclear physics studies at the CAlifornium Rare Isotope Breeder Upgrade (CARIBU) ion source at the ATLAS facility. Particular emphasis was placed on advanced fuel cycle (AFC), nuclear structure and astrophysics research studied through decay studies of fission fragments. The workshop was attended by over 70 nuclear physicists from around the world (of which approximately 20 came from within Argonne National Laboratory), beginning on Thursday, 14 April 2011, and ending at noon on Saturday, 16 April 2011.

The extensive technical program consisted of a series of review and contributed presentations, along with additional talks by local groups describing the status of their relevant in-house projects and available equipment. All of the presentations from the workshop can be found at the following Web site:

http://www.ne.anl.gov/capabilities/nd/AFC-Apr11/program.shtml

Time was also set aside to discuss and develop working collaborations for future studies at CARIBU, and the practicalities of organizing and running experiments. Topics of interest included:

- decay data of relevance to AFC applications with emphasis on reactor decay heat,
- discrete high-resolution gamma-ray spectroscopy following radioactive decay and related topics,
- calorimetric studies of neutron-rich fission fragments by means of the Total Absorption Gamma-ray Spectrometry (TAGS) technique,
- beta-delayed neutron emissions and related topics, and
- decay data needs for nuclear astrophysics.

The above goals and their critical value to the evolving program were spelled out clearly in the welcome address by R.V.F. Janssens (ANL), followed by C.J. Lister and F.G. Kondev (ANL) in their opening remarks as the main organizers of the workshop. Strong emphasis was placed on the "User Facility" operation of CARIBU and the need for input from the community of potential users concerning both the science and operation of the facility.

2 Session I

2.1 Role of Decay Heat in Advanced Fuel Cycles (R.N. Hill)

During the course of a comprehensive overview of proposed advanced fuel cycles within the USA, R.N. Hill (ANL) focused attention on the quantification of decay heat and nuclear data needs in their safety management. Brief descriptions of the three generic forms of fuel cycles were noted: once-through systems, modified once-through systems with fuel treatment and at least one re-burn procedure, and complete fuel recycling systems. All three types of fuel cycles have well-defined performance and safety goals. Waste management issues are identified with the following timescales after fuel irradiation:

- short-term – reactor safety,
- medium-term – maintenance of adequate cooling, and
- long-term – design and utilization of repository associated with geological disposal.

Short-term decay heat up to 200 s after shutdown is primarily identified with continued fission multiplication driven by delayed-neutron precursors, with radionuclide decay becoming of significance after ~ 100 s. Beyond 200 s after shutdown, α-, β- and γ-decay processes play a much more dominant role. Furthermore, throughout this medium/long timescale, resulting gamma rays and particle emissions are useful in radionuclide detection, and allow the rapid identification of fissionable material of importance in fuel management.

Consideration has been given to the long-term environmental burden of nuclear energy (removal of transuranics from waste), enhanced extraction of energy by recovery of uranium from spent irradiated fuel for re-utilization, enhanced safeguards through improved spent fuel management, and more competitive fuel-cycle economics. Higher uranium consumption is envisaged: 20%-50% for modified once-through systems, and > 90% for fully recycled systems based on the standard fast-neutron breeder with complete conversion of ^{238}U to ^{239}Pu.

All waste material is assumed to be contained in an engineered repository for ~ 10,000 years, with the long-term dose resulting from the ^{237}Np decay chain. The radiotoxic hazard is identified with complete release and uptake on this timescale. Such repositories are constrained by the heat load which is specified in terms of the following:

- peak temperatures below the local boiling point of 96°C at all times midway between adjacent storage drifts, and
- drift wall reaching peak temperatures below 200°C.

There are various potential treatments that would improve the integrity of the radionuclide loading of a repository drift:

- separate from Pu and Am (factor of 6, with 99.9% removal),
- separate from Cs and Sr (factor of 50, with 99.9% removal), and
- removal of Cm (greater than a factor of 100, with 99.9% removal).

Long-term decay heat, radiotoxicity and dose are dominated by the $^{241}Pu \rightarrow ^{241}Am \rightarrow ^{237}Np$ decay chain. Thus, some form of separation process(es) is required to extract and consume transuranic nuclides elsewhere by means of a high burn-up strategy (closed fuel cycle with actinide management). Under these circumstances, emphasis is placed on the domination of actinide decay heat ~ 60 years after fuel irradiation and discharge – while fission products are important for decades and are addressed by well-controlled spent-fuel storage, actinides impact significantly on the safe design of a final disposal repository to be adopted beyond 200 years.

2.2 *Total Absorption Spectroscopy Technique and Applications (J.L. Tain)*

J.L. Tain (IFIC – Univ. Valencia, Spain) presented an extensive review of Total Absorption Gamma-ray Spectroscopy (TAS/TAGS), outlining the nature and advantages of the technique for the measurement of β intensities/strengths (I_β and S_β), particularly for complex decay schemes. TAS spectral analyses can be complex, and much effort has been expended in recent years to improve the models adopted to determine I_β (S_β). The Valencia group has carried out systematic studies of the uncertainties in TAS, demonstrating the accuracy of Monte-Carlo simulations to obtain the spectrometric response and calculating pulse pile-up with good accuracy to give the intrinsic background close to the endpoint. Various algorithms have also been investigated to derive the optimum method of solving the problem of TAS inversion.

A number of powerful 4π detector systems have been assembled over the previous 40 years to measure full gamma cascades, and so avoid spectral omissions that give rise to what is commonly described as the Pandemonium effect (erroneous lack of detection of gamma strength by Ge-based detectors that also results in erroneous gains in the proposed beta strengths). Various TAS facilities were described: ISOLDE/OSIRIS (new detector - Lucrecia), LNPI, INEL and LBNL (at GSI), culminating in recent work at Valencia-Jyväskylä. The latter involves refractory sources purified and prepared by means of IGISOL and the JYFLTRAP Penning trap, followed by gamma strength studies by the PNPI TAS – future studies will involve detectors consisting of segmented BaF_3 crystals (as designed and assembled by co-workers at the University of Surrey).

The Valencia-Jyväskylä experimental campaigns in 2008 to 2010 focused on potential Pandemonium fission products ($^{86,87,88}Br$, ^{101}Nb, $^{102,104,105,106,107}Tc$, ^{105}Mo and ^{137}I), with significant success achieved in improving the input data for decay heat calculations of ^{239}Pu thermal-neutron fission. This work, along with studies of anti-neutrino spectral oscillations, continues to assist in the continuous non-invasive monitoring of reactor plants in order to detect and deter clandestine operations.

Beta-strength measurements close to the third *r*-process peak have also been proposed to test and improve the predictive capabilities of the theoretical models for element/nuclide formation in astrophysics (^{204}Au, $^{203,204}Pt$, ^{201}Ir, etc.). Such unusual experiments are accessible at GSI Darmstadt. Other relevant work under development was also highlighted: NUSTAR collaboration and DESPEC experiment (AIDA – stack of DSSSD); $LaBr_3(Ce)$ prototype detector; NaI(Tl) prototype detector (150 x 150 x 250 mm^3 crystal, with Teflon reflector/damper and aluminum containment).

2.3 *Nuclear Structure of Neutron-rich Nuclei in the Fission Product Region – A Theoretical Perspective (P. Möller)*

P. Möller (LANL) provided a theoretical prospective to the nuclear structure of neutron-rich nuclei in the fission-product region, based on an evolutionary process of model developments from the early 1980s onwards. Much of the material presented in this semi-historic manner can be found in more detail within papers on Web site: http://t16web.lanl.gov/Moller/abstracts.html

Calculations of nuclear binding energies based on the FRLDM (Finite-Range Liquid-Drop Model) have been compared with experimental data across almost the full chart of the nuclides in 1981 (P. Möller and J.R. Nix, *Nucl. Phys.* **A361** (1981) 117) and again in 1995 (P. Möller *et al*., *At. Data Nucl. Data Tables* **59** (1995) 185) after making various refinements to the macroscopic-microscopic model – over this 14-year timeframe of improvements, discrepancies between calculation and experiment had been reduced across the mass range of study. Reasonable agreement has also been observed between 1992 calculations of nuclear masses and the more recent 2003 atomic mass evaluation of Audi *et al*., *Nucl. Phys.* **A729** (2003) 337 (also known as AME2003), although this agreement was found to be more substantial for neutron-deficient than neutron-rich nuclei. Nuclear mass calculations carried out with an unpublished 2009 version of FRLDM agree to an accuracy of 0.5788 MeV with respect to AME2003. Furthermore, this approach to the modelling of nuclear structure generates a large amount of parametric data that goes far beyond that available from laboratory measurements. Thus, theoretical studies can confidently be applied to nuclides beyond the mass limits of the AME2003 evaluations to explore detail within the *r*-process of astrophysics. However, significant issues still remain within the available model, not least the need to improve the predictive abilities for lighter nuclei ($N \leq 60$).

A global study of nuclear shape isomers has been completed, and a paper will appear soon in *At. Data Nucl. Data Tables*. Furthermore, the macroscopic-microscopic method within the FRLDM (1992) of nuclear ground-state masses and shapes has been enhanced to perform:

(a) global calculations of nuclear shape isomers in which the ground-state and isomer minima are characterized in terms of their relative energies and shapes; and
(b) calculations of fission potential-energy surfaces for more than five million different shapes for each of 5254 nuclei from A = 170 to 330 (see P. Möller *et al*., *Phys. Rev.* **C79** (2009) 064304).

An appropriate treatment of dynamic evolution within five-dimensional potential-energy space is sufficiently retractable to permit modern computers to explore the deformation of all nuclei at excitation energies above the fission barrier. Saddles, minima and valleys can be determined in an automatic manner for storage as comprehensive data sets:

- energy release as a function of proton number,
- axial symmetry defined in terms of spherical deformation, and
- evolution and quantification of spherical, elongated and dumb-bell shaped geometries for nuclei (e.g. ^{242}Am).

Observed features such as energy thresholds for symmetric and asymmetric fission, and fission-fragment mass and kinetic-energy distributions are closely related to the properties of the valleys and passes found in the calculated five-dimensional energy landscapes. A fission-yield model has also been developed recently and applied to the 5254 nuclei to good effect.

A combinatorial level-density model with folded-Yukawa single-particle levels is in the process of being finalized to derive level densities at the calculated barrier shapes. The fission-yield model will be improved further to take into account the metric of the deformation grids, and efforts will continue to improve the mass model for light nuclei, as well as apply the various theoretical improvements to astrophysical calculations. A final comment was also made with respect to CARIBU which can be expected to provide experimental data of high value to these theoretical models, particularly above N = 60 and far from the line of stability.

2.4 *Understanding the r Process (F.A. Montes)*

While the r-process as proposed for element formation in the cosmos is well-defined, numerous uncertainties arise when considering the existence and nature of the actual reaction sequences. F.A. Montes (MSU) posed a series of questions that need to be addressed and resolved if mankind's understanding of the formation of the universe is to advance substantially:

- where does the *r* process occur?
- what are the reaction sequences?
- are there multiple processes in the early galaxy?
- what does the *r* process tell us about extreme environments?

Old stars are defined as "metal poor", based on plots of [Sr/Eu] against [Eu/Fe] ratios that exhibit a marked, systematic decline in [Eu/Fe] with increasing [Sr/Eu]. The Light Element Primary Process (LEPP) generates elements that are heavier than Sr with some suggestion that only Sr to Ag may be produced, while the formation of heavy elements (Z > 30) occurs by means of both slow (s) and rapid (r) neutron-capture processes.

Most nuclides postulated to form in the *r* process have yet to be prepared and studied, but are known to arise in the merging neutron stars. However, the merging rates are believed to be too low to explain the Eu/Fe ratios, and the composition of the ejected material remains unknown. Other evidence for the *r* process has been identified with the detection of gamma-ray bursts and the behavior of supernovae. The hot *r* process takes place under (n,γ)-(γ,n) equilibrium, and the associated nuclear data requirements can be specified:

- atomic masses (by Penning trap),
- half-lives (stacked Si detectors combined with gamma-ray spectroscopy),
- neutron-capture rates,
- neutron emission probabilities, and
- possibly fission and neutrino interaction rates.

These needs are very similar to those of the cold *r* process, which involves competition between β^- decay and neutron capture:

- neutron-capture rates (atomic masses),
- half-lives,
- neutron emission probabilities, and
- possibly fission and neutrino interaction rates.

CARIBU is capable of producing *r* process nuclides for mass measurements from atomic number 30 to 40 and 46 to 52. β^- spectroscopic studies should be undertaken with these sources to determine:

a) β^--delayed neutron branching ratios extending to $^{82,83}Zn$, $^{85,86}Ga$, $^{88,89}Ge$, ^{89}As, ^{94}Se and ^{96}Br,
b) progenitor of Sc, Y and Zr abundances in order to shed light on the main *r* process and LEPP, and
c) basic nuclear physics from A = 80 to 95.

CARIBU mass measurements will have a direct effect on *r* process calculations, and will address shell closure at N = 82. In addition, half-life and P_n measurements will better establish the nuclear physics involved in the *r* process identified with the Sr, Y and Zr abundances.

2.5 *Nuclear Data and r-Process Nucleosynthesis (R.A. Surman)*

The astrophysical importance of rapid neutron-capture nucleosynthesis (*r* process) and the links to various nuclear physics parameters were described by R.A. Surman (Union College). Significant nuclear solar abundances at the (Z,N) locations of (30,50), (48,82) and (69,126) were noted, and the nuclear data requirements to understand the evolution and existence of supernovae, neutron-star mergers, gamma-ray bursts and other deep-space phenomena were defined:

a) atomic masses,
b) β^--decay rates,
c) neutron-capture rates (particularly β^--decay chains of closed-shell nuclei, and nuclei in the lanthanide region),

d) neutrino interaction rates, and
e) fission probabilities and daughter product distributions.

A neutrino-driven wind process has been proposed within supernova, but the necessary conditions for core collapse could not be realized in calculations of this *r* process. Compact mergers have also proved to be a promising approach, but the timescales are inconsistent with the available data.

Theoretical and experimental data for nuclear masses, β^--decay rates and β^--delayed neutron emission rates were compared. Examples were presented on β^--delayed neutron emission that provides a break on neutron-capture reactions, and can move this process to a later position for *N* = 126. Neutron-capture rates influence the onset of neutron freeze-out and affect the local and overall abundance distributions. Individual neutron-capture rates can make global changes to abundances - thus, the ^{131}Cd(n,γ)^{132}Cd reaction will steal neutrons from within a system, reducing and preventing neutron-capture reactions by other nuclei. Finally, the precise form and location of the *r* process remains unknown, while quantification and understanding the nuclear physics of the neutron-rich nuclei will be crucial in comparing observations with theoretical simulations.

3 Session II

3.1 Nuclear Structure Opportunities (C.J. Lister)

C.J. Lister (ANL) provided insights into a range of possible opportunities provided by CARIBU to explore nuclear structure, including experimental studies of modifications to single-particle states, pairing correlations, and new shapes and collective modes. Such work could focus on deviations from normal observations of the P-scheme and Grodzin's rule, with efforts made to pursue the formation of mixed symmetry states (new shapes and shape transitions – X(5), octupoles, tetrahedrons, etc.).

Effort should be expended to find and study new even-even nuclei within the *Z* and *N* ranges of 64 to 70 and 104 to 112, respectively, and the deformation inferred from B(E2: 2->0) and B(E2: 4->2)/B(E2: 2->0) measurements. Direct electronic timing techniques have long been established for the measurement of sub-nanosecond states, but the opportunity should also be taken to study and test new scintillators with good energy resolution and timing (e.g. $LaBr_3$(Ce) and SrI_2). Many specialists would also accept that any proposed decay-data studies will require a strong combination of HPGe-scintillator spectroscopy.

Vibrational bands are very important in quantifying nuclear deformation, and can be studied in CARIBU for highly neutron-rich nuclei. Other questions to be addressed could include the existence and form of β bands, identification of the lowest $J^\pi = 0^+$ (pairing isomers), and the γ bands of vibrational as opposed to rigid nuclei. The example of neutron-rich barium nuclei was described – fission-fragment spectroscopy and β^--decay studies have revealed the existence of parity-doublet bands, but there is virtually no quadrupole or octupole matrix element data. Key work in such studies would be the β⁻-decay of ^{146,148}La to nuclear levels of ^{146,148}Ce to measure the energies of non-yrast states, mixing ratios and branching ratios.

Beams of many new even-even nuclides deep into the lanthanide region will be produced, with odd-odd to even-even decays involving both low and high spin β⁻ decays. Axially deformed nuclei can be safely assumed (lanthanide rotors), but there may be some surprises in store. Examples of inadequate nuclear data were given , for example, in the ^{132}In β⁻ decay to ^{132}Sn the spin of only one state in ^{132}Sn has been firmly established, while about 20 levels are known in this key spherical even-even nucleus. Angular correlations following β-decay should redeem this shortcoming. Neutron-rich Sr, Y and Zr nuclei possess some of the largest ground-state deformations known, and some surprises may still lie undiscovered in this particular area. These latter nuclei are refractory and hard to produce in traditional ISOL facilities, so data are still sparse.

3.2 *Commissioning Trials and Status of CARIBU*

A series of informative presentations were made that described the status and proposed experimental studies to be initiated at CARIBU. The facility will provide neutron-rich radioactive beams for re-acceleration through ATLAS up to 15 MeV u^{-1}, as discussed by G. Savard and R.C. Pardo (ANL). Descriptions of particle production, control and analysis included the ^{252}Cf sources, gas catcher/RFQ cooler, isobar separator, low-energy buncher, charge breeder, beam diagnostics and experimental analysis equipment to determine atomic masses, decay data and other nuclear parameters. Work is completed or on schedule for all of the main components, including ongoing operational studies with 2.5- and 100-mCi ^{252}Cf sources. Ion extraction yields at low energy (50 keV) for 1 Ci ^{252}Cf source are estimated to be of the order of 20% of the total activity, and this performance would apply to all nuclides. With a mass resolution of 1/8,000, efforts are focussed on improving this value up to 1/20,000 along with the transmission efficiencies. Sixty-five species will be produced at accelerated intensities over 10^5 s^{-1} and further 150 additional species at 10^4 s^{-1}.

Ion-trap studies in support of β⁻-spectroscopy measurements were reported by N.D. Scielzo (LLNL). This method of isolation and analysis is most suited to the handling of difficult-to-measure particles – nuclei are suspended nearly at rest in a vacuum, and the activity is localized in a well-defined geometry. A β⁻-decay Paul Trap (BPT) has been constructed for decay-data studies, in which the ions are confined by means of RF and DC electric fields in a 1-mm^3 volume surrounded by an open geometry layout to accommodate four sets of HPGe and DSSD detectors. Measurements of ^{8}Li β⁻-decay angular correlation have been performed to good effect online.

Based on all aspects of consideration, the physics of β⁻-delayed neutrons emerged from the workshop as most important in the improvement of reactor control, "cold" *r* processes, strength functions and nuclear structure. The "open trap" developed for β⁻-neutrino correlations offers a new method for studying β⁻-delayed neutrons. Velocity spectra of β^--delayed neutrons can be inferred from the recoil of the parent emitter. This concept would appear to be very powerful, and was discussed with enthusiasm for future facilities. A proof-of-principle experiment has been conducted as part of an off-line fission study of ^{137}I β–n decay with detector-array efficiencies of 3% and beams of 30 ions s^{-1}. There is much room for improvement in the efficiency of the set-up, and a dedicated trap will eventually be needed for these studies. This improvement, together with the beams from CARIBU, should encourage a new era of β^--delayed neutron spectroscopy.

Equipment developments identified with the decay-data station were described by D. Seweryniak (ANL):

- HPGe – high-resolution γ-ray spectroscopy,
- NaI – high-efficiency γ-ray spectroscopy,
- $LaBr_3$ – good energy resolution for short half-lives,
- Si/plastic – β^- particles,
- neutron detector – β^--delayed neutrons, and
- three moving-tape collectors to achieve a significant reduction in background.

The X-array consists of five clover detectors in a box-like geometry, of which four are 60 x 60 mm^2 (~ 200% each) and one 70 x 70 mm^2 (~ 300%) to be dedicated to CARIBU and FMA. Beta-veto plastic paddles will be used to identify β^- particles entering the Ge detectors. With automatic liquid-N_2 filling systems, each detector can be moved independently along its axis, and the complete array can also be moved as a unit. The FMA implantation-decay station also possesses a number of detectors: HPGe clovers, large-area Si crystal, Si/PIN, plastic β^- detectors and 160 x 160 mm^2 DSSD. The design of all three tape transport systems under test has been commonly adopted elsewhere, and they will be located as follows to assist in various key functions:

- CARIBU diagnostics,
- ATLAS diagnostics, and
- research
  – beam line for the X-array and TAGS, FMA, and Gammasphere.

Important operational issues for consideration at the decay station include fission yields, isobaric purity, background activity and transport times.

M.P. Carpenter (ANL) reminded workshop participants that Gammasphere can accommodate up to 110 Compton-suppressed Ge detectors, each with a relative efficiency of 70% to 75%. Gammasphere provides near 4π angular coverage to determine total γ-ray energy, precise γ-γ angular correlations to derive level spins and parities, and high coincidence efficiency to assist in the assessment of nuclear level structure. Several options are being considered for transporting CARIBU activities to GAMMASPHERE, including a separate transport line, drifting activity through ATLAS, modest acceleration and transport, or a helium jet system. When the tandem Van de Graaff is retired, it may be possible to relocate GAMMASPHERE close to CARIBU for a campaign of research. Current limitations of the Data Acquisition system for Gammasphere, which was originally optimized for high multiplicity physics, include Ge-shape processing times of ~ 10 μsec (resulting in ~ 6% pileup at 10,000 cps, and 30% pile-up at 50,000 cps), and inoperable DAQ over at least 25 μsec for triggered events. Hence, the analog electronics will be replaced with a digital-pulse processing system based on the ten-channel GRETINA digitizer module in order to achieve the following:

- decrease in the processing time of the Ge shaper to ~ 2 μsec,
- improvement of throughput limits,
- permit Gammasphere to accumulate data in excess of a factor of five times the current rates, and
- extend studies in the ^{100}Sn region, Z > 100, and exotic hyperdeformation modes.

As discussed by J.A. Clark (ANL), the Canadian Penning Trap (CPT) with a prototype gas catcher delivery system has been used in recent years to study ~ 70 neutron-rich nuclides. One important aim during the CARIBU project will be to measure a further ~ 100 neutron-rich masses that have previously never been determined. The ion beam from CARIBU will pass through an electrostatic deflector located beyond the gas catcher and isobar separator to direct ions into the low-energy delivery line. Masses are measured in CPT by determining the cyclotron frequency:

$$\omega_c = \frac{qB}{m}$$

in which ω_c depends on the magnetic field strength (B) and mass (m) of the ion as determined from a time-of-flight spectrum. CPT has already been moved and re-commissioned in close proximity to the CARIBU/ATLAS beam line. Further improvements are required to the transport efficiency (currently ~ 20% from buncher to CPT), along with the need to check reference masses and reduce the impact of contaminant ions.

P. Mueller (ANL) outlined the introduction of laser spectroscopy into the CARIBU project to measure isomer shifts, nuclear charge radii, hyperfine structure and nuclear moments. The laser laboratory will be located in place of the CPT after the initial campaign. High spectroscopic resolution and sensitivity will be achieved in order to study Rh and Ru with this technique for the first time, and extend work already begun on various isotopic chains (e.g. Mo and Nb). Cold bunched beams will reduce the spread of ion energy, and the open geometry of a liquid-N_2 cooled linear Paul trap will ensure a large light-collection efficiency and sensitivity to single-ion detection. Experimental studies are now required to investigate the conditions for optimal operation, buffer gas quenching with H_2, and cooling with liquid N_2. Nuclear spin polarization and magnetic moment measurements with optical pumping are proposed in a solid noble-gas matrix (Ne-Xe), and feasibility studies have begun with Yb and other lanthanides. Points of note include the following:

- limitations on isotopic yields,
- potential of laser spectroscopy dependent on each element (not universal),
- tight space limits in the low-energy beam area of CARIBU, and
- possibility of combining laser spectroscopy and decay-data measurements into a very powerful nuclear analysis technique.

Direct light-ion reactions on stable nuclei have provided much spectroscopic information on nuclei, especially details of the wave functions of spherical and near spherical nuclei. Historically, these studies have been limited to the valley of stability. However, the adoption of inverse kinematics with radioactive beams has provided access to direct reactions for all nuclei that can be produced in beams of $>10^5$ particles s^{-1}. The traditional approach to such experiments involves the use of magnetic spectrometers, but they have far too low an efficiency for radioactive beam physics. An alternative is arrays of segmented silicon detectors, which has been aggressively pursued. However, such studies pose their own problems that arise from ($\Delta E - E$) identification at low energies, kinematic compression, and strong angle dependency. Many of these difficulties have been overcome by the HELIOS demonstrator project, which was described in detail by B.B. Back (ANL). A highly homogeneous magnetic field is to be maintained along the flight path of the radioactive ion beam, which has been achieved by acquiring and modifying a Magnetic Resonance Imaging (MRI) scanner obtained from Germany. This field contains all the reaction products and makes them spiral back to the beam axis where they can be detected in a modest silicon array. The measured quantities are the flight time, position and energy of the ion under study that permit derivation of the identity, energy and axial position (angle) of the particle beam. A prototype array of Si detectors in the form of extended probes have been successfully tested within the MRI chamber by means of the inverse $d(^{28}Si,p)^{29}Si$ and $d(^{136}Xe,p)^{137}Xe$ reactions to produce well-resolved proton-emission spectra. Various improvements continue to be made to the equipment, including the addition of a PPAC + Bragg recoil detector acquired from the University of Manchester, development of gas targets to study the (^{3}He,p), (^{3}He,d) and (^{3}He,α) reactions, 2-cm wide silicon wafers to function as full-efficiency backward arrays, and the introduction of forward Si-detector arrays.

Finally, G. Savard (ANL) briefly mentioned a proposal to assist in the study of double-beta decay as an adjunct to the EXO-200 project:

$$^{136}_{54}Xe(\beta^-\beta^-)^{136}_{56}Ba^{2+}$$

One aim would be to measure the lifetime of the Ba^{2+} ion in a solid Xe matrix which could be attempted in CARIBU.

At the conclusion of the day's proceedings, attendees were given an extensive tour of ATLAS, which included the partially-assembled CARIBU facility, Gammasphere, Fragment Mass Analyzer (FMA), Canadian Penning Trap (CPT), and other important beam-handling and analysis equipment.

4 Session III

4.1 Power Reactor Decay-heat Calculations: Identifying Fission Products to Benefit from Study by Means of Total Absorption Gamma-ray Spectroscopy, TAGS (A.L. Nichols)

Commercial nuclear power plants require various types of analytical study to ensure their safe and efficacious operation, and most specifically with respect to the determination of the decay heat of irradiated fuel at and beyond shutdown and in the case of severe reactor accident scenarios. Under these circumstances, A.L. Nichols (Univ. of Surrey, UK) judged that relevant actinide decay-chain data are in reasonably good order and activation-product decay data are well defined. However, the decay data of a number of fission products within a total of just over 1000 contribute significantly to decay heat while remaining poorly characterized. This unsatisfactory situation can be explained in terms of certain radionuclides emitting high-energy gamma rays that are undetected by high-resolution, low-efficiency Ge-based spectrometers (Pandemonium effect).

Sensitivity studies have been conducted over many years and acted as a focus for data improvements, with the most noteworthy arising from Schmittroth in the 1970s. Uncertainties in the resulting β, γ and total decay heat of individual fissioning actinides were quantified as a function of the cooling time, and broken down in terms of the contributions of the estimated uncertainties of the independent and cumulative fission yields, decay constant (related in a simple fashion to the half-life), and decay energy of each fission product. Thus, priority lists for improved data can be formulated as a function of cooling time. This type of sensitivity study has been undertaken specifically to address the significant lack of agreement between decay-heat benchmark measurements and calculations for thermal-neutron irradiated U-Pu fuel between cooling times of 0 and 20 s and 300 and 3000 s (see figure, below).

Assessments by Yoshida *et al*. in 1997/1999 involved the artificial addition of a two-nuclide β^--decay chain with an energy release of 1.5 MeV per decay which reduced the discrepancy between 300 and 3000 s cooling time – the proposed candidates for this additional release included ^{102,104,105}Tc.

Short-lived fission products with high-energy gamma rays and half-lives less than 1 m are difficult to characterise fully because of the low efficiency of HPGe detectors with respect to $E_\gamma > 1.5$ MeV (referred to as the Pandemonium effect). This inability to detect low-intensity, high-energy gamma transitions results in the erroneous reduction in the proposed γ-strength and a concomitant incorrect increase in the β-strength. Total Absorption Gamma-ray Spectroscopy (TAS/TAGS) represents a most appropriate measurement technique for the quantification and elimination of this effect. Various TAGS studies have been made, of which the most significant from the point of view of fission product nuclides were carried out by Greenwood *et al*. at INEL in the 1990s. Example spectra were shown and modified nuclear level data were proposed, involving previously unobserved pseudo-levels introduced to explain the TAGS gamma data.

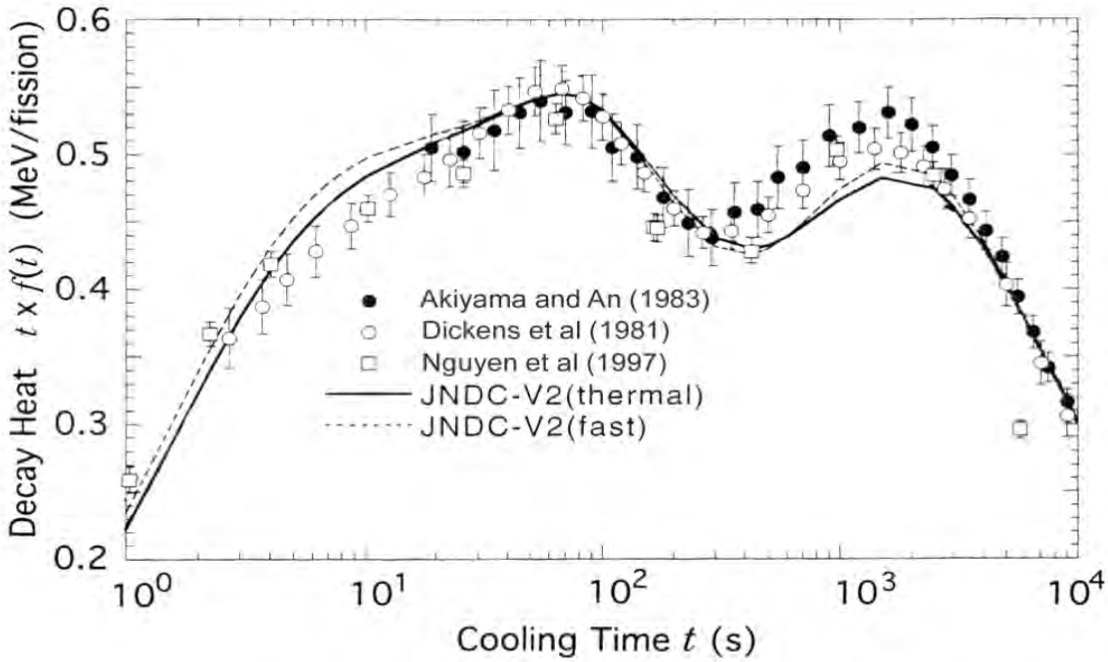


Fig.39 Gamma-ray discrepancies seen in ^{239}Pu decay heat after a fission burst (Yoshida et al, 1999).

Further sensitivity studies have been carried out recently under the auspices of an OECD-NEA Working Party on International Nuclear Data Evaluation Cooperation, Subgroup 25 (see OECD-NEA report No. 6284, NEA/WPEC-25, 2007), which brings the nuclear data requirements up to date for the U-Pu fuel cycle for decay heat calculations. The defined data needs were as follows:

Radionuclide	Priority	Q_β-value (keV)	Half-life
^{86}Br	1	7626 (11)	55.1 s
^{87}Br	1	6852 (18)	55.65 s
^{88}Br	1	8960 (40)	16.36 s
^{89}Kr	1	4990 (50)	3.15 min
^{90}Kr	1	4392 (17)	32.32 s
^{90}Rb^{m}	2	6690 (15)	258 s
^{92}Rb	2	8096 (6)	4.49 s
^{89}Sr	2	1493 (3)	50.53 d
^{97}Sr	2	7470 (16)	0.429 s
^{96}Y	2	7096 (23)	5.34 s

^{99}Zr	3	4558 (15)	2.1 s
^{100}Zr	2	3335 (25)	7.1 s
^{98}Nb	1	4583 (5)	2.86 s
^{99}Nb	1	3639 (13)	15.0 s
^{100}Nb	1	6245 (25)	1.5 s
^{101}Nb	1	4569 (18)	7.1 s
^{102}Nb	2	7210 (40)	1.3 s
^{103}Mo	1	3750 (60)	67.5 s
^{105}Mo	1	4950 (50)	35.6 s
^{102}Tc	1	4532 (9)	5.28 s
^{103}Tc	1	2662 (10)	54.2 s
^{104}Tc	1	5600 (50)	18.3 min
^{105}Tc	1	3640 (60)	7.6 min
^{106}Tc	1	6547 (11)	35.6 s
^{107}Tc	2	4820 (90)	21.2 s
^{132}Sb	1	5509 (14)	2.79 min
^{135}Te	2	5960 (90)	19.0 s
^{136}I	1	6930 (50)	83.4 s
^{136}I^{m}	1	7580 (120)	46.9 s
^{137}I	1	5877 (27)	24.13 s
^{137}Xe	1	4166 (7)	3.82 min
^{139}Xe	1	5057 (21)	39.68 s
^{140}Xe	1	4060 (60)	13.6 s
^{142}Cs	3	7308 (11)	1.69 s
^{145}Ba	2	5570 (110)	4.31 s
^{143}La	2	3425 (15)	14.2 min
^{145}La	2	4110 (80)	24.8 s

The TAGS group from Valencia attended the subgroup meetings held at the IAEA, Vienna, December 2005, and OECD-NEA, Paris, May 2006, and have subsequently performed measurements at the University of Jyväskylä for ^{101}Nb, ^{105}Mo and ^{102,104,105,106,107}Tc (see A. Algora *et al*., *Phys. Rev. Lett*. **105** (2010) 202501). These data for ^{104,105}Tc have been shown to address the disagreement between the benchmark experiments and theoretical calculations very well for ^{239}Pu(n$_{th}$,f).

A similar sensitivity study of Th-U (^{233}U(n,f)) combined with a subjective assessment of the nuclear structure of all of the highlighted fission products was completed in 2010 by Gupta *et al*. (IAEA report INDC(NDS)-0577, May 2010). Not surprisingly, the nuclear data requirements for the Th-U fuel cycle have a lot in common with the needs for U-Pu fuel:

Cooling time (s)	Radionuclides – Th/U and U/Pu fuel
10	^{86}Br, ^{87}Br(β$^-$,n), ^{88}Br(β$^-$,n), ^{90}Kr, ^{92}Rb, ^{96}Y, ^{99}Zr, ^{100}Zr, ^{98}Nb, ^{99}Nb, ^{100}Nb, ^{101}Nb, ^{102}Nb, ^{135}Te, ^{136}I^m, ^{137}I(β$^-$,n), ^{139}Xe, ^{140}Xe
100	^{86}Br, ^{87}Br(β$^-$,n), ^{89}Kr, ^{90}Kr, ^{98}Nb, ^{103}Mo, ^{103}Tc, ^{132}Sb, ^{136}I, ^{136}I^m, ^{137}I(β$^-$,n), ^{137}Xe, ^{139}Xe
1 000	^{89}Kr, ^{102}Tc, ^{104}Tc, ^{137}Xe
5 000	^{104}Tc

However, there are some problem fission products that can be more exclusively identified with the decay-data requirements for irradiated Th-U fuel:

Cooling time (s)	Radionuclides	
	Priority 1	Priority 2
10	^{89}Br, ^{91}Kr, ^{94}Rb, ^{96}Y^m, ^{97}Y, ^{100}Nb^m, ^{102}Nb^m	^{86}Se, ^{146}La^m
100	^{85}Se, ^{98}Zr (?)	^{99}Nb^m, ^{133}Sb
1 000	^{101}Mo, ^{130}Sb^m, ^{138}Xe	^{84}Br, ^{87}Kr, ^{92}Sr, ^{129}Sb^m
5 000	–	^{87}Kr, ^{88}Rb, ^{92}Sr, ^{128}Sb^m, ^{129}Sb^m, ^{139}Ba, ^{141}La
10 000	–	^{87}Kr, ^{88}Rb, ^{92}Sr, ^{128}Sb^m, ^{139}Ba, ^{141}La

A number of nuclear data requirements persist despite the recent good work of Algora *et al*., and the CARIBU facility offers the potential to generate, purify and study fission-product nuclides identified as meriting study by TAGS in order to elaborate on and resolve specific ill-defined decay schemes.

4.2 *Beta-delayed Neutrons – Physics and Detection (A. Algora)*

A. Algora (IFIC – Univ. Valencia, Spain) gave a brief description of the β^--decay process and the important competitive role of delayed-neutron emission in the case of neutron-rich nuclides. The neutron emission probability (P_n) measures the fraction of β-strength above the neutron separation energy (S_n), and constitutes an important parameter along with the half-life for nuclides far from the stability line. Studies of these delayed-neutron emitters require a combination of measurement techniques:

- TAGS for β^--decay data free of Pandemonium,
- 4π neutron counter to measure P_n, and
- neutron time-of-flight spectrometer (TOF) to determine E_n.

These data contribute significantly to our understanding of the *r* process in astrophysics (P_n, in particular), and would improve the efficacy of decay heat calculations for advanced reactor systems and the minor actinide waste arising.

The Valencia group is working on the development of a number of new detector systems for the DESPEC experiment at FAIR (GSI), in conjunction with other specialist teams:

- modular TAGS (responsibility of IFIC – Univ. Valencia),
- 4π neutron detector (responsibility of UPC), and
- modular TOF neutron detector based on cells of BC501A liquid scintillator (responsibility of CIEMAT).

P_n studies require efficient detectors with reasonably flat efficiency curves, high-purity sources to minimize background complications, moderation of neutrons, and calorimetric-like measurements. With these aims in mind, the BELEN-20 detector has been developed at the University of Jyväskylä with JYFLTRAP operational because of the high purity of the beam and commensurate healthy yields. The first P_n measurements were made on ^{88}Br, ^{94,95}Rb and ^{138}I(^{138}Te) nuclides – P_n values of ^{88}Br and ^{95}Rb have been used to determine an average efficiency of (27.1 ± 0.8)% for BELEN-20. This new detector system will be used in conjunction with the GSI FRagment Separator (FRS) to study very important Rh, Pd and Ag nuclei and the third *r*-process peak in astrophysics. The original design of the neutron detector for DESPEC consisted of forty-four ^{3}He counters arranged as three crowns, while the final BELEN detector for FAIR will consist of 110 counters.

Consideration is also being given to a neutron TOF spectrometer – DESPEC MOdular Neutron SpectromeTER (MONSTER). This work is being shared between co-workers at CIEMAT (Spain), VECC (India), University of Jyväskylä (Finland) and University of Uppsala (Sweden). Component cells of BC501A liquid scintillator are under manufacture, and acceptance trials will be carried out at Jyväskylä.

4.3 *Decay Spectroscopy of Fission Products for Nuclear Fuel Cycle at the HRIBF (K.P. Rykaczewski)*

The US Department of Energy created the first innovative nuclear energy hub at ORNL in May 2010 – Consortium for Advanced Simulation of Light Water Reactors (CASL). One of the first tasks is to develop computer models that simulate fully the operational behaviour of light-water nuclear power plants. Other models will address the desire to reduce capital and operational costs per unit of energy generated, while safely extending the lifetime of existing stations and reducing waste volumes. However, such highly appropriate aims require correct input data that include the well-defined nuclear properties of a wide range of transuranic nuclides and fission products.

K.P. Rykaczewski (ORNL) focused on the capabilities of the Holifield Radioactive Ion Beam Facility (HRIBF) at ORNL, in which proton-induced fission of ^{238}U can generate a significant number of differing neutron-rich nuclei, including many important (β^-,nγ) emitters. Beam-handling capabilities were described: IRIS-1 and 2 for mass separation, positive and negative ion isobar separation, negative ion acceleration, and Low-energy Radioactive Ion Beam Spectroscopy Station (LeRIBSS) for decay spectra. Various separation processes deliver high-purity ions for spectral analysis:

- pure Cu beams free of Zn contamination have been generated to give extremely well defined spectra, and most particularly ^{77}Cu which led to resolution of this complex decay scheme (including 70(2)% β^- decay of which 30(2)% is by β^-n decay);
- observation of much higher β^-n branching ratios in the ^{78}Ni region which more closely match calculations by Borzov that model proton orbital inversion; and
- LeRIBSS studies of $^{82,83}Zn$, $^{85,86}Ga$ fission products involved RIB production with IRIS-2 to generate ion concentrations that were a factor of 10 higher than those obtained by normal procedures, improving the resulting quality of the measured data substantially.

The ORIGEN code was developed in the 1970s to determine neutron-irradiated fuel inventories leading on to the decay heat generated after reactor shutdown and postulated reactor accidents. Other outputs include detailed gamma-ray spectra for adoption in nuclear safeguards initiatives, and assistance in the development and design of advanced reactors and fuel cycles. Doubts are being expressed about the adequacy of available β^-n decay data that do not appear to match and explain integral experiments. The impact of less common transuranics also needs to be explored because of the move towards the popularization of high burn-up fuel concepts – there is good evidence that ORIGEN calculations are missing data for a number of short-lived β^-n fission products.

Detector developments include Si-triangle inside 3Hen (segmented neutron counter of nearly 80% efficiency) which acts as a trigger for β^--energy loss, and a Modular Total Absorption Spectrometer (MTAS) for the study of neutron-rich nuclei produced in the ^{238}U(n,f) reaction at HRIBF. The latter has the capability to provide input data for the derivation of β-strength functions in the analysis of decay heat. Coupled with the Oak Ridge Isomer Separator and Spectrometer (ORISS), detailed isomer analyses could be achieved with ΔM/M ~ 1/400,000 and an efficiency of 50%.

4.4 *Beta Decay Studies with the Total Absorption Technique: A Remedy Against Pandemonium - Nuclear Physics Colloquium (B. Rubio)*

A comprehensive presentation was given of beta-decay studies by means of Total Absorption Spectroscopy (TAS) by B. Rubio (IFIC – Univ. Valencia, Spain). The β^- and β^+-decay processes were described in terms of single Fermi and triple Gamow-Teller states, expressed on the basis of Δl, Δs and Δπ selection rules for the electron, positron, anti-neutrino and neutrino. Beta strength or transition probability is governed by the spin-isospin operator that can be defined experimentally as follows:

$$B(GT) = k\frac{I_\beta(E)}{f(Q_\beta - E,Z)T_{1/2}} = k\frac{1}{ft},$$

in which the determination of beta feeding to states in the daughter nucleus ($I_\beta(E)$) was the main topic of this colloquium.

As postulated, waiting points in the rapid neutron-capture process (*r* process) are particularly important astrophysical phenomena, and TAS provides a means of studying the nuclei within this area of significant uncertainty in a comprehensive manner to quantify unknown stellar conditions. The half-lives of nuclides in the vicinity of the $N = 82$ waiting points have been determined and reviewed by Grawe *et al*., and found to agree reasonably well with the various theories. However, the same cannot be said for the $N = 126$ waiting points at which large differences are observed. TAS could be used to explore these areas and resolve existing uncertainties and problems. Another topic of argument involves oblate-prolate deformation, which is competitive around mass 70 in the $N \sim Z$ region. The sign of these deformation processes has important consequences, as outlined on the basis of changes in shape when moving from ^{76}Sr-^{78}Sr-^{80}Sr, as the clearly prolate deformation of ^{76}Sr distorts to more triaxial and softer nuclei at high excitation energy and in the more neutron-rich isotopes.

Important applications of nuclear physics would also benefit from TAS studies, as exemplified by comprehensive measurements of β- and γ-ray emission probabilities to define with much greater confidence the average light-particle and electromagnetic energies for decay-heat calculations. Approximately 8% of the total energy generated in the fission process of a commercial nuclear reactor is derived from the decay of the resulting fission products. This energy continues to be generated after the reactor is shut down, and coolant needs to be sensibly maintained.

An important feature of any TAS measurement is the isotopic purity of the nucleus of interest by separation from the other nuclei produced in the instigated nuclear reaction. Following recoil from the target of interest, the resulting charged particle would normally undergo mass separation and deposition onto a moving-tape transport system for spectral study by an array of γ-ray detectors that are capable of absorbing all of the resulting gamma decay. Such preparative and analytical facilities are available at GSI, MSU, GANIL, RIKEN, Jyväskylä and elsewhere, based on extensive arrays of γ-ray detectors to absorb all gamma activity and so avoid the Pandemonium effect.

TAS was described in terms of the spectral observations that arise from the total absorption of all resulting radiation – electrons, positrons, X-rays and γ transitions. Various existing 4π detector systems were described, including those to be found at ISOLDE/OSIRIS, St. Petersburg, INEL (now at ANL) and LBNL. A new TAS system has been assembled at ISOLDE, CERN consisting of a 38 x 38 cm^2 single NaI crystal, with ancillary Ge detectors for X-rays and plastic scintillators for β^- particles. The important aim of such equipment is the total absorption of all emitted radiation. Thus, sources of interest need to be placed inside the body of the detector, and the major problem is achieving full physical enclosure of the radioactive source to ensure full absorption. Tain *et al*. have dedicated much effort to the development of accurate response functions to the beta particles and gamma rays by the whole apparatus (see J.L. Tain *et al*., *Nucl. Instrum. Methods Phys. Res.* **A571** (2007) 719 and 728). Experimental spectral data were shown from six Euroball cluster detectors for which significant fine structure was observed: ^{150}Ho with 1064 γ transitions were observed and 295 nuclear levels derived; furthermore, $S_\beta(HR)/S_\beta(TAS) = 0.4$, revealing that only 40% of the nuclear levels had effectively been seen by the high-resolution HPGe detectors when compared with TAS.

TAS measurements to assist in more reliable decay-heat calculations have become increasingly difficult as demand has developed to study important contributory fission products that are known to be refractory (Nb, Mo, Tc and Ru) and hence difficult to purify for γ analysis. The Valencia group has undertaken TAS measurements at the University of Jyväskylä, as reported elsewhere in the workshop (see Sections 2.2 and 4.1). A key feature of this work is the gas-filled ion guide technique for mass and isobar separation (JYFLTRAP), along with a fast-moving tape system, and the TAS from St. Petersburg. Excellent mass separation and resolution of the Nb, Mo, Tc and Ru was achieved – example spectral data for ^{102,104}Tc were shown. While the resulting new average energy data had little to no effect on decay-heat calculations for ^{235}U(n,f), the impact of the ^{104,105}Tc data on ^{239}Pu(n,f) was highly significant. However, much remains to be done for both the U-Pu and Th-U fuel cycles.

5 Session IV

5.1 The Decay Spectroscopy Program with the 8π Spectrometer at TRIUMF: Lessons Learned and Future Plans (P. Garrett)

P. Garrett (Univ. of Guelph, Canada) gave a brief description of the ISAC facilities used to study nuclei generated by means of a 100-μA, 500-MeV proton beam from the main

TRIUMF cyclotron. Twenty Compton-suppressed HPGe detectors and ten BaF_2 detectors are used for γ-ray studies, along with twenty scintillators for β decay and five Si(Li) detectors for conversion-electron spectroscopy (combination referred to as 8π spectrometer). Garrett stressed the importance of including ancillary detectors, and that the 8π spectrometer always was supported by various additional systems. Such facilities also require a powerful and highly flexible moving tape system to transport implanted activity for rapid spectral analysis.

SCEPTAR is regularly operated in conjunction with the 8π spectrometer, and consists of two hemispheres, each containing ten ~ 1.60-mm thin plastic scintillator panels arranged in the form of two pentagonal rings. Various experimental studies were described, including ^{32}Na (low beam rate), ^{62}Ga by β-γ coincidence, discovery of ^{174}Tm, and the observation of E0 transitions in lanthanide nuclei.

The DANTE array of ten BaF_2 detectors has been used for timing studies, including the installation of this device in the 8π facility to characterize short-lived isomers (e.g. 2^+ state in ^{152}Sm populated by β^- decay of ^{152}Eu). However, this array of detectors is in the process of being replaced with an equivalent $LaBr_3$ system.

Future plans at TRIUMF were described in detail:

- Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei (GRIFFIN) consisting of sixteen large-volume un-segmented clover detectors (fully funded); phase II will involve fitting BGO shields to the full array, with commissioning in 2014;
- DESCANT, 1.1π sr deuterated-scintillator, neutron-detector array to be mounted on TIGRESS and GRIFFIN for measurements of E_n from ~ 100 keV to 10 MeV; and
- ARIEL upgrade, with funding already available for the development of a new 500-kW, 50-MeV e-LINAC as a photofission driver – target station, mass separator and beam transport facilities must await the next budget cycle beginning in 2015.

GRIFFIN, ARIEL and proton-induced spallation on actinide targets will generate much nuclear structure data in neutron-rich species.

5.2 *Radioactivity Studies at TRISTAN and ISOLDE from Coryell to CARIBU (W.B. Walters)*

After paying tribute to Charles Coryell (1912-1971) whose research teams discovered element 61 (promethium) and identified the solar abundance peaks at N = 50, 82 and 126 with closed neutron shells to provide the basis for *r*- and *s*-process nucleosynthesis, W.B. Walters (Univ. of Maryland) focussed on the study of fission-product decay from MIT (chemical methods of purification), TRISTAN (on-line mass separation with limited ion-source selectivity), and ISOLDE (on-line mass separation with laser ionization, ion-source selectivity, and molecular-ion selectivity).

Chemical separations were exemplified by Ge(Li) spectral studies of ^{130,131,132,133}Sb involving purification by means of fast gas chemistry with SbH_3 and halogen chemistry with ^{86,87}Br and ^{134,136}I. Isomeric states were also identified in this manner for a significant number of Sn and Sb nuclides, along with the detection of high-spin states (e.g. 15/2⁻ isomer of ^{127}Sb).

A multi-detector system for γ-γ coincidence and angular correlation measurements was developed for TRISTAN, consisting of four large axial Ge crystals set at fixed positions so that six distinct angles can be simultaneously scanned. Initial studies involved the characterization of a wide range of Sn, Xe and Ba nuclides. Measurements of the β^- decay of ^{144}Ba led to extensive IBA calculations and provided a verification of the NpNn counting scheme to systematically categorize the development of deformation. More than 400 gamma rays were observed and the derivation of 80 nuclear levels for the β^- decay of odd-odd ^{144}La was carried out. Greenwood *et al*. (INEL) suffered similar problems of handling complex decay schemes in TAS studies, and adopted the procedures developed for ^{144}La β^- decay to simplify their evolution and presentation of their data.

New interest in *r*-process nucleosynthesis and supernovae re-occurred in the late 1980s, and motivated the measurements of the decay and nuclear structure properties of the most relevant radionuclides. The first successful determination of the ^{130}Cd half-life of importance in the *r* process was made with considerable difficulty at ISOLDE, boding ill for further proposed work with the plasma-ion source. However, chemically-selective laser ionization was popularized in the 1990s starting with a study of the β^- decay of ^{101}Sn, and leading on to Tm, Yb nuclides and neutron-rich Ag experiments. A half-life of 46^{+5}_{-9} msec was measured for ^{129}Ag which lowers the impact of this nuclide as a waiting point for the *r* process, and also suggests that lighter N = 82 isotones will not constitute major waiting points either.

The development of the <u>R</u>esonance <u>I</u>onization <u>L</u>aser <u>I</u>on <u>S</u>ource (RILIS) paved the way to the successful study of Cd, In, Sn and Sb nuclides. Experimental studies of ^{130}Cd β^- decay to ^{130}In indicated significant differences between the measured and calculated mass of ^{130}Cd, revealing that this nucleus is 1.6 MeV less bound than predicted by FRDM (<u>F</u>inite-<u>R</u>ange <u>D</u>roplet <u>M</u>odel). The energy of the 1^+ nuclear level of ^{130}In is 740 keV higher than the calculated value, implying 30% reduction in the proton-neutron interaction strength of which the consequences need to be addressed. Note was also made of the anomalous 68(3) ms half-life and P_n value of 3.5% determined for ^{131}Cd that merit further attention.

Over the previous 15 years, half-lives have been measured from ^{129}Ag to ^{139}Sb, and studies at N = 82 have improved the ability to extrapolate down the chain in order to estimate the nuclear properties at other potential N = 82 waiting points and furnish a model fit. Experimental studies possess the potential to identify model calculations that do not provide good fits to the nuclear data. Studies of ^{134,135,136}Sn β^- and β^-n decay were described, and their proposed decay schemes were defined in detail – results were obtained with an ISOLDE ion source and ^{34}S-enriched sulphur gas to generate SnS^+ ions.

^{252}Cf spontaneous fission in CARIBU will produce exotic fission-product nuclei at the higher masses that are well separated from their slower decaying daughters. Furthermore, the low mass peak possesses some interesting high-yield fission products that are located on the higher mass shoulder of this segment of the distribution.

5.3 *Fast Electronics Scintillation Timing (FEST) (V.R. Werner)*

A small $LaBr_3$ scintillator array has been assembled at Yale University, and the performance of this system is in the process of being compared with standard, conventional scintillators. V.R. Werner (Yale Univ.) also believed that the adoption of this new detector system in future CARIBU decay studies should be fully assessed.

B(E2) systematics within lanthanide nuclei involves modelling in terms of fixed boson charge and "effective valence" to define the apparent saturation of collectivity in this region. Fast timing can be implemented, with or without a β^- gate, and three $LaBr_3$ cylindrical scintillators have been tested that exhibit superior energy resolution ($\geqslant$ 3%) and time resolution comparable to BaF_2. Further improvements could also be made, including the introduction of BGO suppression. Various means of undertaking background subtraction have been considered, and comparative tests have been carried out with ^{152}Eu sources and both the $LaBr_3$ and BaF_2 detectors. Other studies include lifetime measurements of ^{168}Hf and ^{174}W in particular that suggest trends which deviate significantly from the Interacting Boson Approximation (IBA) and the effective valence nucleus models.

A thirty-six $LaBr_3$ detector array is proposed to surround the beam stopper of FAIR/GSI, developed under the auspices of the NUSTAR collaboration for DESPEC. High-efficiency Ge detectors are also envisaged, with the possibility of a European-USA collaboration to drive forward the enhancement of the $LaBr_3$ scintillator arrays. The FRIB Scintillation Working Group is also considering alternative materials such as $CeBr_3$, neutron detector arrays and TAS for future nuclear physics studies. CARIBU would benefit from these proposed detector developments and ancillary activities for studies of E2 transitions in the Zr-Mo-Ru region, intruder configurations and shape co-existence in the Ce-Ba region, and perturbed angular correlations, along with an appropriate moving-tape system for magnetic moment measurements.

5.4 *Shape Changes and Isomers in Neutron-rich Zr-Mo-Ru Nuclei (F.G. Kondev)*

Nuclear deformation is an important concept in defining how single-particle orbitals near the Fermi level affect the shape of the nucleus, and more specifically quantify the impact of A and Z on the deformation process. Direct electronic-timed gamma-ray detectors are required: both Ge ($\sim$ 1 ns) and BaF_2 (good timing, but inadequate energy resolution) are unsuitable, while $LaBr_3$(Ce) would appear to be fully appropriate down to 40 ps.

F.G. Kondev (ANL) described specific odd-odd Y-Nb-Tc parent nuclei of interest with both high and low spin β⁻-decaying states: ^{102,104,106}Y, ^{108,110}Nb and ^{112,114,116}Tc. These particular nuclides can be generated by CARIBU, and studied by operating Gammasphere as a calorimeter with modest upgrade (high-resolution γ-ray spectroscopy and TAGS). Nuclei shape studies would benefit from TAGS measurements, as outlined for ^{74}Kr and ^{76}Sr. Gamma-ray studies would also benefit from the adoption of $LaBr_3$(Ce) detectors operated in coincidence with Gammasphere, as explained in terms of the complex nuclear structures of ^{177}Lu and ^{177}Hf. Such fast-timing capabilities would be a valuable addition to the CARIBU decay-spectroscopy station to study deformation changes in neutron-rich Zr-Mo-Ru nuclei.

6 Sessions V and VI

6.1 TAGS

The Modular Total Absorption Spectrometer (MTAS) was manufactured, assembled and tested by Saint Gobain Crystal in Ohio in preparation for acceptance to undertake experimental studies at ORNL. MTAS consists of a bundle of eighteen 21″-long hexagonal units of NaI(Tl) scintillator, in which the central unit contains a hole of 2.5″ in diameter. M.P. Karny (Univ. of Warsaw, Poland) described tests with a broad beam of ^{137}Cs to determine a resolution of 6.8% to 8% (FWHM) for the 661-keV gamma line, with the central module being just below 8.5% and the threshold for all twelve summed signals occurring below 30 keV. Uniformity of γ-ray detection was also shown to be of good quality between 5 to 17″ within each 21″-long hexagonal scintillator unit. The measured performance characteristics have been compared to good effect with GEANT4 modelling simulations of non-linear light generation and energy deposition of the optical photons in MTAS. Light propagation in the central unit was calculated to be 8% FWHM for the 661-keV γ line of ^{137}Cs and 6.5% FWHM for the 1332-keV γ line of ^{60}Co, subject to further envisaged improvements. Measurements of background activity levels and shielding tests with Pb blankets and a paraffin wall have also been completed. Other aims include the incorporation of auxiliary Si detectors for β-γ coincidence measurements and an ionization chamber for incoming counts into the MTAS facility.

R.B. Firestone (LBNL) outlined the history of the Lawrence-Berkeley Total Absorption Spectrometer (TAS) as conceived and operated by Nitschke's research group in the late 1980s. The design of the spectrometer was described in some detail:

- 356 x 356 mm^2 NaI(Tl),
- 51 x 203 mm^2 well, with 43 x 150 mm^2 plug of NaI(Tl), and
- 16 x 10 mm^2 Ge X-ray detector and two 18 x 1 mm^2 Si β⁻ detectors located inside the sealed well.

This detector system was commissioned at LBNL, but only one set of measurements was performed before the unit was moved to GSI in the mid-1990s. The studies at LBNL were undertaken on $^{117\text{-}121}$Xe, $^{117\text{-}124}$Cs and $^{121\text{-}124}$Ba, for which Firestone possesses complete I_β spectra, Q_{EC} values and S_β strengths. Coincidence data and γ-ray strengths from the plug-detector data also survive for ^{124}Cs. Example data were shown of the resulting level excitation energies for both the even- and odd-A Cs nuclides, along with Q_{EC} values determined from the endpoint energies of the γ-ray sum spectra. The Q_{EC} value of ^{122}Cs is consistent with the 8^- isomer and not the 1^+ ground-state decay; and agreement between the Audi *et al*. AME and TAS data is excellent, apart from ^{117}Cs. Equivalent data were also presented for $^{117-121}$Xe and $^{121-124}$Ba. Cs beta-strength functions per 20-keV energy interval increase exponentially up to 4 MeV as expected, but fall dramatically at higher energies, in disagreement with the statistical model of β^- decay. Firestone is re-visiting this neglected set of data, and would hope to publish his findings at some future date. Finally, he pointed out the LBNL TAS is open to proposals for new measurements, although he stated the plug-detector system would be best replaced by an external HPGe γ-ray detector for isotopic identification.

Monte-Carlo modelling of the Argonne TAGS facility has been developed by M.L. Smith (Australian National Univ., Australia). The GEANT4 code was adopted, which is based on a C++ update to GEANT3 (written in Fortran). Data input for the equipment include the design and dimensions of the NaI(Tl) detector used by Greenwood *et al*. at INEL in the 1990s. Other facets of the model are as follows:

- simulation of the resolution,
- correction for non-proportionality of the light signal,
- pile-up definition of particle (type, direction and energy), and
- detailed decay data (default data taken from ENSDF),

with model output data defined for each event. TAGS simulation tests have been carried out with a ^{60}Co source placed in the well for the derivation of spectral data, with the addition of an optical photon model. Despite very good agreement with measured data, a major disadvantage has been that simulation times are a factor of ~ 1000 longer than acceptable. Efforts to fit the experimental data of Greenwood *et al*. for ^{148}Ce-^{148}Pr decay by simulation and the introduction of pseudo-levels were also described, underlining the need to continue these studies in order to develop GEANT4 further for optimal use with the ANL TAGS.

6.2 Nuclear Structure

Lessons learned from the RISING decay studies at GSI-Darmstadt and the known merits of isomeric separation at Jyväskylä would considerably aid the CARIBU project. As described by A.M. Bruce (Univ. of Brighton, UK), RISING consists of 15 x 7 element Euroball cluster which is mounted on a beam line of the GSI accelerator capable of producing ^{238}U and medium-mass nuclei with beam intensities of 10^8 and 10^9 pps, respectively. A wide range of phenomena has been explored by using the accelerator and time-of-flight fragment separator to produce and control secondary radioactive ion beams with energies between 100 and 700 MeV u^{-1}. Example data for ^{112,113}Tc and high-mass Ir, Pt and Au nuclides were discussed. Active stopper measurements with 5 x 5 cm^2 DSSSD (16 x 16 strip) detectors have provided a means of determining half-lives up to minutes based on delayed γ rays (for example, ^{106}Y, ^{188,190,192}Ta and ^{205}Au).

The IGISOL isotope separator at Jyväskylä has provided the means of isolating the ^{100}Nb ground state while also generating 50-50 mixed ^{100}Nb/^{100}Nb^{m} sources. Nuclear structure studies of this nature offer great potential, and should form an integral part of the CARIBU project.

M. Madurga (Univ. of Tennessee) presented preliminary results from the Low-energy Radioactive Ion Beam Spectroscopy Station (LeRIBSS). This spectrometer is an integral part of the IRIS-2 and HRIBF at ORNL. Recent experimental studies have been directed towards ^{78}Ni (Z = 28, N = 50 shell closure), P_n measurements (^{81,82,83}Zn, ^{85,86}Ga, ^{88}Ge, ^{89}As, ^{94}Se and ^{96}Br), progenitor of Sr, Y, Zr abundances, and nuclear physics in the A = 80 to 95 region. New detectors at LeRIBSS include MTAS (Modular Total Absorption Spectrometer) as a gamma calorimeter, 3Hen and VANDLE (both for neutron detection). Commissioning trials with VANDLE have included time resolution, efficiency and proof-of-principle measurements with ^{89}Br, which demonstrated this neutron detector to be entirely suited to the study of beta-delayed neutron decay.

Some features of the *r* process challenge our understanding, such as quantification of the nuclear forces that drive the core collapse of supernovae. S.L. Tabor (Florida State Univ.) pointed out that appropriate models show the r-process would require an order-of-magnitude greater entropy to induce such behavior – the nuclear physics is commonly based on Hauser-Feshbach calculations and the competition between neutron capture and β^- decay. Hence, nuclear data requirements to address known anomalies within supernovae are as follows:

- neutron-capture rates, especially low-lying s-wave resonances,
- atomic masses, and
- β^--decay lifetimes.

Experiments at the National Superconducting Cyclotron Laboratory (NSCL) with 3 to 4 GeV, $A \sim 30$ ion implants are addressing these needs by undertaking measurements at a β^--counting station and SEgmented Germanium Array (SEGA) of sixteen HPGe detectors. Furthermore, 40 x 40 DSSD detectors have been used to study implant-β-γ-γ coincidence of ^{30}Ne to assist greatly in the characterization of the half-life and β^- decay of this nuclide. Equivalent measurements of βp and pure p decay of ^{94}Ag^{m} at the ISOL facility at GSI-Darmstadt were also discussed. When the experience gleaned from this work is applied to the implementation of CARIBU, a number of salient conclusions can be drawn:

- isobaric purity is important,
- need to quantify and eliminate contaminants, daughters and grand-daughters,
- β-γ coincidences assist greatly in the removal of background activity,
- neutron detectors are essential for the study of β^-n decay,
- lifetime range is determined by the [diffusion time – bunching time] parameter, and
- DSSD would achieve greater speed of data assimilation, but particle penetration of the dead layer is problematic.

S.P. Lalkovski (Univ. of Sofia St. Kl. Ohridski, Bulgaria) reported on single-particle states and the determination of transition probabilities for nuclides immediately below ^{132}Sn. Relevant half-lives were evaluated for Zr, Mo, Ru, Pd, Cd and Sn nuclides, and more precise measurements were made to improve these data and fill known gaps. Spectral arrangements at NIPNE, Romania, were described:

- 7 to 8 HPGe detectors at backward angles and 90° with respect to the axis of the beam;
- 5 to 8 $LaBr_3$(Ce) detectors placed at backward angles; and
- electronics triggered when signals from one HPGe and two $LaBr_3$(Ce) detectors are in coincidence.

Targets of ^{94,96,98}Mo and ^{107}Ag and beams of ^{7}Li, ^{12}C and ^{18}O were used to produce and study ^{95}Mo, ^{103,105,107}Cd, ^{111}Sn and ^{113}Sb.

With beam intensities of the order of 10^6 ions s^{-1}, A.Y. Deo (Univ. of Massachusetts Lowell) viewed CARIBU as an appropriate facility for the study of neutron-rich isotopes in the region of ^{132}Sn. Isomer half-lives are sufficiently long (seconds to minutes) for extraction and study, and the energy difference between ground and isomeric states is large enough for separation by means of the Canadian Penning Trap (CPT). Predictions for ^{131}Sn and ^{132,134}Sb were defined – all the isomers undergo 100% β^- decay, and their excitation energies can be determined by either β-γ coincidence or mass measurements. CPT studies of this type have previously been undertaken for ^{78,84}Rb by Bollen *et al*. (Phys. Rev. C46 (1992) R2140). As proposed, such a work program would provide experimental data to test shell-model calculations of important neutron-rich nuclides.

Spectroscopic studies of neutron-rich nuclides close to A ~ 110 were presented by B.M. Bucher (Univ. of Notre Dame). Nuclear structure within this area of interest is poorly understood – rapid changes in shape occur, along with isomerism and triaxiality. Sub-nanosecond lifetimes for excited states populated by β^- decay have been measured at Jyväskylä by means of β-γ-γ fast-timing with two $LaBr_3$(Ce) scintillators and two HPGe detectors. Preliminary data were shown for ^{109}Tc(β^-)^{109}Ru(β^-)^{109}Rh(β^-)^{109}Pd that will significantly re-define the nuclear structure of ^{109}Ru and ^{109}Rh.

^{180}Ta^m is the only naturally-occurring isomer with a half-life specified as greater than 1.2×10^{15} years (spin and parity of 9^-, and level energy of 75 keV). G.J. Lane (Australian National Univ., Australia) debated whether this isomeric state could survive in the stellar environment. Population from a higher-energy intermediate state would be required in such conditions. Belic *et al*. (Phys. Rev. Lett. 83 (1999) 5242) have measured resonances identified with the 1085-, 1295- and 1505-keV nuclear levels of ^{180}Ta, leading on to the greater complexity of back decays from "doorway" states observed in the studies of Walker *et al*. (Phys. Rev. C64 (2001) 061302). CARIBU would be a suitable vehicle to search for these "doorway" states in a similar manner to the successful studies of ^{176}Lu by Dracoulis *et al*. (Phys. Rev. C81

(2010) 011301). More generally, the fission-yield distribution of ^{252}Cf(sf) shows the predominant emission of fission products that exhibit (a) large deformations and shape changes within the lower-mass peak and (b) octupole collectivity in the upper-mass peak. These trends need to be investigated experimentally and their characteristics determined with greater confidence. Thus, ANU has a strong interest in the A = 110 region that could be probed with CARIBU by undertaking direct lifetime measurements with $LaBr_3$(Ce) detectors provided from Canberra.

6.3 Related Studies

W.A. Schier (Univ. of Massachusetts Lowell) presented studies of the fission process for ^{235}U(n_{th}, n_{fast}), ^{238}U(n_{fast}) and ^{239}Pu(n_{th}) as performed at Lowell to provide suitable nuclear data for fast-breeder design calculations. These data included input to the ENDF/B-VI data file for nuclear applications, delayed-neutron energy spectra from 0.17 to 85 s to assist in fast reactor control, beta and gamma decay-heat studies at cooling times from 0.3 to 50,000 s, and cumulative and independent fission yields. The ^{7}Li(p,n)^{7}Be reaction on thick targets in the 5.5-MV Van de Graaff accelerator generated moderated or fast neutrons, and neutrons were also taken from the thermal-neutron column and fast-neutron port of the 1-MW research reactor. Fission foils were contained within a 17-mm radius hemispherical chamber and the resulting fission fragments were stopped in 3 atm. of He gas, collected on a tape by means of a He-jet system, and subsequently transported to the counting station (β^- spectrometer and shielded HPGe detector). Measured independent fission yields have been compared with equivalent data in ENDF/B-VI and Rudstam measurements to good effect, and relative yields have been derived as a function of neutron energy. Beta decay-heat measurements were carried out by means of β^- spectrometry, and exhibit good agreement with equivalent ORNL studies and ENDF/B-V calculations. However, the equivalent gamma decay-heat studies by means of NaI(Tl) detector and photomultiplier tube reveal discrepancies between measurements and calculations at cooling times ranging from 300 to 12,000 s for neutron-irradiated ^{235,238}U and ^{239}Pu.

T. Kawano (LANL) has developed a microscopic technique to calculate delayed-neutron and γ-ray spectra based on the following:

- Finite Range Droplet Model (FRDM) and Quasi-particle Random Phase Approximation (QRPA);
- neutron and γ-ray emission probabilities obtained from the statistical Hauser-Feshbach model; and
- nuclear structure data to be found in ENSDF (Evaluated Nuclear Structure Data File).

Nuclear fission produces two fission fragments that emit prompt neutrons and γ rays as they de-excite to their ground states. Delayed neutrons are also emitted when the final energy state of the β^- decay is higher than the neutron separation energy. Beta-delayed γ-ray emissions take place in both the daughter and the grand-daughter nuclei, and much detail in the nuclear structure of such nuclides needs to be determined and brought together. Such a project is on-going, and preliminary calculations were shown of gamma, electron and neutrino emissions for a series of Cs nuclides ($^{141-144}$Cs). Delayed-neutron and γ-ray spectra have been calculated for 1412 precursors, and the results converted into a CINDER library for transmutation studies. This work has been extended to the modelling of decay heat, as exemplified by comparisons of the β and γ decay-heat components for ^{235}U and ^{232}Th/U fuels compared with benchmark experiments – these studies exhibit much improved agreement with the benchmark data compared with QRPA-only form of analysis.

7 Discussion

Formal discussions at the end of the workshop were effectively led by R.V.F. Janssens (ANL). He began by pointing out that well-informed answers to some of the questions posed during the course of earlier discussions had proved problematic because of the current status of CARIBU – thus, specific aspects of performance would only become clearer when the facility was fully operational. Clearly, guiding principles applied to the emerging program of work, such as:

- primary mission is to achieve the best possible science,
- ATLAS is a user facility, with CARIBU playing an important role as a low-energy beam area for nuclear physics experiments, and
- users of CARIBU will become more closely involved in the approval processes for their experiments after the necessary operational experience has been gained with the facility.

A Program Advisory Committee (PAC) has existed for many years to review proposals for experiments on ATLAS and recommend the allocation of beam time based on scientific merit. PAC also plays an advisory role to ATLAS with respect to strategic plans and new initiatives, meeting approximately twice every year. The Chair is John Hardy (Texas A&M University), with an eminent membership from within the USA and abroad (Poland and the UK) to provide both national and international perspectives. This current expertise embraces nuclear structure, reactions and dynamics, astrophysics and fundamental interactions – ATLAS proposals not satisfactorily covered by these topics are normally reviewed from outside PAC membership by recognized external specialists. However, if evolving experience with CARIBU indicates that a new member of PAC is required to address various program items not covered by the existing team, such a person will be appointed in consultation with the user community.

Scheduling issues were broached, although little of real consequence arose because of the current lack of regular day-to-day operational experience with CARIBU. As defined by the PAC, experiments on ATLAS will possess the following order of priority:

(a) accelerator-driven beams will be assigned the highest priority,
(b) CARIBU studies involving low-energy beams are envisaged as next in priority, and
(c) equipment development and maintenance activities will be held at a lower priority under normal circumstances.

This situation will require continual review over the early periods of operation of CARIBU. Other points of note include:

- ANL requires "letters-of-intent" from users wishing to place their own equipment within the facility,
- recruitment of an accelerator nuclear physicist is under discussion, and
- CARIBU progress reports will be issued two or three times per year to ensure that everyone interested is kept abreast of all facets of commissioning and future development.

Timetables defining the status of individual pieces of equipment would be useful to maintain within these progress reports so that anyone wishing to move forward with their own experimental proposals can optimise their time for application.

TAGS/TAS:

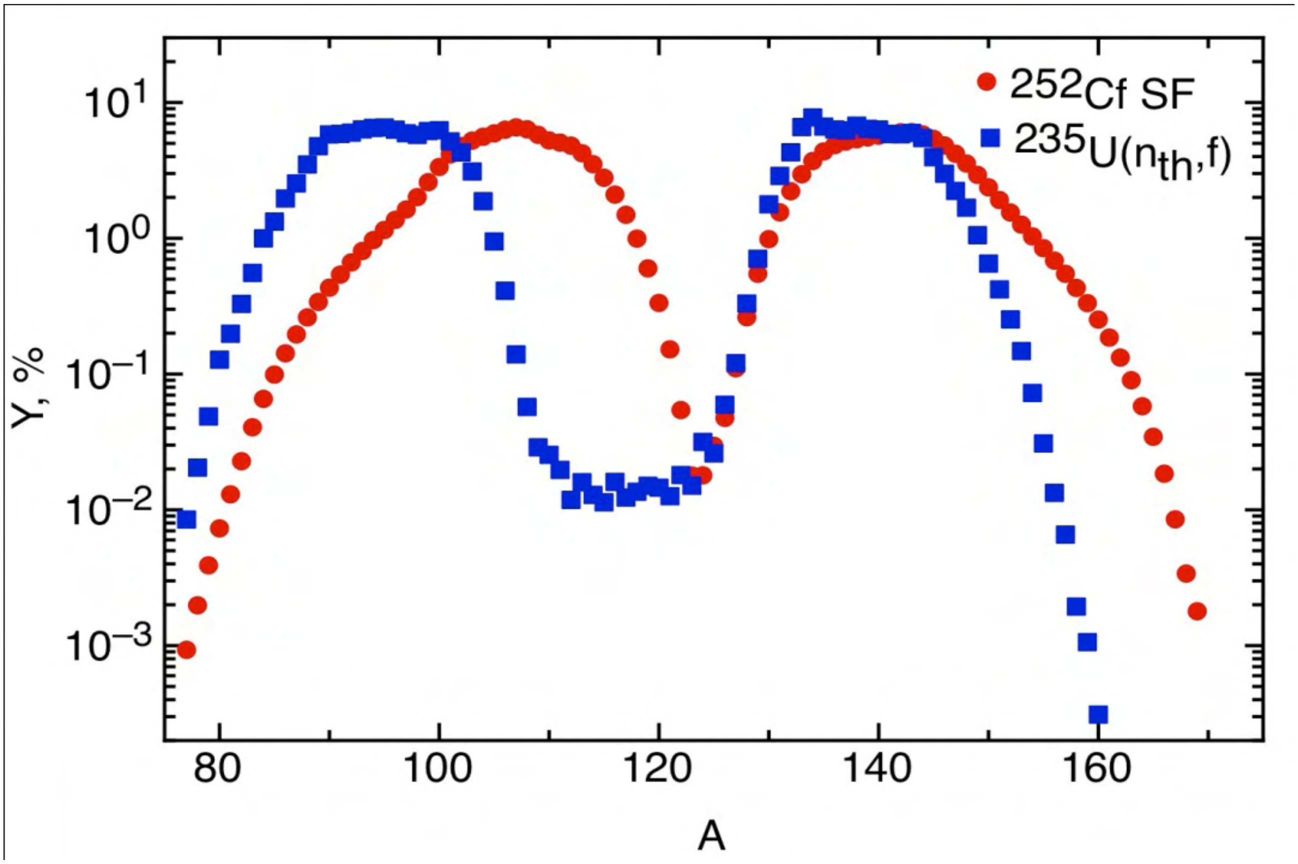
Both short- and long-term needs were spelled out within the workshop. A reasonably healthy number of TAGS facilities were now believed to be in place to address data inadequacies identified with nuclear applications and fundamental nuclear structure as specified in the presentations of Rubio, Hill, Nichols, Tain and Algora. The focus at this time is upon improved decay-heat calculations for neutron-irradiated fuel, although advantages of undertaking TAGS measurements to improve our understanding of the nucleus should not be overlooked.

Astrophysics:

While elemental abundances throughout the galaxy can be explained in terms of nuclide transmutation processes across much of the chart of the nuclides, our ability to demonstrate the existence and quantify the nature of the fundamentally important *r* process has proved elusive. The CARIBU facility will provide the means of investigating the rapid neutron-capture process and define the associated nuclides and nuclear reactions in greater detail. Key measurements in such well-focussed studies would include atomic masses (Canadian Penning Trap), half-lives, neutron-capture rates and neutron emission probabilities. Hopefully, as discussed by Montes and Surman, analyses of the ion beams generated from the spontaneous fission of ^{252}Cf can unlock some if not all of the these nuclear-based mysteries and uncertainties in astrophysics.

Fundamental nuclear physics:

There would appear to be a high potential for fundamental nuclear physics measurements with CARIBU. While the lighter-mass peak of the fission-yield curve of ^{252}Cf(sf) differs significantly in location from that of ^{235}U(n_{th},f) – see figure, below –, we can assume there will be greater overlap with the equivalent part of the curve for ^{239}Pu(n_{th},f). The heavier mass fragments from ^{252}Cf(sf) fall within the middle of the known lanthanide rotors, which arguably may not prove fruitful for the observation of new phenomena. Neutron-rich Sr, Y, Zr nuclei are identified with the lighter mass fragments for which some of the largest ground-state deformations are known, with a greater likelihood of finding surprises in their nuclear properties and structure – also referred to as the CARIBU "sweet spot" by Lane.



8 Concluding Remarks

Both the presentations and comments of participants provided project staff and the potential user community with guidance and encouragement in their preparative work to ensure the production, control and analysis of fission-product nuclei within the CARIBU/ATLAS facility. As agreed, the spontaneous fission of ^{252}Cf will generate a wide range of fission products of direct research interest and application in the key fields of astrophysics, nuclear structure and fuel-cycle applications. We have the clear potential to address a number of important practical and philosophical issues within one facility:

- combine with Total Absorption Gamma-ray Spectroscopy (TAGS/TAS)
  - (a) to determine specific component and total decay energies for nuclides of importance in carrying out reliable decay-heat calculations with full confidence for irradiated commercial fuels, and
  - (b) to address nuclides believed to possess gaps and inadequacies in their known nuclear properties and structures;

- clarification of the nuclear physics of the *r* process in nuclear astrophysics; and
- expansion of our fundamental knowledge and understanding of nuclear parameters and phenomena across significant areas of the chart of the nuclides by means of well-directed studies of the fission products generated by ^{252}Cf spontaneous fission.

Over the next year, CARIBU should advance from a research project into a fully-fledged scientific tool. The quantity of beam will increase with the introduction of the 1 Ci ^{252}Cf source. Nevertheless, many aspects of the project are in their infancy. A great deal of ion-source research is still required to produce intense and clean beams consistently. The isobar separator needs to be refined to obtain sufficient mass resolution (>1/10,000) to provide the most interesting and exotic species for decay studies.

A key finding of the workshop was that the User Community must be kept informed of progress in the project so that they can gauge when and how they can become involved in the intended research. A frequently updated schedule of progress and expectations should be made available to the User Community.

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