Coordinator's Report
Beta-Particle Spectrometry Working Group

Background

The Beta Particle Spectrometry Working Group is devoted to the development of the metrological aspects of beta spectrometry and its applications. This includes:

- Theory. Beta ($\beta^{\pm}$) and electron capture (ε) transitions; Theoretical shape factors and influence of the nuclear current; Atomic effects.
- Experiments. Instrumentations used for beta spectrometry; Techniques that need beta information; Confidence on experimental shape factors; Data analysis and unfolding methods.
- Simulations. Confidence on the physical processes: low energies, radioactive decays, atomic rearrangements; Comparison of the results of different codes.
- Evaluations. Confidence and uncertainties on experimental shape factors; Procedure for establishing recommended shape factors; Mean energies, log *ft* values, database.

Interested communities in radionuclide metrology are: nuclear decay data, liquid scintillation counting, ionising chambers, 4π β-γ counting.

The dedicated website http://www.lnhb.fr/icrm_bs_wg/ has been updated with Working Group reports and a preliminary list of recommended publications.

Recent and on-going activities

- Theory

  i) New versions of the BetaShape code have been released: 2.3 in September 2023, 2.3.1 in December 2023 and 2.4 in June 2024. Some changes have been implemented upon request of the NSDD network to comply with ENSDF evaluation rules: forbiddenness assignment when spins and parities of the nuclear levels are ambiguous; treatment of the N and PN records for the normalization factor and its uncertainty; treatment of non-numeric uncertainties; option to treat asymmetric uncertainties; option to modify the rounding limit; provision of f-values and neutrino mean energies in CSV files; provision of experimental shape factors in ENSDF format; separate description of the CSV format. In addition, the beta decay model has been improved by including precisely various atomic corrections (overlap, screening and exchange) thanks to extensive tabulations. Electron capture calculations have also been accelerated by a factor of 50 thanks to, again, extensive tabulations. Executables have been made available for various platforms on LNHB website and IAEA-NSDD GitHub.

  http://www.lnhb.fr/rd-activities/spectrum-processing-software/

  https://github.com/IAEA-NSDDNetwork/BetaShape

  ii) Developments are ongoing for the next version, which release is expected in 2025.

  iii) Inclusion of a realistic nuclear structure in beta decay calculations has been conducted. Several forbidden non-unique transitions for which accurate measurements exist (^{36}Cl, ^{99}Tc, ^{151}Sm, ^{176}Lu) have been studied in minute details, highlighting the importance of the conserved vector current hypothesis and of the

Coulomb displacement energy for accurate estimate of relativistic vector matrix elements. In addition, ^{99}Tc spectrum has been used to extract new, high-precision effective values of the weak interaction coupling constants. Many other transitions have been calculated in the context of antineutrino flux from nuclear reactors and dark matter detection.

iv) A custom atomic model based on the relativistic density functional theory has been developed and validated against experiment. The influence of different atomic models on electron capture probabilities and shaking processes has been studied.

- Measurements

i) The beta spectrum of ^{151}Sm decay measured with metallic magnetic calorimeters at LNHB has been carefully analyzed in a collaboration with PTB. A new Q-value has been extracted from the spectrum with an uncertainty decreased by a factor of seven compared to the latest recommended value. The ξ approximation has been found to be insufficient if a 3% precision or less is aimed for to describe the spectrum shape. New branching ratios have also been established and could be used for updating the ^{151}Sm DDEP evaluation.

ii) The beta spectrum of ^{176}Lu decay measured with solid scintillator crystals at TU Delft (Gonitec) has been carefully analyzed in a collaboration with LNHB and NSCL (Michigan, USA). Thanks to a Penning trap measurement, new transition energies have been established with uncertainties decreased by a factor of 1.5. The spectrum shape of the dominant transition has been found to be very sensitive either to the Coulomb displacement energy or to the effective value of the axial-vector weak interaction coupling constant.

iii) The beta spectrum of ^{99}Tc decay measured independently with metallic magnetic calorimeters at both LNHB and PTB has been carefully analyzed. A new Q-value has been extracted from the spectrum, not compatible with the latest recommended value with an uncertainty decreased by more than a factor of five. The best theoretical description of this second forbidden non-unique transition necessitates an adjustment of the value of the weak interaction coupling constants g_V and g_A.

iv) The beta spectra of ^{14}C and ^{204}Tl decays measured at LNHB with a detection system based on silicon detectors in a quasi-4π configuration have been reanalyzed. Extracted transition energies have been found perfectly consistent with the latest recommended Q-values. The ^{14}C shape factor has been found linear in energy, with a coefficient fully consistent with the best theoretical predictions available of the weak magnetism term. The ^{204}Tl shape factor has been found consistent with the reference value in the literature, extending the experimental knowledge of the spectrum down to 60 keV.

v) In order to retrieve the originally emitted spectrum, two robust unfolding methods have been adapted to beta spectrometry. The first method, called MLEM (Maximum Likelihood Expectation-Maximization), is based on a regression model following the Poisson distribution. Since Poisson noise increases with each iteration, an optimal criterion for stopping the iteration has been developed. The second method, called Tikhonov regularization, adds a bias to the least square method, thereby introducing a regularization parameter. The optimal parameter has been determined with the GCV (Generalized Cross Validation) method. These two approaches have been validated by studying a series of 12 simulated beta spectra (^{10}Be, ^{14}C, ^{35}S, ^{36}Cl, ^{39}Ar,

^{63}Ni, ^{79}Se, ^{90}Sr, ^{99}Tc, ^{135}Cs, ^{147}Pm, ^{204}Tl), covering a wide range of atomic numbers, masses, energies, spectral shapes and statistics. These spectra have been simulated with Geant4 for a quasi-4π configuration of a two-silicon detector device. Their respective performances have been quantified and compared, concluding that the Tikhonov method has a better overall performance.

- Evaluations

  i) The adoption of the BetaShape code has been proposed for ENSDF evaluations at the 24th Technical Meeting of the NSDD network (October 2022, Australia). The NSDD network have given its final agreement with the release of version 2.3. Additional improvements are regularly suggested to improve the recommended decay data.

  ii) A collaborative work has been carried out between B. Singh from McMaster University (Canada), S. Turkat and K. Zuber from TU Dresden (Germany) and X. Mougeot (LNHB) aiming for an update of the 1998 review of log-*ft* values. Decay schemes and data with beta transitions and electron captures have been updated manually. BetaShape (version 2.3) has been run over the entire database to update the mean energies and the log-*ft* values. Selection of well-defined transitions which data can be trusted has been performed, and potential Pandemonium nuclei have been flagged.

Related projects

- European metrology project (EURAMET, EMPIR programme) MetroBeta 15SIB10, 2016-2019. Website: http://metrobeta-empir.eu/. Partners are from Czech Republic, France, Germany, Netherlands, Poland and Switzerland.

  Summary. The MetroBeta project is taking both theoretical and experimental approaches to improving the knowledge of beta spectra. On the theoretical side, existing knowledge of the calculation of nuclear wave functions is being used to take into account the nuclear structure effect on these spectra. On the experimental side, beta spectrometry with MMCs is being developed, as well as solid scintillators containing the beta emitters in the structure of the scintillator crystal. Comparison of the newly calculated and measured spectra will validate the quality of the spectra.

- European metrology project (EURAMET, EMPIR programme) MetroMMC 17FUN02, 2018-2021. Website: http://empir.npl.co.uk/metrommc/. Partners are from France, Germany, Portugal, South Korea and United Kingdom.

  Summary. The main objective of the MetroMMC project is to improve the knowledge of electron capture decay and subsequent atomic relaxation processes. New theoretical calculation techniques and extensive experiments using MMCs will be developed to determine important decay data which are relevant for primary activity standardisations in radionuclide metrology, in cancer therapy on the DNA level, and when studying the early history of the solar system. The experimental parts will be complemented with a new approach based on microwave coupled resonators.

- European metrology project (EURAMET, EMPIR programme) PrimA-LTD 20FUN04, 2021-2024. Website: https://prima-ltd.net/. Partners are from France, Germany, Portugal, Spain and Switzerland.

Summary. Radionuclide metrology and specifically activity standardization are based on well-established measurement techniques, which have been used and improved for decades. However depending on the decay mode, for some nuclides, the achievable uncertainty on the activity is up to an order of magnitude larger than usual. The aim of this project is to achieve new primary activity standardization methods based on low-temperature detectors, in particular by measuring with high statistics the ^{55}Fe and ^{129}I decays. A high-precision theoretical description of these two decays, including both nuclear and atomic structure, will also be conducted.

Recent and future meetings

- Joint radionuclide metrology meetings took virtually place at LNHB (October 26-30, 2020):
  - *i)* Decay Data Evaluation Project (October 26, 2020).
  - *ii)* Nuclear Decay Data Working Group (October 27, 2020).
  - *iii)* Beta-Particle Spectrometry Working Group (October 27, 2020).
  - *iv)* Radionuclide Metrology Technique Working Group (October 28, 2020).
  - *v)* Gamma Spectrometry Working Group (October 29-30, 2020).

- The virtual character of the Working Group meeting (October 27, 2020) noticeably increased the audience, with 26 attendees. This possibility should be kept for future meetings, even without any travel restriction. Four presentations were given:
  - *i)* M. Loidl (LNHB), Measurement of nuclear decay data by means of metallic magnetic calorimeters within European metrology research (EMPIR) projects.
  - *ii)* P. Ranitzsch (PTB), MMC measurements at PTB-BS.
  - *iii)* A. Singh (LNHB), Measurements of beta spectra with silicon detectors.
  - *iv)* X. Mougeot (LNHB), New version of the BetaShape code.

  B. Zimmerman (NIST) announced that the Radioactivity Group successfully defended a project dedicated to the development of a cryogenic facility for radiation measurements. This project will last 5 years and will start in 2021.

- The 2nd MetroMMC stakeholders meeting took place at NPL (December 17, 2021).

- The PrimA-LTD Workshop took place at CIEMAT (November 24, 2022).

- The most recent Working Group meeting took place in Bucharest during the ICRM 2023 conference (March 27-31, 2023). The meeting was in hybrid format, with attendees of the ICRM conference and 24 additional attendees online. Four presentations were given, with one online:
  - *i)* K. Kossert (PTB) – Overview of the European project PrimA-LTD.
  - *ii)* D. Bergeron (NIST) – Progresses and plans on Decay Energy Spectrometry with Transition Edge Sensors.
  - *iii)* G. Cavoto (Sapienza Uni. Roma & INFN Roma) – Development of detectors for ultra-low energy neutrinos. (*online*)

iv) X. Mougeot (LNHB) – Recent collaborative studies on beta decays.

- A virtual MMC Workshop was organized within the PrimA-LTD project (May 2-3, 2024).

- The 2nd stakeholders Workshop of the PrimA-LTD project took place at PTB Braunschweig (May 23, 2024).

- The next Working Group meeting will take place in Paris during the ICRM 2025 conference (May 19-22, 2025). Three presentations are expected:

  i) K. Kossert (PTB) – Outcomes of the PrimA-LTD partners.

  ii) D. Bergeron (NIST) – Towards beta spectroscopy with transition edge sensors at NIST: Experience with ^{239}Np.

  iii) X. Mougeot (LNHB) – Theoretical calculation of the ^{99}Tc forbidden non-unique transition.

- A workshop will be held at CEA Saclay (France) in the framework of the Espace of Structure and Nuclear reaction Theory (ESNT) from 7 to 11 July 2025. It is organized by B. Charles Rasco (Physics Division, Oak Ridge National Laboratory) and X. Mougeot (LNHB) on the topic “Probing nuclear structure with β-decay energy spectra, present and near future state”. A balanced mix of theorists and experimentalists is expected.

On behalf of the Beta-Particle Spectrometry Working Group,

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