Title: Energies of radionuclides on the highest metrological level

Abstract

Mean and maximum energies of relevant beta emitters are required with unprecedented precision to overcome current limitations in radioactivity determination. In addition, precisely measured X-ray energies are key fundamental parameters needed to benchmark theoretical calculations and to establish a comprehensive X-ray database with the most sophisticated code based on the multi-configuration Dirac–Fock method. Research is needed to improve the accuracy with which the energies of radionuclide gamma and X-rays are known to enable the achievement of the sub-eV uncertainties required to provide the precise calibration lines for new experiments in fundamental physics and for studies related to nuclear optical clocks. Metallic magnetic calorimeters (MMC) have a unique combination of high detection efficiency and excellent energy resolution for photon spectrometry making them candidates for measurements of the highest energy resolution, but MMC require further development to enable their greater uptake and use.

Keywords

Low temperature detectors (LTDs), metallic magnetic calorimeters (MMCs), beta energies, atomic mass, photon energies, ultra-high energy resolution spectrometry, nuclear clocks, theoretical modelling of beta decay

Background to the Metrological Challenges

Precise knowledge of the energies of particles and photons emitted during radioactive decay is crucial for radionuclide metrology applications such as nuclear medicine and the long-term management of spent nuclear fuel. Nuclear data is also important for the study of exotic atoms and the development of nuclear optical clocks and contributes to reduced uncertainties in determinations used in neutrino physics, geo- and cosmo-chronology. Pure beta radionuclide activity determinations by liquid scintillation counting (LSC) rely on accurate knowledge of the nuclide's maximum beta energy and its beta spectrum shape. These parameters are also required for activity determinations using classical microcalorimetry. Literature values for ^{241}Pu, a low energy beta emitter, indicate deviations of its maximum beta energy of 4 %, and of its mean beta energy 10 %, whilst evaluated maximum energies indicates that relative uncertainties are often generally several per cent (e.g. ^{107}Pd, ^{171}Tm). For some beta emitting nuclides discrepancies as high 25 % between published values are common. The most advanced existing theoretical models require validation against experimental beta spectra with higher accuracy than currently achievable. Such comparisons are essential to evaluate the inevitable approximations used and to quantify model accuracy. The need for high-accuracy experimental data to validate theoretical models is of particular importance for forbidden non-unique transitions (e.g. ^{241}Pu and ^{171}Tm) due to the dependence on nuclear structure effects.

Energy dispersive cryogenic detectors have demonstrated excellent energy resolutions, with resolving powers in energy of up to 5 000 from a few keV to a few MeV, unattainable with conventional solid-state detectors. In addition, they offer detection efficiencies several orders of magnitude higher than those of wavelength dispersive spectrometers. Therefore, by combining high detection efficiency and excellent energy resolution for photon spectrometry, cryogenic detectors open new fields of exploration in physics such as the testing of quantum electrodynamics under extreme conditions in exotic atoms or for the precise characterisation of the very low-energy isomeric state of ^{229m}Th. This is indispensable for the development of a future nuclear clock. However, cryogenic calorimeters are not absolute energy detectors and are intrinsically non-linear depending on their sensor type and configuration. A precise energy resolution calibration for determining electromagnetic transitions with sub-eV uncertainties is needed based on utilising accurate X-ray or gamma-ray lines and non-linearity corrections. Suitable calibration energies are, however, scarce and their measurements are outdated and partly inconsistent. Beyond their relevance for energy calibration, precisely measured X-ray energies are key fundamental parameters needed to benchmark theoretical calculations and to establish a comprehensive X-ray database with the most sophisticated code based on the Multi-configuration Dirac–Fock method.

A research proposal is invited for the high precision determination of maximum beta energies using MMCs, an independent approach that needs further development and extension to enable its use to plug the gaps in nuclear datasets and with the potential to contribute to future atomic mass evaluations (AME). The proposal should contribute to the development of MMC through detector design, metrological characterisation, analysis techniques including source-absorber preparation and use these developments to generate advances in nuclear data theoretical modelling to produce precise and relevant nuclear decay data (e.g. mean and maximum beta energies, X-ray and gamma-ray energies). In addition, the most advanced existing theoretical nuclear data models also require experimental beta spectra with higher accuracy than currently available for comparison during validation approximations and to quantify model accuracy (e.g. for ^{241}Pu and ^{171}Tm forbidden non-unique transitions due to the dependence on nuclear structure effects).

Objectives

Proposers should address the objectives stated below, which are based on the PRT submissions. Proposers may identify amendments to the objectives or choose to address a subset of them in order to maximise the overall impact, or address budgetary or scientific / technical constraints, but the reasons for this should be clearly stated in the protocol.

The JRP shall focus on new measurement techniques for the determination of beta and photon energies of radionuclides with outstanding high precision.

The specific objectives are

1. To develop MMC-based measurement and analysis techniques for the determination of beta particle and photon reference energies for beta-emitting radionuclides and gamma-ray emitting radionuclides.
2. To determine the maximum and mean energies of selected beta emitters (e.g. ^{241}Pu, ^{33}P, ^{171}Tm, ^{107}Pd) using the developed MMC-based measurement and analytical techniques and by using magnetic spectrometers (e.g. ^{94}Nb, ^{46}Sc, ^{170}Tm) with the aim of reducing radioactivity measurement uncertainties by more than one order of magnitude.
3. To determine gamma-ray energies of selected radionuclides (e.g. ^{241}Am, ^{243}Am, ^{133}Ba) with a target uncertainty of better than 0.5 eV.
4. To extend the most precise theoretical nuclear decay models to enable the description of the spectra from beta decays and atomic relaxation.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs, DIs, research laboratories), research organisations (ICRM WGs Beta-Particle Spectrometry, Nuclear Decay Data, Radionuclide and Metrology Techniques, the Decay Data Evaluation Project (DDEP)), standards developing organisations (ISO/TC85 'Nuclear energy, nuclear technologies and radiological protection', IEC/TC45 'Nuclear instrumentation', CEN/TC 430 Nuclear energy, nuclear technologies, and radiological protection, the International Network of Nuclear Structure and Decay Data Evaluators of the IAEA) and end users (authorities with responsibilities in radiation protection and environmental monitoring, researchers in allied fields).

These objectives will require large-scale approaches that are beyond the capabilities of single National Metrology Institutes and Designated Institutes. Proposers shall give priority to work that aims at excellent science exploring new techniques or methods for metrology and novel primary measurement standards, and brings together the best scientists in Europe and beyond, including other European Partnerships, whilst exploiting the unique capabilities of the National Metrology Institutes and Designated Institutes.

Proposers should establish the current state of the art and explain how their proposed project goes beyond this. In particular, proposers should outline the achievements of the EMPIR 17FUN02 MetroMMC and 20FUN04 PrimA-LTD, and how their proposal will build on those.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 2.0 M€ and has defined an upper limit of 2.5 M€ for this project.

EURAMET also expects the EU Contribution to the external funded beneficiaries to not exceed 40 % of the total EU Contribution across all selected projects in this TP.

Any industrial beneficiaries that will receive significant benefit from the results of the proposed project are expected to be beneficiaries without receiving funding or associated partners.

Potential Impact

Proposals must demonstrate adequate and appropriate participation/links to the ’end user’ community, describing how the project partners will engage with relevant communities during the project to facilitate knowledge transfer and accelerate the uptake of project outputs. Evidence of support from the “end user” community (e.g. letters of support) is also encouraged.

You should detail how your JRP results are going to:

- Address the SRT objectives and deliver solutions to the documented needs,
- Feed into the development of urgent documentary standards through appropriate standards bodies,
- Facilitate improved industrial capability or improved quality of life for European citizens in terms of personal health, protection of the environment and the climate, or energy security,
- Transfer knowledge to the radiation protection and environmental monitoring sector.

You should detail other impacts of your proposed JRP as specified in the document “Guide 4: Writing Joint Research Projects (JRPs)”

You should also detail how your approach to realising the objectives will further the aim of the Partnership to develop a coherent approach at the European level in the field of metrology and include the best available contributions from across the metrology community. Specifically, the opportunities for:

- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards
- the metrology capacity of EURAMET Member States whose metrology programmes are at an early stage of development to be increased
- organisations other than NMIs and DIs to be involved in the work.

Time-scale

The project should be of up to 3 years duration.