The NEXT-SABAT R&D for Barium Tagging

The NEXT collaboration

LOI submitted to the following groups: Instrumentation Frontier: IF08 (Noble); Neutrino Physics: NF05 (Neutrino Properties); Rare Events: RF04 (Lepton Number Violation Processes)

1 Future background free experiments based in detection of the daughter atom in $\beta\beta$ decays

The discovery of neutrinoless double beta decays ($\beta\beta0\nu$) would demonstrate that neutrinos are Majorana particles [1], with a deep impact in particle physics and cosmology. In particular, it could shed light in one of the deepest mysteries of our current understanding of the Universe, that of the cosmic asymmetry between matter and antimatter [2].

The next generation of $\beta\beta0\nu$ experiments aiming to explore the inverse hierarchy of neutrinos masses will require exposures of 1 ton·year and backgrounds of 1 event per year in the region of interest. Exploration of the normal hierarchy will require experiments with exposures of 10 ton·year and backgrounds of 0.1 event per year in the ROI.

In a $\beta\beta0\nu$ decay, the daughter atom is displaced two steps higher in the periodic table w.r.t. its mother. In particular, the decay $^{136}\mathrm{Xe} \rightarrow \mathrm{Ba}^{2+} + 2\ \mathrm{e}\,(+2\ \overline{\nu}_{\mathrm{e}})$, will create a Ba^{2+}cation. No known radioactive process will produce the appearance of such ion in the middle of a detector full of xenon. Furthermore, Ba^{2+} appears at the same time as the two electrons emitted in the decay.

A molecule whose response to optical stimulation changes when it forms a supramolecular complex with a specific ion is a fluorescent indicator, and ions thus bound to molecules are generally referred to as being chelated (one also refers to molecules having formed a complex with the ion as "chelated molecules"). In 2015, Nygren proposed a Ba^{2+} sensor based on fluorescent molecular indicators that could be incorporated within a high-pressure gas xenon TPC (HPXe) [3], such as those being developed by the NEXT Collaboration [4, 5, 6, 7]. The concept was further developed in [8] and followed by an initial proof of concept [9] which resolved individual Ba^{2+} ions on a scanning surface [9] with more than 12 standard deviations.

After this seminal work, the NEXT collaboration launched an intense R&D program. Two complementary approaches are being pursued. The GodXilla R&D, explores the possibility of a barium-tagging detector based on radio-frequency (RF) carpets whose goal is to focus the Ba^{2+} ion in a small scanning region, while the SABAT (Single Atom BArium Tagging) R&D envisions a cathode fully equipped with sensors and scanned by a movable microscopy system. Both approaches use dry molecular indicators to capture the Ba^{2+} ion. Those currently explored by GodXilla are of the type On-Off (*e.g.*, light emission is greatly enhanced for molecules which have chelated an ion w.r.t. uncoordinated states). SABAT is based in a new type of fluorescent bicolor indicator (FBI) which responds to coordination with Ba^{2+} enhancing the emission and shifting its color.

The LOI summarises the progress achieved and plans of the SABAT approach. A separate LOI is also submitted for GodXilla. It is envisioned that both approaches will converge towards an optimised solution for barium tagging in NEXT in the next few years.

2 Fluorescent bicolor indicators

The SABAT R&D is based in a newly synthesised fluorescent bicolor indicator (**FBI**) [10, 11], designed to bind strongly to Ba^{2+} and to shine very brightly when complexed with Ba^{2+} *in a dry medium*, so that the chelated indicator emits ∼300 times more light than molecules which have not captured the ion. Crucially, **the emission spectrum of the chelated indicator is significantly blue-shifted with respect to the unchelated species**, allowing a robust separation of both spectra that provides an additional discrimination factor.

3 BOLD

The goal of the SABAT R&D is to produce a technical design of a detector implementing a fully operative Ba^{2+} tagging system, that we call BOLD (**Barium atOm Light Detector**).

BOLD will be an electroluminescent TPC, building on the experience acquired with the NEXT series of detectors. It will have three major systems: **a**, a sensor capable of tagging, with high efficiency, the single Ba^{2+} ion produced in a $\beta\beta0\nu$ decay, called the **Barium Tagging Detector (BTD)**, located at the cathode; **b**, a barrel detector, made of optical fibres coated with a suitable wavelength shifter, whose goal is to measure the event energy with high resolution (**Energy Detector**, ED); and **c**, a tracking detector, capable of measuring with high resolution the barycentre of the event, the **Tracking Detector (TD)**, located at the anode. The information of these three systems is linked to produce the **Delayed Coincidence Trigger, DCT**, which permits suppressing radioactive backgrounds to virtually zero. The suppression of $\beta\beta2\nu$ to negligible levels is guaranteed by the excellent energy resolution of the detector.

4 SABRA and pBOLD

The next steps in the SABAT R&D program are the construction of two prototypes that will allow us to develop the technical solutions needed for BOLD and demonstrate the feasibility of the detection concepts. These prototypes are called Single Atom Barium-Radium Apparatus (**SABRA**), and prototype-Bold (**pBOLD**). SABRA will demonstrate that Ba^{2+} can be efficiently captured in gas xenon at high pressure by a MTE made of a SAM of FBI indicators and revealed by laser interrogation; pBOLD will demonstrate that physics events can be reconstructed in BOLD with good energy resolution (1% FWHM at Q) and a barycentre precision of better than $1\,\mathrm{cm}^2$ and will provide a proof of concept of the delayed coincidence trigger.

SABRA will use an ion beam producing Ba^{2+} ions of low energy, that can be injected in the test chamber through differential pumping, allowing a detailed study of the barium capture efficiency at low pressure. The beam intensity will be determined by single-ion counting using a secondary electron multiplier (SEM) which will be positioned along the beam axis.

Furthermore, SABRA will include a tagged radium source. As proposed by L. Arazi, Radium is an ideal surrogate for barium, since the first and second ionisation energies are almost identical (5.28 eV and 10.15 eV for Ra, 5.21 eV and 10.0 eV for Ba) and the atomic radii of their ideal gas cores are also very close. We have indeed, already shown in [10, 11] that FBI captures Ra^{2+} efficiently. This allows the use a ^{228}Th source to inject Ra^{2+} ions directly into the gas phase. This type of sources, made of a silicon wafer (which acts also as a detector) coated with a very thin layer of ^{228}Th, finds applications in radiotherapy and can be obtained from specialised companies. A Ra^{2+} source allows individual-atom-tagging (through the alpha particle emitted in the decay), which can be correlated with the observation of a Ra^{2+} in the detector. It also allows a detailed study of the barium capture efficiency at high pressure.

The development of SABRA will run in parallel with the R&D carried out by the GodXilla program, and the outcome of both efforts will be combined in a prototype (pBOLD), will allow a full demonstration of the BOLD concept, and will be a small-scale version (most likely re-using the NEXT-White detector but NEXT-100 is also a possibility) of the proposed ton-scale apparatus.

References

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