Unveiling the neutrino nature by the bolometric investigation of the double beta decay of the nucleus Mo-100

Dévoilement de la nature des neutrinos par l'étude bolométrique de la double désintégration bêta du noyau Mo-100

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Abstract – This thesis project is directed to the experimental study of fundamental neutrino properties, such as the absolute mass scale, the ordering of the neutrino masses and the nature itself of this elusive particle: Majorana or Dirac fermion? In the first case, neutrino would be equal to its antiparticle, representing a new form of Matter. This investigation is performed by searching for a rare nuclear transition, named neutrinoless double beta decay, with advanced detectors operated in above-ground and underground sites with the help of sophisticated cryogenic instruments. The objective of this thesis work is two-fold and implies a data-analysis activity on an existing experiment plus an R&D activity for the improvement of the related detector technology. The PhD student will collaborate to data taking and data analysis of a search based on twenty Li$_2$MoO$_4$ scintillating bolometers performed underground in the Gran Sasso laboratory in Italy (named CUPID-Mo) and searching for neutrinoless double beta decay of the isotope $^{100}$Mo, in the context of an international collaboration. At CSNSM, he/she will perform R&D studies of Li$_2$MoO$_4$ detector prototypes with innovative techniques for background reduction, much more effective than the presently adopted ones and leading to a simplification of the detector structure. This R&D activity will pave the way to a large-scale next-generation experiment, with a high discovery potential, based on the Li$_2$MoO$_4$ technology.

THE CONTEXT OF THE THESIS PROJECT: NEUTRINO PHYSICS WITH DOUBLE BETA DECAY

The proposed thesis project deals with the search for a very rare hypothetical nuclear process: neutrinoless double beta decay ($0\nu\beta\beta$) [1,2]. The current half-life limits on this transition are impressively long, of the order of $10^{25}$-$10^{26}$ y [2]. This feature makes clear why one of the hardest challenges in $0\nu\beta\beta$ decay search is to achieve very low background levels, fighting against any form of environmental radioactivity and locating the experiments underground.

The search for $0\nu\beta\beta$ is a major topic of contemporary elementary particle physics, with strong implications in cosmology. Its possible observation would change dramatically our vision of the intimate nature of matter and would represent a discovery at the roots themselves of human knowledge. Several international collaborations are searching for this nuclear transition with a variety of experiments in Asian, American and European underground sites. The research line proposed here promises to be competitive with the most advanced experiments.

$0\nu\beta\beta$ plays a unique role in understanding fundamental neutrino properties (clarifying if neutrino is a Dirac particle like all the other fermions or a Majorana one, coinciding with its antimatter partner) and exploring the lepton number violation (LNV) [1,2]. Lepton number is a conserved quantity in the Standard Model of elementary particles, and it implies that neutrinos and antineutrinos are different particles. $0\nu\beta\beta$ consists in the transformation of an even-even nucleus into a lighter isobar containing two more protons and accompanied by the emission of two electrons and no other particles (Fig. 1), with a change of the total lepton number by two units: $(A,Z) \rightarrow (A,Z+2)+2e^-$ [1,2]. $0\nu\beta\beta$ can be induced by a plethora of hypothetical LNV mechanisms. Among them, the so-called « mass mechanism » occupies a special place, since it is mediated by the ordinary massive

Figure 1 – Neutrinoless double beta decay.
neutrinos which undergo flavor oscillations observed in the last twenty years. In this mechanism, the rate of the process is proportional – within an uncertainty due to nuclear physics effects – to the square of the effective Majorana neutrino mass $m_{\beta\beta}$, which is a parameter related to the absolute neutrino mass scale and to the mass ordering [1,2]. In fact, it is a linear combination of the three neutrino masses. Present limits on $m_{\beta\beta}$ are in the range 60-600 meV [1,2]. In case of a special combination of the three neutrino masses (named « inverted hierarchy ») $m_{\beta\beta}$ could be higher than 20 meV, opening the way to the observation of $0\nu\beta\beta$. None of the current experiments has the potential to measure such a low value. This is in fact the objective of next-generation $0\nu\beta\beta$ experiments on a 5-10 year time scale. The technology for these searches has not been selected yet.

A very promising approach consists in the construction of a large bolometric experiment, named CUPID [3], exploiting the present CUORE infrastructure. (CUORE is currently one of the most sensitive $0\nu\beta\beta$ experiments and is under commissioning in the Gran Sasso underground laboratory in Italy [4].) CUPID is supposed to probe the inverted-hierarchy hypothesis thanks to a dramatic background improvement with respect to CUORE, achieved – in its baseline version – by the use of luminescent bolometers [3,5], which allow rejecting the surface alpha background that currently limits the CUORE sensitivity.

**DESCRIPTION OF THE THESIS PROJECT**

The present thesis project intends to explore and develop a technology that can be applied in prospect to CUPID, searching for $0\nu\beta\beta$ decay of the promising isotope $^{100}$Mo. The devices proposed to investigate this rare process will be bolometers containing the $^{100}$Mo itself [6-10], acting at the same time as source and detector of the phenomenon.

As in any classical macro-bolometer, the device will consist of a single high-purity dielectric crystal cooled down below 20 mK and thermally coupled to a temperature sensor, which will provide a heat signal for each event. In this type of devices, the detection is mediated by the production of phonons (heat) due to nuclear energy depositions. $0\nu\beta\beta$ decay events of $^{100}$Mo will produce heat signals with a well-defined amplitude. For detector construction, the compound $\text{Li}_2\text{MoO}_4$ is one of the most promising in terms of energy resolution, intrinsic radiopurity and ease of crystal growth [6,7]. The $0\nu\beta\beta$ signal of $^{100}$Mo is a peak at 3034 keV in the sum energy spectrum of the two emitted beta electrons. This spectral region is very clean, since it is outside the bulk of the gamma natural radioactivity (which stops at 2615 keV), but the background is dominated by alpha and beta surface contaminations, which produce an almost flat spectrum. The surface alpha component can be eliminated by matching the $0\nu\beta\beta$ detector with a light detector (which will be a bolometer as well) capable of detecting the scintillation light generated by nuclear events in $\text{Li}_2\text{MoO}_4$ (Fig. 2). Alpha-particle light yield is about 15% of beta-particle light yield at the same thermal energy. Therefore, the simultaneous measurement of heat and scintillation light allows us to reject the alpha background component, just because of the low intensity of the light they emit (Fig. 3).

When this thesis project starts (October/November 2017), a pilot experiment based on this technology, named CUPID-Mo, will be in data taking. The related setup will be completed in summer 2017, in the Gran Sasso underground laboratory in Italy, in the framework of a large international collaboration (France – that has the leadership –, Italy, Russia, Ukraine, and in prospect US and China). CUPID-Mo is based on an array of twenty scintillating bolometers of $\text{Li}_2\text{MoO}_4$.
containing about 3 kg of $^{100}$Mo. The student will perform the data analysis of CUPID-Mo, after joining the analysis team of the collaboration, and participate to shifts at the Gran Sasso laboratory. The objective of the analysis activity is to set limits on the $0\nu\beta\beta$ half-life of $^{100}$Mo (which will be the best ever achieved) and on the Majorana neutrino mass $m_{\beta\beta}$. The CUPID-Mo sensitivity to this parameter is of the order of 100 meV, among the best ones in the international context. However, simulations show that the elimination of the alpha contribution to the background would not be enough to reach the final CUPID goal ($m_{\beta\beta}<20$ meV). In fact, the remaining surface beta component will still populate the region of interest of $0\nu\beta\beta$ with spurious counts. In this thesis project we plan to study, at CSNSM, an innovating promising alternative method to reject alpha and surface beta spurious events, using pulse shape discrimination (PSD). Two different mechanisms will be exploited: (i) On one hand, we will use a feature already observed in many molybdates and recently confirmed by the CSNSM group in Li$_2$MoO$_4$ bolometers. In these devices, one notices a slight difference between alpha and beta events in the pulse shape of the heat signals. The goal is to achieve 99.9% efficiency in alpha event rejection with > 90% of beta signal acceptance, according to the CUPID requirements. (ii) On the other hand, once that alpha events are rejected, beta surface events must be eliminated with an efficiency of at least 90%, keeping an acceptance larger than 90% for bulk events (to which the $0\nu\beta\beta$ signals belong). This will be obtained by fully coating the Li$_2$MoO$_4$ crystals with superconducting Al films of 1-10 $\mu$m, which will act as pulse-shape modifiers for surface events due to subtle solid-state physics phenomena, schematically represented in Fig. 4 and briefly explained in the caption.

The student will study, optimize and characterize both PSD mechanisms in low-mass samples above ground at CSNSM and in large crystals underground, in the Modane underground laboratory, developing the proper algorithms and PSD parameters.

**CANDIDATE PROFILE AND PROGRAM OF THE PhD THESIS ACTIVITY**

**Candidate profile** – The PhD student should be in possession of an M2 degree (or equivalent if he/she is a foreigner) with a specialization in elementary particle or astroparticle physics. He/she is expected to work both on analysis topics, with use and development of numerical codes, and on laboratory-oriented subjects, such as detector preparation / operation and measurement maintenance. He/she should be available to work in at least two experimental sites (CSNSM and an underground laboratory).

**First year** – (i) CUPID-Mo: the PhD student will become familiar with the results and the data structure of the CUPID-Mo experiment and with the related data-analysis tools; he/she will also participate to the measurement maintenance at Gran Sasso – (ii) PSD activity: the PhD student will start to understand how
alpha and beta events can be distinguished by PSD in the CUPID-Mo data; in parallel, he/she will fabricate and study small-scale prototypical Li$_2$MoO$_4$ bolometers at CSNSM with Al film coating.

**Second year** – (i) CUPID-Mo: the PhD student will participate to the data analysis of CUPID-Mo with well defined tasks – (ii) PSD activity: the PhD student will study the efficiency of alpha/beta rejection in CUPID-Mo data with different analysis tools; in parallel, he/she will study the surface rejection efficiency in the Al-coated prototypes fabricated at CSNSM with specially developed analysis tools.

**Third year** – (i) CUPID-Mo: the PhD student will contribute to the extraction on results on $0\nu2\beta$ half-lives and $m_{\beta\beta}$, and to study the residual background – (ii) PSD activity: the PhD student will fabricate and test underground in Modane large Li$_2$MoO$_4$ detectors with Al-film coating.

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