Suggestions on UK strategy in neutrinoless double beta decay

UK Interest group in $0\nu\beta\beta$ decay

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1 Executive summary

In this letter we suggest a possible road map for the UK involvement in the future neutrinoless double beta decay programme. We will lay down a strategic plan and show what in our view the mid-term and long-term priorities should be. We believe that the most important goal of reaching ~ 10 meV sensitivity to Majorana neutrino mass is only realistically achievable through an intermediate step of reaching ~ 40 meV. We also believe that the UK has a unique opportunity to be among the leaders to achieve the first milestone of ~ 40 meV in the next 10-12 years and a sensitivity of ~ 10 meV in the next ~ 20 years through participation in the SuperNEMO and COBRA projects.

2 General information

One of the most exciting results of the last decade has been the growing evidence that neutrinos are massive. In the Standard Model neutrinos have only left handed chiral components and therefore must have exactly zero mass. There are presently a few neutrino measurements which have started to revolutionise the thinking behind neutrinos. The SuperKamiokande and SNO experiments have produced very strong evidence for non-zero neutrino mass by studying atmospheric and solar neutrinos [1, 2]. Recently the KamLAND reactor antineutrino experiment has confirmed the existence of neutrino flavour oscillations and has set stringent limits on the neutrino mass-mixing mechanisms [3].

The significance of this fact, of course, cannot be overstated but the critical factor which will always elude neutrino oscillation experiments is the positive identification of the fundamental type of the neutrino. All the fermions in the Standard Model are Dirac particles by nature, where the antiparticle is the charge conjugate of the particle and has equal but opposite quantum numbers. Neutrinos, however, have an extra possibility due to their neutral charge. It is not forbidden for neutrinos to have a Majorana mass which would imply that the neutrino and antineutrino are the same particle. This possibility seems to be favoured by the theoretical community [4], indeed it is a requirement of some GUTs and theories such as SO(10) or strings.

The only practical way to determine the neutrino nature is to search for neutrinoless double beta decay ($0\nu\beta\beta$) in certain nuclei. Another question which can not be answered by oscillation experiments is the neutrino absolute mass scale. The best current limit for absolute electron neutrino mass comes from $0\nu\beta\beta$ experiments: < 0.3-0.9 eV. [1] Another way of probing the absolute neutrino mass is to study the β spectrum of tritium decay at its end point. This method does not depend on the neutrino nature (Majorana or Dirac). However, the minimum mass scale one can reach with such an approach is $\sim$0.2 eV which is an order of magnitude higher than the mass scale accessible by $0\nu\beta\beta$ experiments.

The oscillation experiments indicate that at least one neutrino has a mass greater than $m_{scale} \approx 50$ meV, a region accessible by future $0\nu\beta\beta$ experiments. It is also worth noting that despite existing uncertainties in nuclear matrix element evaluations and unknown Majorana CP-violation phases neutrinoless double beta decay is the only laboratory approach which can reach the 10-50 meV mass scale. Reaching this sensitivity will be fundamentally important even in absence of the effect. It will rule out the degenerate and inverse mass hierarchies for Majorana neutrinos leaving the normal hierarchy as the only option: one of the few situations where a negative result will be conclusive evidence of a different effect.

The complicated neutrino mass puzzle can only be solved by feeding in experimental information from both neutrino oscillations and $0\nu\beta\beta$ experiments. The current UK leadership in oscillation experiments is widely recognised thanks to vital contributions to SNO and MINOS and important R&D programmes for neutrino factories. Now when neutrino physics has started yielding fundamental results it is very important that the UK takes a leading role in neutrinoless double beta decay which is highly complementary to the existing and planned neutrino oscillation programme.

This was the unanimous view expressed at a meeting held at RAL in September and attended by over 40 people from the particle physics and nuclear physics communities. Those attending that meeting have formed an interest group, subsequently joined by another six from the nuclear physics community. A steering group has been set up to take forward the initiative and a half day meeting has been organised for January in Sussex and a longer three day meeting at the Institute for Particle Physics Phenomenology at Durham in April. The initiative is of interest to both theorists and experimentalists, but also, importantly, is demonstrating the potential to bring together the UK particle physics and nuclear physics communities to pool expertise in a common, exciting physics quest. The big question which has exercised the interest group is which road we should follow given a big variety of existing $\beta\beta$ proposals. There are two main criteria for a successful choice. They are competitiveness and the potential for the UK leadership in the project.

Because the sensitivity to Majorana neutrino mass varies as the square root of the experimentally measurable quantity $-$ the half-life, in order to improve it from existing 300 meV to 10 meV one has to increase the experimental sensitivity by approximately three orders of magnitude! It is therefore now widely accepted by the $\beta\beta$ community that a realistically achievable region for the next generation experiments is at the level of 40 meV. If the decay is not observed it will be necessary to go down further to 10 meV. But even if the decay is observed at, say, the 50 meV level it will be necessary to conduct experiments with 10 meV sensitivity to explore $0\nu\beta\beta$ in greater detail. Thus, our strategy should be to pick up projects best suitable for achieving both milestones.

Given the criteria described above we think that the UK strategy should include mid-term (40 meV) and long-term (10 meV) priorities. Based on the available information we believe that the most competitive project to reach 40 meV sensitivity is SuperNEMO [5] while COBRA [6] which is a novel approach to $\beta\beta$ decay detection appears to be the most promising project to reach 10 meV sensitivity

[1] The result is valid for Majorana neutrinos. The range is determined by uncertainties in nuclear matrix element calculations.

in the long term. An additional advantage is that the UK has already recently become involved in these two projects.

3 SuperNEMO

The detector will be very closely based on the current incarnations of the NEMO-III detector running in the Frejus underground laboratory, in which a UK group has been involved since January 2003. The experiment will use a thin foil of an enriched $\beta\beta$ source hung between tracking chambers and scintillator calorimeters for timing and energy measurement. This experimental method is distinct from the bolometer and semiconductor experiments which only measure energy: both energy and event topology are recorded for greater ease of background removal.

The main isotope which will be studied in SuperNEMO is ^{82}Se . Its main advantages are high $Q_{\beta\beta}$ value and slow Standard Model 2ν decay. Because of this, 100 kg of ^{82}Se should be sufficient to reach 40meV sensitivity in 5 years of measurement which reduces significantly the cost and time of the project [2]. Other isotopes can also be investigated with the SuperNEMO apparatus.

There are two main ingredients which make the project feasible. The first is a zero background from radioactivity. This is being checked by the currently running NEMO-III which is yielding promising results. The second is an improvement of the scintillator energy resolution by a factor of 1.5-2, to have the only background from the tail of the $2\nu\beta\beta$ decay of ^{82}Se below 2 counts in 5 years of data taking. This is the main R&D needed to reach the planned sensitivity, and the UK group is planning to play the lead role in the scintillator development next year (a proposal has been submitted to the PPRP requesting the money for scintillator R&D).

The discovery potential of SuperNEMO can be illustrated with the following example. If $< m_\nu > =$ 0.05 eV and the nuclear matrix element of ^{82}Se is favourable, in 5 years of data taking 4.5 "golden" $0\nu\beta\beta$ events will be observed (two clearly identified electron tracks emitted from the source and having the right summed energy). For an energy resolution of $8\%/\sqrt{E}$ (which is the aim of the R&D) 0.6 background events from $2\nu\beta\beta$ decay are expected for the same time period.

This approach has the advantage of not needing a long lead time for R&D, the feasibility having been demonstrated in the previous incarnations over more than 10 years. The collaboration believes that the most promising site for the future SuperNEMO detector is the Boulby mine (subject to approval from the Boulby facility management). Basing the detector in Boulby will naturally give the UK a strong leadership in the construction and running of the experiment and will turn the Boulby facility into a truly international underground laboratory.

Given the modest R&D needed and the very well known technology, with the appropriate investment, SuperNEMO will have a significant head start on the competition. The experiment can be the first to reach 40 meV sensitivity by 2014.

[2] One of the main parts of a $\beta\beta$ project budget is for enriched materials production. It is also a lengthy process with typical current enrichment capabilities of 30 kg/yr

4 COBRA

Studying much larger isotope quantities (500-1000 kg) with an experiment of the SuperNEMO type does not seem practical as the detector in this case becomes too big for low background physics. If SuperNEMO does not show any evidence, a different approach is necessary to go to even smaller mass scales. Even in case of a positive identification, an independent confirmation with other isotopes and an attempt to disentangle the underlying physics mechanism is mandatory. COBRA is such an approach. The idea is to use a large array of CdZnTe semiconductor crystals [6], the advantage being that the decay occurs inside the detector volume. CdTe contains 7 (9) double beta isotopes, where ^{130}Te and ^{116}Cd are the most promising ones for the neutrino mass search. To be more specific, using CdZnTe detectors, going below a 50 meV sensitivity would imply about 350 kg in the case of ^{130}Te and $\sim$ 1700 kg for ^{116}Cd . In order to keep the masses of detectors under control, an enrichment in ^{116}Cd is necessary. Here, an enrichment factor of five would be sufficient, however factors of 15 are easily obtainable. Using commercially available enriched ^{116}Cd and ^{130}Te could significantly reduce the number of detectors needed, the only requirement is that about 500 moles of each isotope should be used.

With the currently favoured 1 cm^3 detectors, an array of 40x40x40 cm^3 would result in 370 kg, leaving a small safety margin. The number of detectors and corresponding readout channels would be 64000, a number small compared to semiconductor readout in high energy physics experiments. However, the final mass used should be chosen in a way to account for full coverage of the expected neutrino mass range, including nuclear matrix element uncertainties. The latter will be partly compensated by the fact that with ^{116}Cd and ^{130}Te two isotopes will be brought into the interesting region.

Yet another strong motivation for the COBRA experiment is the fact that even if really observed, the underlying physics process mediating $0\nu\beta\beta$ remains unknown. In addition to the popular light Majorana neutrino exchange, other possibilities are discussed in the literature, such as the exchange of heavy Majorana neutrinos, double charged Higgs bosons, leptoquarks or right-handed weak currents and R-parity violating SUSY couplings. Thus it is necessary to explore other processes in double beta decay such as transitions to excited states or double positron decay and double electron capture. Three different decay channels can be considered for the latter

$$(Z,A) \to (Z-2,A) + 2e^+ + (2\nu_e) \qquad (\beta^+\beta^+)$$
$$e^- + (Z,A) \to (Z-2,A) + e^+ + (2\nu_e) \qquad (\beta^+/EC)$$
$$2e^- + (Z,A) \to (Z-2,A) + (2\nu_e) \qquad (EC/EC)$$

where the last two cases involve electron capture (EC). These modes are mainly driven by right handed weak currents instead of light Majorana neutrinos. The isotope of special interest in COBRA is ^{106}Cd .

Currently COBRA is running four detectors in the Gran Sasso Underground Laboratory to get first information on background components and their possible reduction. In 2004 a neutron shield will be added and various improvements on the shielding are foreseen. A request has been submitted to PPRP for seed money, which would allow the purchase of more detectors and equipment to test various readout options and the fundamental concepts. COBRA is running already under a UK leadership.

5 Conclusion

There is an exciting opportunity for the UK to lead the search for neutrinoless double beta decay which will greatly enhance the current UK leadership in neutrino physics. We have identified a mid-term and long term strategy that in our view will maintain the best equilibrium between competitiveness and UK leadership in the field. The SuperNEMO experiment, based on very well known technologies with more than a decade of R&D work already done, can be started on a short time scale reaching 40 meV sensitivity before other competitors. For the next step, going down further in neutrino mass sensitivity, a COBRA-like approach is foreseen. Being a rather new concept never used before in ultralow-background physics, its R&D phase should be pushed forward in the time period of SuperNEMO construction. The two experiments are complementary and successive steps with major UK contributions and leadership which will hopefully culminate in the discovery of neutrinoless double beta decay.

References

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