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THE β–DECAY OF ^{187}Re STUDIED WITH A CRYOGENIC μ–CALORIMETER

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Abstract

An experiment to study the β-decay of ^{187}Re using a cryogenic μ-calorimeter is presented. The physical motivations for undertaking a rhenium experiment, in the context of providing a limit on the $\overline{\nu_e}$ mass, are briefly discussed. Preliminary results on the ^{187}Re β spectrum, obtained with a NTD-Ge thermistor coupled to a superconducting rhenium crystal, are included, where the energy resolution is measured by an external ^{55}Fe X-ray source to be σ of 54 eV at 5.9 keV. Future considerations relating to radioactive background, improved detector performance, energy calibration and ^{187}Re β-spectral analysis are proposed.

1. Introduction

The merits of developing a cryogenic rhenium detector to perform a sensitive measurement of the $\overline{\nu_e}$ mass from the observation of the β decay of ^{187}Re, will be discussed in the context of the current tritium experiments. The kinematical limit to the electron anti-neutrino mass is derived from experiments[1,2,3,4] that, by means of high resolution magnetic or electrostatic spectrometers, measure the spectrum of the β electrons emitted by a ^{3}H source in the end point energy region. The existence of finite anti-neutrino mass is exhibited theoretically as a distortion in the β energy spectrum with a a counting rate deficit, in first approximation proportional to $m^2_{\overline{\nu_e}}$, near the spectrum end point.

The experimental determination of $m^2_{\overline{\nu_e}}$ from the series of ^{3}H experiments undertaken, yields a consistently negative value, with the most recent upper limit[5] of Lobashev *et*

al. given as $m^2_{\overline{\nu_e}} < -18 \pm 6$ eV^2. The feature of negative $m^2_{\overline{\nu_e}}$, corresponding to excess counting statistics close to the spectral end point, has been speculated in the past to arise from an incomplete knowledge of the final state effects in tritium or unknown systematic uncertainties. A further interpretation[6] is a possible additional neutrino branch of mass 150 eV. To clarify such a speculation, the requirement for a *calorimetric* experiment, where final state effects are removed, is clearly important. The results of Lobashev *et al.*, with the highest statistical accuracy, however indicate that the negative $m^2_{\overline{\nu_e}}$ can be reconciled to a monoenergetic spectral excess on the differential β energy spectrum located 7 eV below the end point. The implications of such a result (new physics) demand that an alternative experiment, with an independent cryogenic detection technique and a different β isotope, ^{187}Re, be made to clarify the situation.

The analysis of the tritium spectrometer experiments requires detailed understanding of the atomic corrections, the energy lost by the emitted electron in the external ^{3}H source and the final state energy distribution of the daughter atomic or molecular system generated from tritium decay. Therefore the total absorption *calorimetric* design of the cryogenic rhenium experiment is chosen to avoid such uncertainties in the final state effects. With a calorimetric measurement of the entire β spectrum, only a small fraction of decay events, proportional to $2(3\ m_{\overline{\nu_e}}/Q)^3$, is contained in the region of the spectrum, near the end point, which is sensitive to anti-neutrino mass, $m_{\overline{\nu_e}}$. The argument for a ^{187}Re absorption experiment in preference to a tritium absorption experiment, is clear when comparing the relative end point energies, $Q = 2.6$ keV and 18.6 keV respectively. For example, to attain a limit $m_{\overline{\nu_e}} < 5$ eV, the corresponding reduction in the counting statistics required with rhenium, in place of tritium, is of order 400.

The end point energy of ^{187}Re is 2.6 keV, which is the lowest known Q value for β emission. Therefore to measure the β spectrum competitively to tritium standards, a sensitive detection mechanism with adequate energy resolution is required. Moreover the total de-excitation energy of the final system must be detected with the same response efficiency as the β-ray energy. The cryogenic μ-calorimeters are presently the only detectors with an energy resolution sufficient to set a sensitive limit to the neutrino mass and an energy response independent of the kind of excitation. The description of the ^{187}Re

isotope and the μ-calorimetric technique and geometry for measuring the β spectrum will be presented respectively in Section 2 and Section 3 below. Preliminary data from X- and γ-ray irradiation which illustrate the detector properties will be included in Section 4, in addition, to measurements of the ^{187}Re β spectra. Finally, a discussion on future improvements required to attain sensitivity to set competitive limits on $m_{\overline{\nu_e}}$ will be the subject of Section 5.

2. The ^{187}Re β Isotope

The nuclear β transition is from $^{187}_{85}$Re (spin $\frac{5}{2}^+$) to $^{187}_{86}$Os (spin $\frac{1}{2}^-$) and is assigned the form of a *unique* first forbidden decay. The description of the transition as being *unique* results from it being governed by a single dominant matrix element, generated from a single β moment which is as reliably calculable as the moment associated with an *allowed* β transition. A shape factor, proportional to this matrix element, can be calculated in exact form, to correct the β energy spectrum from energy dependences associated with the forbidden transition, in such a way as to linearize the Kurie Plot. The theoretical analysis of the Fermi function, $F(Z,E)$ of the ^{187}Re β spectrum requires attention due to the high $Z = 85$ and low energies $E < 2.6$ keV involved. We should like to thank Dr. M.Rysavy for the useful discussions on the subject of $F(Z,E)$ and we acknowledge the effort to perform detailed calculations that M.Rysavy and J.Rizec have undertaken at the Nuclear Physics Institute at Rez near Prague. The decay of ^{187}Re is not as an isolated atom but rather in a rhenium crystal lattice and this is expected to produce an oscillatory modulation of the β-spectrum when the electron wavelength approaches the lattice parameter[7]. However, the effect expected from this phenomenen is minimal and is calculated to be negligible above 1.5 keV.

3. The Properties of the Rhenium μ-Calorimeter

The μ-calorimetric detection mechanism corresponds to measuring the thermal signal, generated by β electrons in the rhenium substrate, by thermally coupling a thermistor to the crystal. The rhenium crystal therefore acts, effectively, as both the source and the

detector. The magnitude of the thermal heat pulse is inversely proportional to the specific heat of the crystal, and this is applied to advantage with rhenium by virtue of it being a superconductor and therefore characterized by low intrinsic specific heat. A detailed study of the contributions to the specific heat of rhenium is reviewed elsewhere[8].

In parallel to the development phase of this cryogenic detector programme, spectral measurements were taken of the rhenium β spectrum. In the most recent measurement, the composite μ-calorimeter detector was fabricated by gluing an NTD germanium thermistor, of dimensions $0.5 \times 0.25 \times 0.25$ mm^3 to a small natural metallic rhenium crystal, $0.5 \times 0.5 \times 0.5$ mm^3. The predominant naturally occurring isotope of rhenium is the β emitter ^{187}Re which has an abundance of 62.6 %. The mass of rhenium used in the experiment, in this case 2 mg, corresponds to a rate of approximately 2 Hz of ^{187}Re β decay events, and this represents the limiting counting rate of the bolometer, where the thermal time response varies between 20 – 50 ms, depending on the specific thermal link. To enable a total absorption experiment, and thereby to prevent partial energy loss at the crystal surfaces, a thin film coating will be evaporated on the rhenium crystal. An investigation is currently under progress in selecting the optimum material.

Thermal and electrical connections to the mixing chamber of the Dilution refrigerator, and electrical connections to a source follower, placed inside the refrigerator, are provided by two ultrasonic bonded 20 μm aluminium wires. A schematic outline of the device is shown in Figure 1. The thermistor signal, after amplification by a factor 8×10^4 and after low pass filtering, is transferred to a 12 bit waveform recorder. The recorded transients are then analyzed off-line and for each pulse the following information is obtained; by optimum filtering, an amplitude proportional to the energy release, and a shape factor that measures the deviation of the pulse form from a reference shape. The reference pulse shape is obtained by averaging several hundred selected input pulses, ensuring that no pulses corrupted by pile-up events are included. Currently, an investigation into an alternative system of *adaptive* filtering is being pursued, and the preliminary results are encouraging[9].

The data acquisition and analysis system are described in detail, in previous publications[10,11]. In summary, a Camac waveform recorder (LeCroy 6810) is controlled by a

Digital VAX station through a crate controller 3929 from Kinetics System. The maximum acquisition rate is approximately 50 Hz, however this exceeds the present attainable rate associated with the rhenium bolometric detectors. The pulse analysis has been transferred from the IBM PC running ASYST to the VAX station, with the result that a considerable improvement in the processing time for a single waveform (approximately 20 ms) has been achieved.

4. Experimental Results

The linearity of a μ-calorimeter has been tested previously[10] with a detector made with a 1 mm^3 rhenium crystal and a 1 mm^3 thermistor, where the overall thermal capacity was greater by a factor of 30 compared to the present detector. No deviation from linearity was observed within instrumentation limits in the energy ranges 14 – 60 keV ($\pm$ 0.1 %) and 36 - 384 keV (1 %) after exposure with ^{241}Am and ^{133}Ba sources respectively.

With the present μ-calorimeter detector, outlined above, which has the smaller thermistor sensor, the response to X- and γ-rays from an ^{241}Am source was investigated. The spectrum is displayed in Figure 2 and includes the ^{241}Am 59.6 keV γ-ray and lower energy X-rays associated with Pb collimator fluorescence, characteristic Np X-rays and Re X-ray escape peaks. The detail of the low energy X-rays are illustrated in the inset. The energy linearity over this range was evaluated from a polynomial fit and this yielded a quadratic to linear ratio of 1.7 $\pm$ 0.02$\times$ 10^{-4} and a constant offset of -82.80 $\pm$ 62.97.

The spectrum acquired with an external calibration source, ^{55}Fe, in addition, to the rhenium β spectrum, is illustrated in Figure 3. The two calibration Mn X-ray peaks at 5897 eV and 6490 eV are completely resolvable with the energy resolution σ measured to be 54 eV. A filter was introduced in front of the detector to produce K_α and K_β X-ray lines of equivalent intensity. The lower energy limit of the ^{187}Re β spectrum is approximately 1 keV and the future goal is to reduce this to below 100 eV to allow a greater range for investigation of shape distortions. Recent results, where 90 eV M-shell X-rays have been detected above threshold, were obtained within the Genova μ-calorimetric group. The data was measured with a similar design of detector, with a superconducting tin

substrate substituted for rhenium. Analysis of the β spectrum, in terms of a simple Kurie Plot is illustrated in Figure 4. The feature of note is the linear form of the Kurie Plot. A detailed analysis to extract $m_{\overline{\nu_e}}$ limits has not been applied to the data as the statistics are too low, a greater understanding of the electron response function is required and an investigation of linearity at energies below 6 keV requires to be undertaken.

These results should be compared with previous data[10], that was acquired in 1992 with an identical rhenium crystal. In that case, the resolution σ at 14 kev was 500 eV, and consequently the two Mn K_α, K_β X-ray spectral lines were unresolvable. The improvement in the performance of the new detector results from using a smaller higher quality NTD-Ge thermistor, modifying the electronics and by reducing the environmental noise, in particular attributable to microphonics. The measured energy resolution is completely consistent with the observed signal to noise ratio. The noise amplitude scales according to the square root of the thermistor electrical resistance, as is expected for Johnson noise within the device; the contribution of the amplifier noise, 0.8 nV/$\sqrt{Hz}$ is negligible.

The signal amplitude is limited by the detector heat capacity, mainly due to the thermistor contribution, which is 10 pJ/K at 100 mK (the heat capacity of the rhenium is 4 pJ/K). Indeed, the energy resolution obtained with an ^{55}Fe source irradiating the composite detector, (rhenium crystal + thermistor) is similar to that obtained by irradiating the thermistor alone. It was shown[12] that the energy thermalization is reasonably fast and complete, provided that the operating temperature of the system is maintained above $T_c/T_D = 2 \times 10^{-4}$. In this way, it is possible to produce efficient μ-calorimeters with a superconducting absorber, but, because of the lower limit on the operating temperature the overall heat capacity of the thermistor will be the limiting factor in the achievable energy resolution. However, it has also been observed[12,13] that by applying a thin film coating of a convenient material, either Au or Bi, to the rhenium crystal a more efficient thermalization has been obtained at lower temperatures. This effect, which requires further investigation could enable the detector to be operated below $T_c/T_D = 2 \times 10^{-4}$ and would thereby reduce the thermistor and parasitic heat capacity.

With the present detector it should be possible, in approximately two months of data taking and a reliable means of calibration, to set an upper limit on the anti-neutrino mass

of 20 eV. However the aim first is to proceed further with the μ-calorimeter detector development. In detail, a smaller thermistor ($0.1 \times 0.1 \times 0.25$ mm^3) has been purchased and is presently under test. From preliminary measurements on the new NTD-Ge thermistor, it is anticipated that an improvement in the energy resolution by a factor of about 4 will be achieved, that is, an expected energy resolution, σ of 15 eV at 5.9 keV. After the fabrication and testing of the composite μ-calorimeter, effort will be directed to calibrating the system at lower energies, to enable the level of energy dependence in the resolution and the linearity in the energy range of interest to be established. No convenient X-ray source is available to have direct calibration lines below 5 keV hence the initial plan is to adopt X-ray fluorescent techniques. For example, the fluorescent K X-ray line of chlorine at 2.7 keV can be obtained by irradiating a sheet of PVC with a high activity annular source of ^{55}Fe. However, due to the small dimensions of the detector, a high X-ray intensity is required to obtain sufficient statistics within a reasonable calibration time and with this condition it is difficult to avoid supplementary heating of the detector environment, with a consequent drift of the operating conditions. To address this problem, a system of thermal shields and collimators is being designed and tested.

5. Future Proposals

There are various features of this cryogenic experiment that require to be studied to allow a sensitive measurement of $m_{\overline{\nu_e}}$ to be made. A brief outline of these aspects of the experiment will be presented.

The level of radioactive background, which is superimposed on the low energy rhenium spectrum, requires to be understood and minimized. This originates both from within the rhenium crystal and in the external environment. The former radioactive source will be examined by low activity measurements, and thereafter efforts made to obtain high purity rhenium crystals, to replace the currently commercially bought samples. Communication to this effect has already been established with institutes in Moscow and the Ukraine. For an analysis of the chemical purity of the crystals Auger electron spectroscopy will be applied. Moreover, by isotopic separation, a crystal of pure ^{187}Re could possibly be

prepared which would reduce the active mass of the sample and correspondingly the effects from external radioactivity. To enable low activity from the environment, both active and passive shielding and a low background facility will be considered in the future.

The total absorption criterion requires a thin film coating and to provide a more uniform detector, the stable rhenium isotope ^{186}Re will be considered as a candidate. The preparation of an epitaxial film will ensure minimal lattice mismatch and should thereby ensure the minimum of phonon loss at the surfaces. The exercise of applying a stable rhenium coating to the crystal is however anticipated to be a difficult procedure. With, the cubic shape of the rhenium crystals and the high Z for efficient energy absorption, surface effects in practice should consequently be small.

The long time response of μ-calorimeters limits considerably the counting statistics for a given time period, and hence alternative cryogenic sensors will be considered; superconducting tunnel junctions (STJ) and transition edge thermometers. Two orders of magnitude improvement in time response are feasible with the latter detectors. In the case of the STJ sensor, insight into the coupled quasiparticle and phonon transport within superconducting rhenium would be gained, and with the superconducting rhenium substrate, the mechanism of quasiparticle trapping could be exploited[14,15]. This will be undertaken as a parallel detector development programme.

The fundamental description of the electron response function will require to be studied. Surface effects will first be examined by comparing X-ray responses over a range of energies and interaction lengths. A preliminary study on the feasibility of a calibration method, using an internal source (implanted), either electron capture or internal conversion, will be undertaken. Finally, the details and assumptions of the nuclear physics calculations for rhenium will require clarification and detailed theoretical evaluation.

6. Conclusion

A cryogenic μ-calorimeter, whose properties are sufficient to impose a conservative limit to electron anti-neutrino mass, by studying the ^{187}Re β decay has been successfully tested, and preliminary data obtained. The objective now is to prepare the new detector, with improved energy resolution, and to acquire a high statistics β spectrum, with an energy calibration using low energy X-ray fluorescence. Considerable effort will be directed to realize the experimental aims, outlined in the future proposal.

7. Acknowledgements

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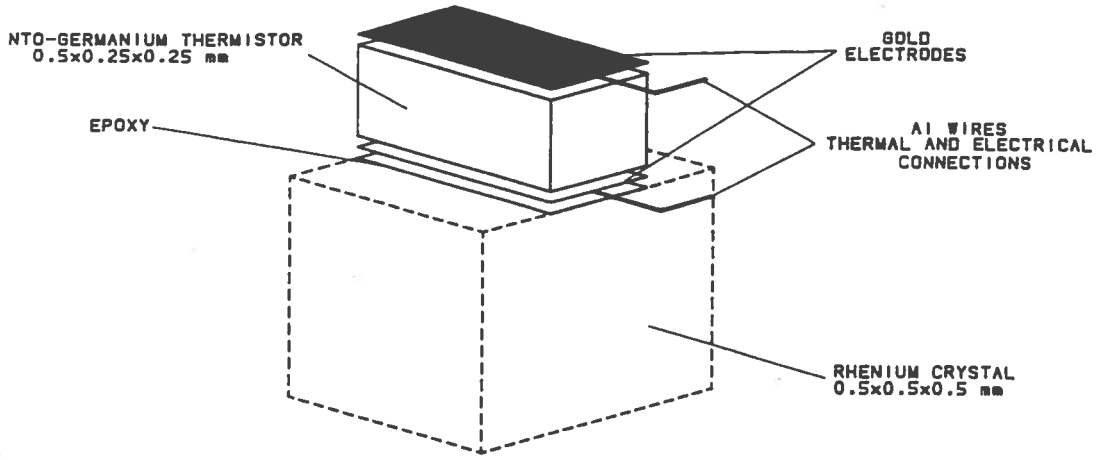

Figure 1. The arrangement of the μ-calorimetric detector with thermal and electrical connections. Thermal connections to the Dilution refrigerator mixing chamber and electrical connections to a source follower, placed inside the refrigerator, are provided by two ultrasonic bonded 20 μm aluminium wires placed sideways. The distributed thermal impedance of the thin gold film electrodes is practically in series to that of the aluminium wires.

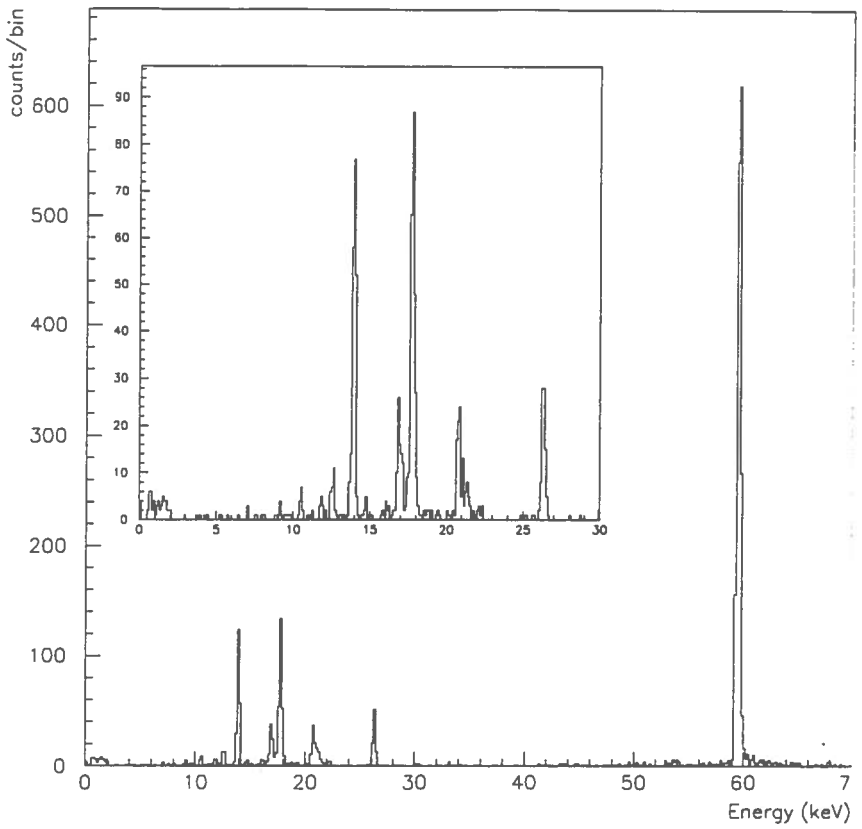

Figure 2. The X- and γ-ray spectrum obtained from a ^{241}Am source. The inset is a detail of the lower energy X-ray range.

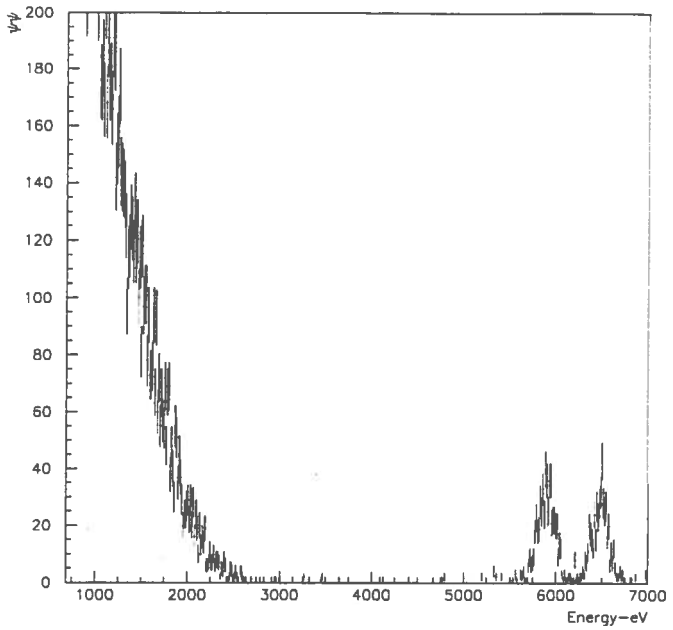

Figure 3. The ^{187}Re β spectrum, including ^{55}Fe calibration X-rays, recently obtained with the test detector.

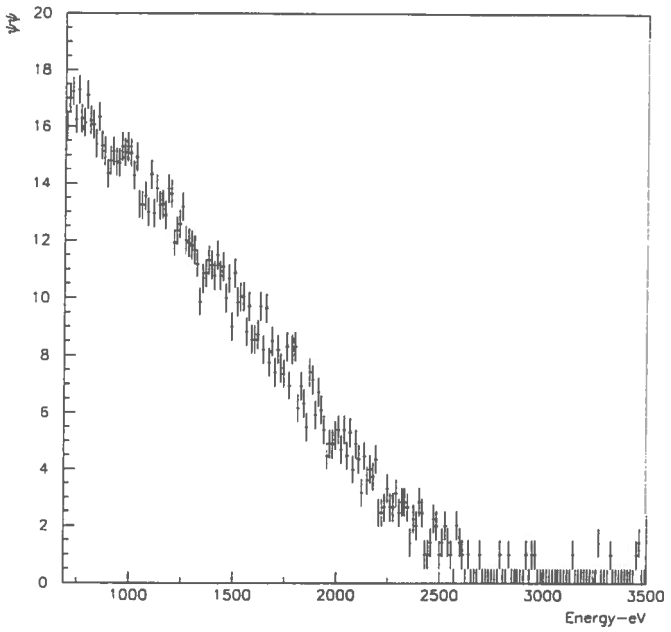

Figure 4. A simple Kurie Plot representation of the ^{187}Re β spectrum obtained with the test detector.