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DETECTION OF ^{187}Re BETA DECAY WITH A CRYOGENIC MICROCALORIMETER: PRELIMINARY RESULTS

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ABSTRACT

^{187}Re, being the nuclide with the lowest known Q-value for β-decay is the best candidate to set a limit to the antineutrino mass in a total absorption experiment.

We report a preliminary measure of the end-point energy of the decay, obtained with a cryogenic microcalorimeter made with a superconducting rhenium crystal and a germanium thermistor .

Limits and possible improvements of the detector are discussed.

In an ideal total absorption experiment on β-decay, the total visible energy release following the decay $E_T = E_\beta + \varepsilon^*$ is measured, including the deexcitation energy ε^* of the final states in which the daughter atom is left.

If after relaxation a definite ground state is reached, the total energy spectrum $N(E_T)$ in proximity of the end-point is much less affected by the variety of intermediate atomic levels following the β transition than the electron energy spectrum $N(E_\beta)$ and the analysis to detect possible deviation due to a finite neutrino mass is consequently easier. Indeed, for an allowed β_--decay, the β energy spectrum is:

$$N(E_\beta) \sim \Sigma_i W_i \, p_{\beta i} \, E_{\beta i} F(E_{\beta i},Z)(E_0 - E_{\beta i})^2 \qquad (1)$$

and the total visible energy spectrum is:

$$N(E_T) \sim (E_0 - E_T)^2 \, \Sigma_i W_i \, p_{\beta i} \, E_{\beta i} F(E_{\beta i},Z) \qquad (2)$$

where W_i is the branching ratio for β transitions to an atomic state with excitation energy ε^*_i, $E_T = E_{\beta i} + \varepsilon^*_i$ and the other symbols have the usual meaning. At the low energies of interest for neutrino mass detection experiments the factor $p_{\beta i}\, E_{\beta i}\, F(E_{\beta i},Z)$ is very slightly dependent on E and $N(E_T)$ is almost proportional to $(E_0 - E_T)^2$.

In a total absorption experiment, as the detector must record the full extension of the spectrum and not only the small region of interest near the end-point energy and because of counting rate limitations, only with very low energy transitions it is possible to reach within a reasonable time the statistical accuracy required to set a significant upper limit to the neutrino mass.

Total absorption experiments were actually made using tritium implanted(1) or diffused(2) in semiconductor detectors.

^{187}Re is a new, interesting candidate for such an investigation: the decay is a first forbidden unique transition, therefore the spectral shape is expected to be simple, and the maximum β energy is under 2.7 kev, which makes rhenium about 10^4 times more efficient than tritium in accumulating data in the region of interest.

However due to the low energy and low specific activity of ^{187}Re, it would be almost impossible to study its β spectrum without using an internal counting method.

Indeed the two previous measurements(3,4) of the rhenium β-spectrum reported in the literature, made with rhenium metallorganic vapor filling proportional counters, belong to this class.

Spins and parities of ^{187}Re and ^{187}Os are $5/2^+$ and $1/2^-$; the β-spectrum for this first forbidden unique transition, in the standard notation of β spectroscopy(5) and taking into account the variety of atomic final states, is:

$$N(E_\beta)dE_\beta \sim p_\beta\, E_\beta\, F(E_\beta, Z) \;\; S(E_\beta, E_{0i})\, (E_{0i} - E_{\beta i})^2 dE_\beta \tag{3}$$

and, for the total energy release we have:

$$N(E_T)\, dE_T \sim (E_0 - E_T)^2 \;\; \{\Sigma_i\, W_i\, p_{\beta i}\, E_{\beta i}\, S\,(E_{\beta i})\, F\,(E_{\beta i}, Z)\} dE_T \tag{4}$$

Coulomb and screening effects, computed in impulse approximation, make the factor $p_{\beta i}\, E_{\beta i}\, F(E_{\beta i}, Z)\; S(E_\beta)$ almost constant in the energy range of interest. According to Buhring calculations, reported by Huster and Verbeek(4), it increases of about 4% between 400 ev and 2100 ev.

We can then write, in good approximation:

$$[N(\, E_T)/p_T\, E_T\, F\,(E_T,Z)]^{1/2} \sim (E_0 - E_T) = (Q_0 - Q_T) \tag{5}$$

where p_T is the momentum of an electron of energy E_T.

We report here a new determination of the end-point energy of ^{187}Re β rays made using a cryogenic Rhenium microcalorimeter.

The device was built gluing a small (.01 mm^3) natural Rhenium (62.8% of ^{187}Re) crystal to a germanium thermistor and was operated at 80 mK in a dilution refrigerator. In working condition the rhenium was superconducting (T_c = 1.6 K). The crystal was coated with a thin sheet of aluminum, about 1 μm thick. A device of this kind has been already described(6).

In Fig. 1 and Fig. 2 the typical pulse shape and the x and γ spectrum from an ^{241}Am calibration source are reported.

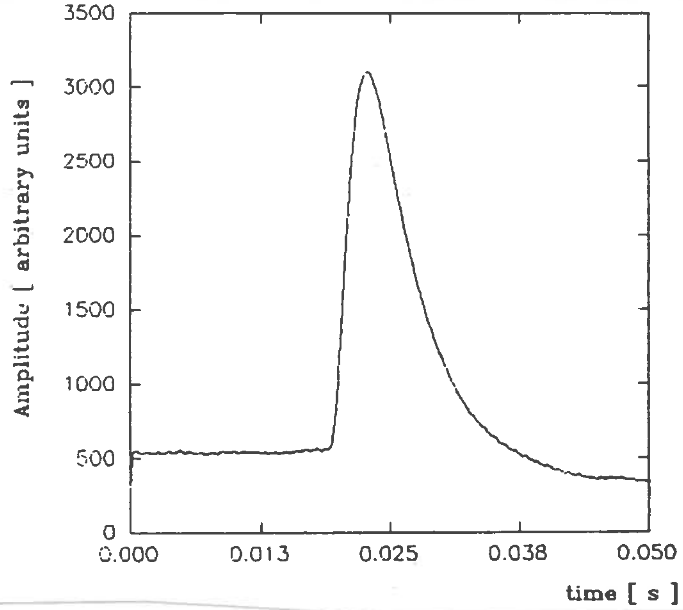

FIG. 1 – Single μ–calorimetrer pulse (60 keV ^{241}Am photon).

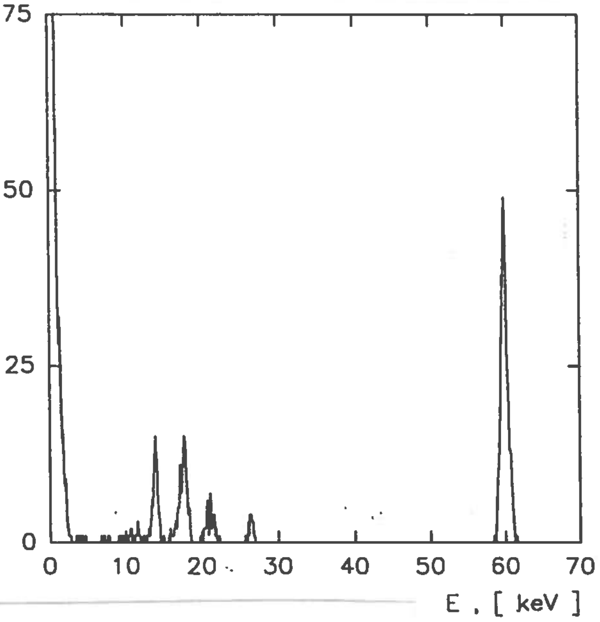

FIG. 2 – X and γ spectrum from ^{241}Am.

The energy resolution resulted to be 550 ev FWHM and the linearity up to 60 Kev better than .1%.

In the spectrum reported in Fig. 3 at the left of the peak, obtained with a ^{55}Fe source, the contribution of the rhenium decay is clearly visible below 2.7 Kev.

A background subtraction of 3 counts/h was applied to the spectrum in the region between 1.2 and 3 kev. The background level, that at 2.0 Kev was below 1% of the counting rate, was determined extrapolating the counting rate between 3 and 5 kev.

A number of measurements was made to investigate the origin of the background, that is mostly due to environmental radioactivity. Assuming secular equilibrium, the counting rate in the region of interest due to the U and Th families was evaluated to be less than 1 count/h. At the low energy end the raw spectrum is dominated by the noise contribution. The counting rate below 500 ev is satisfactorily fitted assuming a gaussian distribution with $\sigma = 200$ev centered at zero energy. The extrapolated contribution of the noise distribution is negligible above 1 kev.

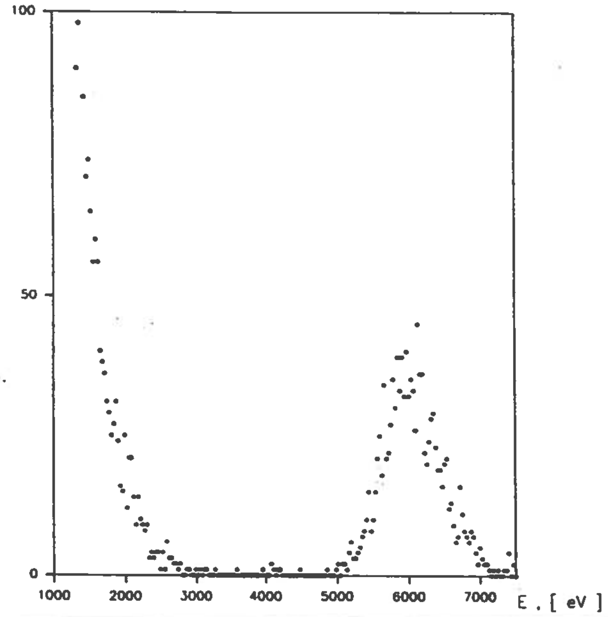

FIG. 3 – ^{187}Re β spectrum and ^{55}Fe calibration peak.

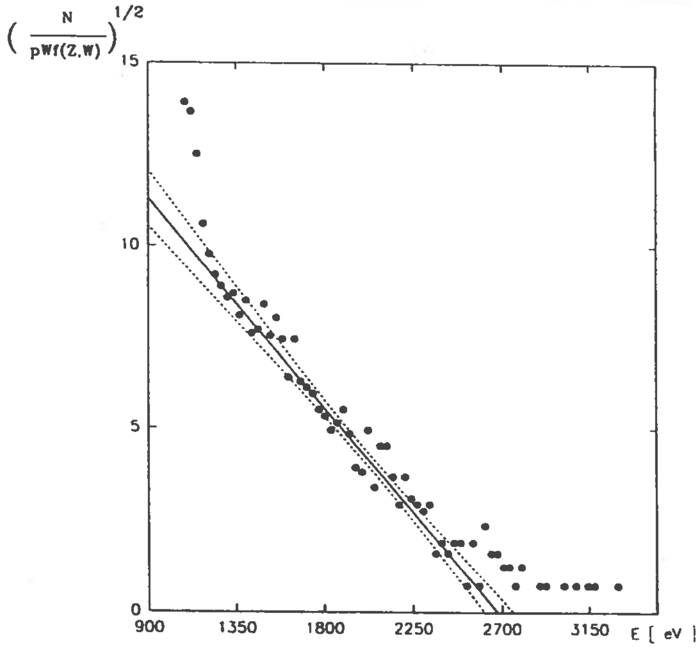

FIG. 4 – Kurie plot of ^{187}Re.

The Kurie plot beyond 1.2 Kev is linear with an end-point energy Q_0=(2667 ± 20)ev. Below 1.2 kev the data indicate an excess of counts with respect to the linear extrapolation of the Kurie plot.

As shown in Table I the Q_0 value is in very good agreement with older experiments performed with gas proportional counters.

Table I – Half-life and end-point energies of ^{187}Re

Half-life, (yr)	End-point energy, (kev)	Method	Ref.
$(6.2\pm0.6)\times10^{10}$*	(2.667 ± 0.020)	Cryogenic μcalorimeter	This work
$(6.6\pm1.3)\times10^{10}$*	(2.62 ± 0.09)	Proportional counter	[3] (1965)
----------------------	(2.65 ± 0.04)	Proportional counter	[4] (1967)
$(4.35\pm0.13)\times10^{10}$	----------------------	^{187}Os growth in ^{187}Re	[7] (1984)

*) Half-life evaluated with a linear extrapolation of the Kurie-plot.

The Rhenium half-life, obtained extrapolating linearly back to Q = 0 the Kurie-plot, results to be $T_0 = (5.5 \pm 2) \times 10^{10}$ year and exceeds, like the value obtained with a similar procedure by Brodzinski and Conway, the reliable results of radiochemical and mass spectrometry experiments $T_0 = (4.35 \pm 0.13) \times 10^{10}$ year(7). The disagreement might be attributed to the observed deviation of the spectrum from a linear Kurie-plot below 1.2 kev and to direct transition to bound states.

A complete understanding of the half-life problem and of the low energy behaviour of the β spectrum requires detailed exact calculations of Coulomb effects and screening corrections and, from the experimental point of view, a better control of noise instabilities and better energy resolution, that are within our aims.

Our main effort, at the moment, is directed toward improvement of the detector time response and energy resolution.

Indeed the limit that can be set to the neutrino mass depends not only on the energy resolution but, mainly, on the statistics in the end-point region and then on the detector time response.

A first factor limiting the detector performance is the thermalization time of the primary energy within the superconductor.

In the rhenium crystal we have complete thermalization within the pulse formation time above 100 mK, as required to approach the energy resolution limit set by phonon noise $\sigma(E) = \eta C k_B T^2$, but the energy fraction quickly thermalized decreases rapidly at lower temperatures [8]. An attempt to speed up the process by means of a weak magnetic field failed(8).

However a systematic investigation on thermalization times in a series of superconductors(9) suggests that in a Rhenium alloy or in a rhenium crystal coated with a thin layer of an appropriate material, complete thermalization may be obtained in μsecond times at much lower temperature; the smaller thermal capacitance and higher responsivity of the sensor in these conditions should improve the energy resolution of about one order of magnitude.

The high thermal capacity and the slow response of the germanium thermistor are also important limitations .

Silicon implanted thermistors in principle should have a small thermal capacity, but the doping level required for operation below 100 mk is very critical and the time response is not faster than germanium.

An interesting alternative is offered by superconductor devices that provide a potentially fast response, good responsivity and low thermal capacitance.

Test are in progress(10) to use Giaver tunnel Junction between superconductors as thermometers.

The use of transition edge thermometers, with a fast squid electronics is also considered(11).

CONCLUSIONS

Our preliminary measure of the β spectrum of ^{187}Re with a cryogenic μ calorimeter indicates the feasibility of a total absorption experiment to set a limit on m_ν with such a technique.

An upgrading of the detector performance is in progress.

The low Q value of ^{187}Re decay is essential to reach an adequate counting statistics in the end point region of the β spectrum in realistic counting times.

Detailed exact calculation on the β spectrum shape are needed.

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