ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Genova

INFN/AE-95/02
3 Gennaio 1995

E. Cosulich, F. Fontanelli, G. Gallinaro, F. Gatti, S. Vitale:

THE β-DECAY OF ^{187}Re STUDIED WITH A CRYOGENIC MICROCALORIMETER. STATUS REPORT

Work supported in part by the
Commission of European Communities
under Contract CHRZ-CI 93-0341

SIS-Pubblicazioni
dei Laboratori Nazionali di Frascati

INFN – Istituto Nazionale di Fisica Nucleare
Sezione di Genova

INFN/AE–95/02
3 Gennaio 1995

THE β–DECAY OF ^{187}Re STUDIED WITH A CRYOGENIC MICROCALORIMETER. STATUS REPORT

E. Cosulich, F. Fontanelli, G. Gallinaro, F. Gatti and S. Vitale
INFN–Sezione di Genova, Università di Genova, via Dodecaneso 33, I–16146 Genova

ABSTRACT

An experiment to study the β–decay of ^{187}Re using cryogenic μ–calorimeters is under course. The physical motivations of the experiment that can give a limit to the neutrino mass are briefly discussed. Problems of the experiment and progresses obtained in the realisation of a detecting device are exposed.

The kinematics limits to the electron anti–neutrino mass result from experiments 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 region.

The effect of a non zero neutrino mass should manifest itself as a counting rate deficit, in first approximation proportional to m_ν^2, near the spectrum end–point.

The most likely value for m_ν^2 from all the recent results[1–5], as shown in Table I, is negative, the Particle Data Group average being -57 ± 30 ev^2 [6].

Table I – Squared electron antineutrino mass from ^{3}H β–decay

-18 ± 6	ev^2	LOBASHEVV	Pre–print INR_862/94
$-39 \pm 34 \pm 15$	ev^2	WEINHEIMER	PL B300 210 1993
$-24 \pm 48 \pm 61$	ev^2	HOLTZSHUH	PL B287 381 1992
$-65 \pm 85 \pm 65$	ev^2	KAWAKANI	PL B256 105 1991
$-147 \pm 68 \pm 41$	ev^2	ROBERTSON	PRL 67 957 1991
-54 ± 30	ev^2	PDG Average	RPP 50 1994

A negative m_ν^2 value corresponds to an excess counting rate in the region approaching the end–point.

To set a meaningful limit to the neutrino mass, very small deviation must be excluded from the β–spectrum expected for $m_\nu=0$.

Great care is necessary in the analysis to take into account theoretically the energy lost by the emitted electron in the source and the final state energy distribution of the daughter atomic or molecular system generated from Tritium decay in ^3He.

Indeed, if the final state is an excited one, the maximum electron energy available in the decay is decreased by a corresponding amount.

The ideal measure of the full energy release spectrum following β–decay near the end point by a total absorption calorimetric method is unaffected in principle by these corrections and would yield the same information.

However, to really perform such an experiment, several problems have to be solved.

Indeed only a very small fraction of decay events, proportional to $(\mu_\nu/Q)^3$, (μ_ν= limit to be set to m_ν), falls in the region of the spectrum sensitive to the neutrino mass near the end–point.

In a calorimetric experiment, the full spectrum contributes to the detector counting rate. The source intensity must be limited to avoid pile–up problems, and the time needed to accumulate a reasonable statistics in the end–point region may become exceedingly long unless Q is very small.

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 adequate to set a sensible limit to the neutrino mass and an energy response independent on the kind of excitation, but they are slow and can sustain only few decays per second.

With a Tritium Q value of 18.6 kev and a μ–calorimeter as total absorption spectrometer, the time needed to set an upper limit of 10 ev to m_ν is not less than one year.

The interest in the ^{187}Re –decay originate since its Q value is the lowest known in nature, only 2.7 kev.

Because of the lower maximum decay energy of Rhenium the allowed counting rate is much less stringent than for Tritium, reducing further the measure time to set a given limit to m_ν.

To perform such an experiment it is however required the development of a completely new instrument and of convenient experimental procedures, especially for calibration at very low energy.

The theoretical analysis of ^{187}Re β–spectrum shape is, at first glance, not too difficult, the decay being a first–forbidden unique transition.

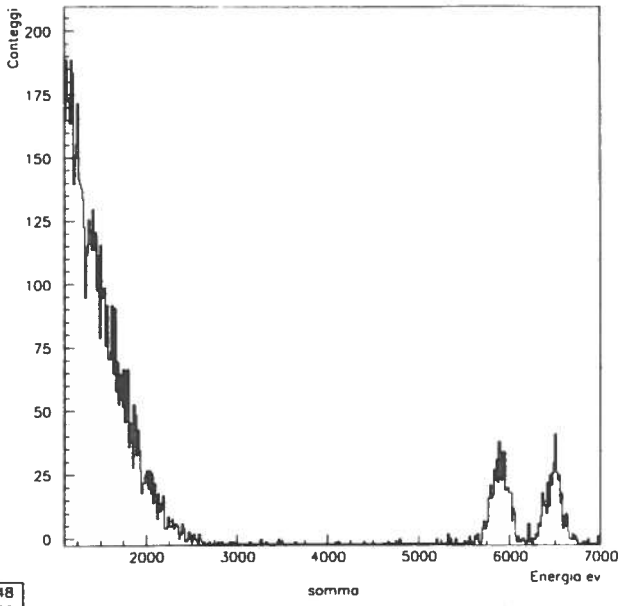
We want to point out, however, that at such low energies great care has to be taken to check the validity of the theoretical approximations in evaluating the Fermi function F(Z,E) and the spectral shape factor.

We thank Dr. Milos Rysavy for the useful discussions on this subjects and we acknowledge the effort to perform detailed calculations that Rysavy and J.Rizec have undertaken at the Nuclear Physics Institute at Rez near Prague.

Moreover, [7] the decay of Rhenium not as an isolated atom but in a crystal lattice is expected to produce an oscillatory modulation of the β–spectrum when the electron wavelength is not far from the lattice parameter. The expected effect however is tiny and should be negligible above 1.5 Kev.

In the following we report the progresses in developing the experimental techniques for the experiment.

In Fig.1a and 1b the Spectrum and the Kurie–Plot recently obtained with a test detector are shown.



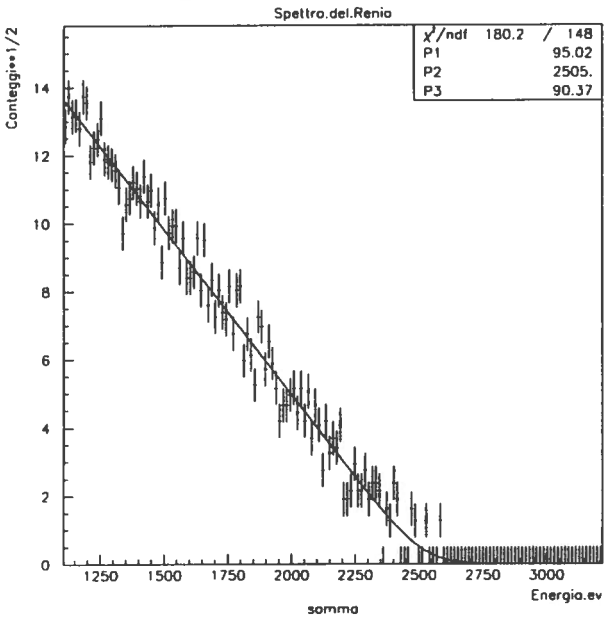


FIG.1a and 1b – The Spectrum and the Kurie–Plot recently obtained with a test detector are shown. The uncoated Rhenium crystal is about 1/8 of a cubic mm, the NTD Germanium thermistor is 0.5 X 0.25 X 0.25 mm^3. At 100 mK the heat capacity of the Rhenium is about 4 pJ/K and that of the thermistor 10 pJ/K. The main limit to the energy resolution is due to Johnson noise of the thermistor. The Rhenium mass is limited because of the detector maximum allowed rate of ^{187}Re decays.

They can be compared with the results, shown in Fig. 2a and 2b that we obtained and published[8] in 1992.

The improvement in detector quality is made evident by the two calibration X–ray peaks at 6490 and 5897 ev from a ^{55}Fe source that are now completely resolved.

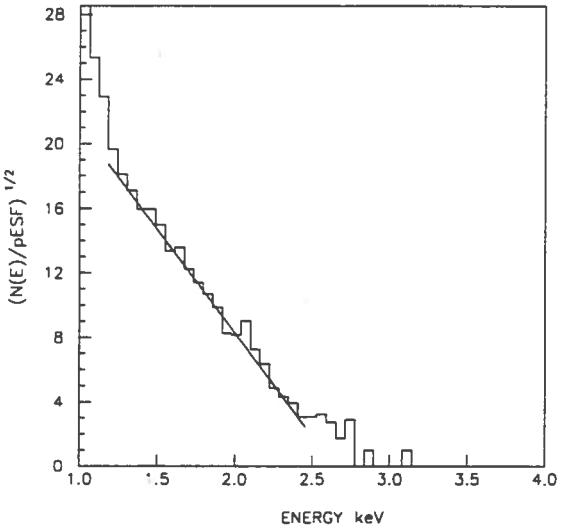
The better performance of the new detector was determined mainly by using a better thermistor and electronics and by reducing environmental noise, mostly microphonics.

The test detector is made with a small natural metallic Rhenium crystal and by an NTD Germanium thermistor(*), 0.5X0.25X0.25 mm3 glued to the crystal.

The Rhenium mass is about the same as that of the old experiment, (≅ 2 mg, imposed by the detector maximum allowed rate of ^{187}Re decays).

(*) Thanks are due to Prof. E.E. Haller of the Lawrence Berkeley Laboratory that kindly supplied the NTD Germanium sensors.

Thermal and electrical connections to the refrigerator mixing chamber and electrical connections to a source follower, placed inside the refrigerator, are provided by two ultrasound bonded 20 μm aluminium wires .



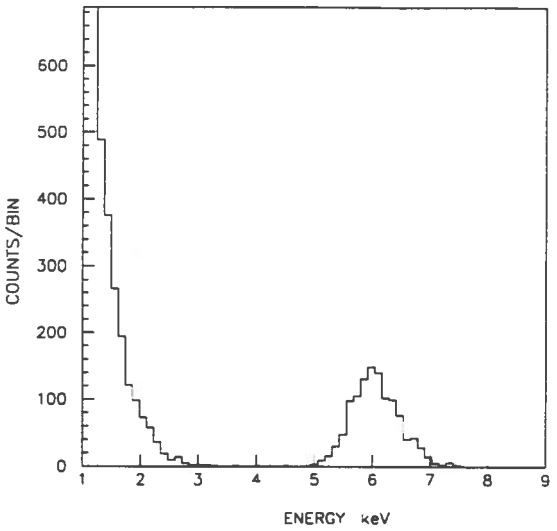


FIG. 2a and 2b – Spectrum and Kurie plot that we obtained and published[1] in 1992. The mass of the Rhenium crystal is 1.83 mg. At 100 mK the heat capacity of the Rhenium is about 4 pJ/K and that of the thermistor 87 pJ/K. The main limit to the energy resolution is due to the external noise as microphonics and EM. pick–up.

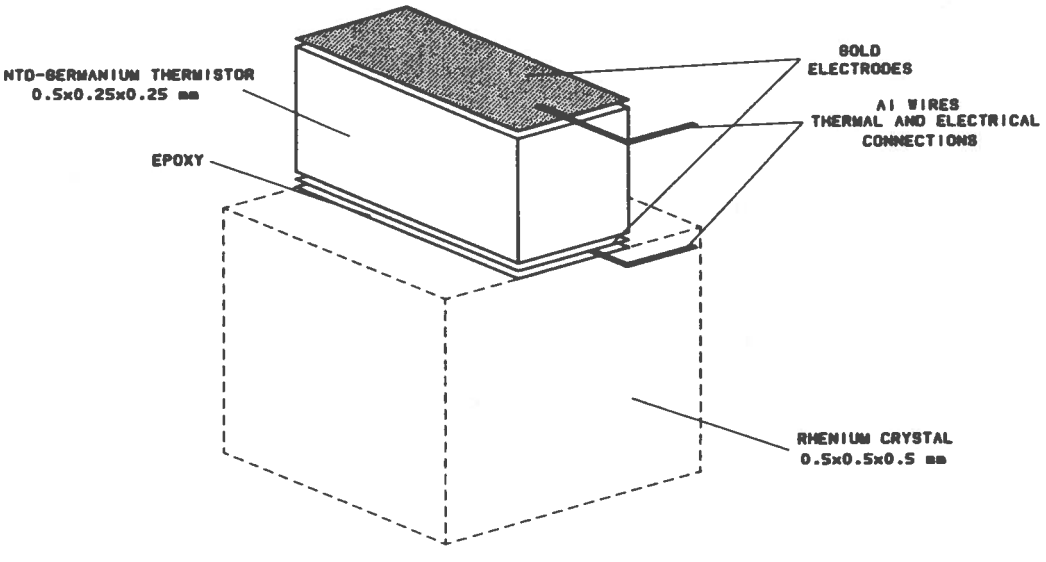


FIG 3 – Test detector set–up with Thermal and Electrical connections. Thermal connections to the refrigerator mixing chamber and electrical connections to a source follower, placed inside the refrigerator, are provided by two ultrasound bonded 20 μm aluminium wires placed sideways. The Distributed Thermal impedance of the Thin Gold film electrodes is practically in series to that of the aluminium wires.

A schematic outline of the device is shown in Fig. 3.

The Thermistor signal, after amplification by a factor 80000 and after a low pass filtering, is transferred to a 12 bits waveform recorder.

The recorded transients are then analysed off–line; from each pulse we obtain, by optimum filtering, an amplitude proportional to the energy release, and a shape factor that measures the deviation of the pulse shape from a reference shape.

The reference pulse shape is obtained by averaging several hundreds input pulses selected by eye to exclude pulses corrupted by pile–up or other disturbances.

The main line of data acquisition and analysis system didn't change with respect to the one previously used and fully described elsewhere[8,9].

Actually the Camac waveform recorder (LeCroy 6810) is controlled by a Digital VAX station through the crate controller 3929 by Kinetics System.

The system not only acquires and stores data, but also does some graphic display of it and provides a preliminary energy spectrum.

The maximum data taking rate is about 50 pulse per second, much more than the physically acceptable rate due to pile–up.

Analysis also has been moved from the IBM PC running ASYST to the VAX station. The processing time for a single waveform is now about 20 ms, with a great improvement compared with the previous system.

The observed energy resolution is fully compatible with the signal to noise ratio. The noise level is scaling with the square root of the thermistor electrical resistance, as expected for the device Johnson noise; the contribution of the amplifier noise(0.8 $nV/Hz^{1/2}$) is negligible.

The signal amplitude is limited by the detector heat capacity, mainly due to the thermistor contribution, about 10 pj/K at 100 mK.

Indeed the energy resolution obtained with a ^{55}Fe source and the complete detector, (Rhenium crystal + Thermistor) is not worse than that obtained by irradiating the thermistor alone.

In this last case the data analysis is quite interesting.

In Fig. 4a the pulse amplitude spectrum is reported. In Fig. 4b the scatter plot of the shape factor versus the amplitude is shown.

The complex structure observed is explained as follows: the X–ray interactions in the electrodes gold film generates pulses with a decay time faster than the average, due to the lower thermal impedance, and then with an higher shape factor, and because of the complete and fast thermalization in the metal, with an amplitude higher than that due to X–ray absorbed in the germanium. In this last case, a fluctuating fraction of the energy, about 15%, is trapped in metastable states, and slowly released.

Indeed, the width of the peaks corresponding to absorption in germanium is slightly worse (σ=68 ev) than that due to absorption in Gold (σ=55 ev).

We have to point out, however, that in the case of interaction in gold, a slight position dependence must be corrected; due to the distributed thermal impedance of the Gold film a position dependent fraction of the energy flows to the heat sink and do not heat the semiconductor if the deposition is concentrated in a spot on the film.

This effect is made evident in the scatter–plot of Fig.4b by the slight deviations from the vertical of the points distributions corresponding to the higher peaks.

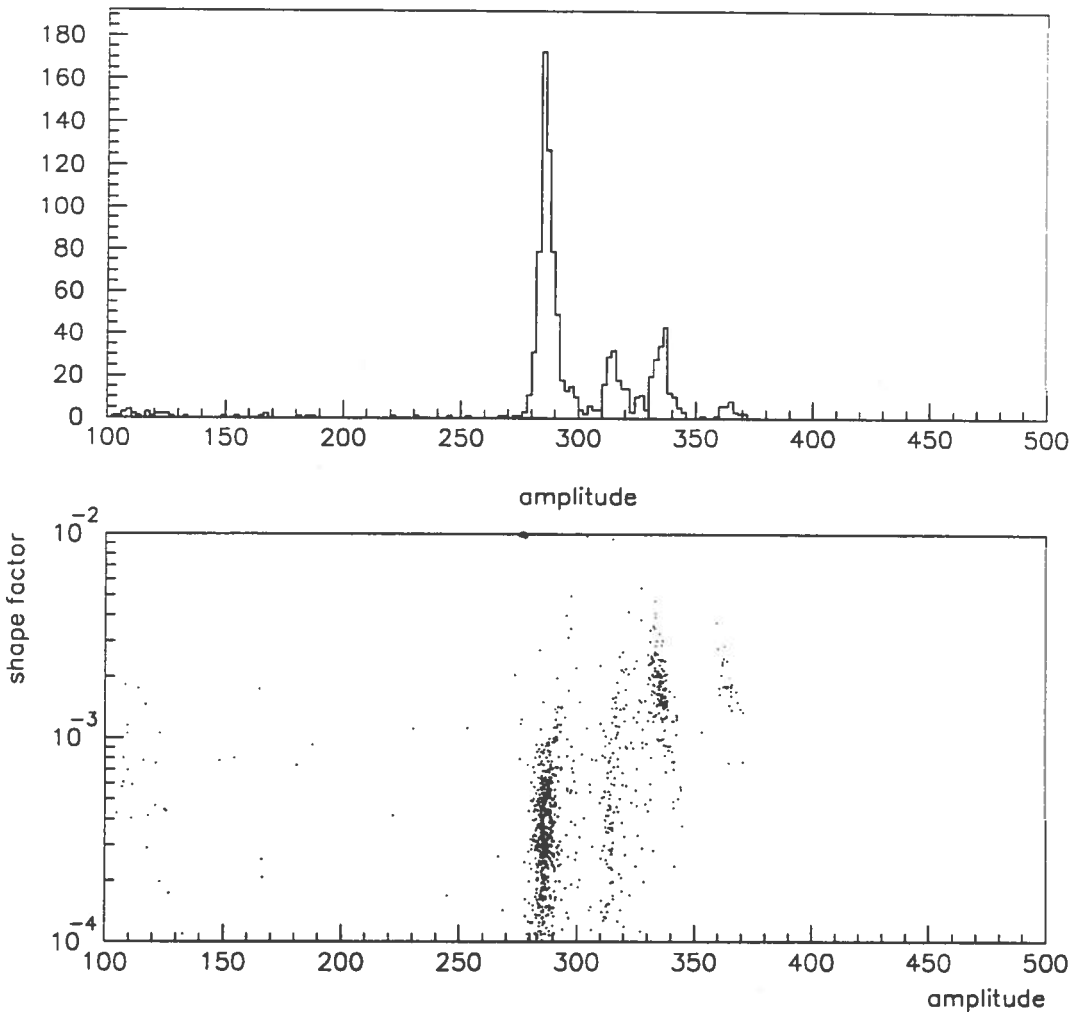


FIG 4a – Pulse amplitude spectrum (arbitrary units) obtained by irradiating with X–rays from an Fe source the NTD Germanium thermistor alone. The two lower peaks correspond to K_α and K_β photons interacting in the Germanium. The two higher peaks correspond to interactions in the Gold electrodes.

FIG.4b – Scatter plot of the shape factor versus the amplitude from the same set of data of Fig.4a. The shape factor measures the deviation of the pulse shape from the reference shape. The reference pulse shape is obtained by averaging input pulses selected by eye to exclude pulses corrupted by pile–up or other disturbances. The selected pulses are mainly generated by X–ray interactions in Germanium. As shown the shape factor is smaller and independent from the amplitude for the lower amplitude peaks, corresponding to interaction in Germanium.The distributions corresponding to the interactions in Gold are slightly inclined and the shape factor is decreasing with increasing amplitude, due to the position dependent response. The spread of the experimental points from the mid–line of the distribution for the K_α line in Gold is less (σ=55 ev) than that due to interactions in Germanium (σ=68 ev). The difference is attributed to fluctuation of the energy trapped in metastable states.

Indeed interaction points in the electrode closer to the thermal connection have a faster decay time.

As a consequence of the energy trapping in metastable states, some energy resolution loss is expected when dielectric and semiconducting absorbers are used. To avoid this inconvenience, the use of a normal metal being impossible for its huge heat capacity, the choice of a superconducting absorber was considered.

It was proved[10] that the energy thermalization is reasonably fast and complete, provided that the operating temperature is kept above $T_c = 2\ 10^{-4}\ T_D$.

It is then possible to build efficient μ–calorimeters with a superconducting absorber, but, because of the lower limit on the operating temperature the overall heat capacity of the detector stays high limiting the achievable energy resolution.

With the present detector it should be possible, in about two months of data taking, to set an upper limit to the neutrino mass below 20 ev.

However we prefer to try further to improve the detector performance and we need an efficient calibration procedure at low energy.

The energy difference of the two lines of ^{55}Fe is rather small and the average energy is more than twice the end point energy of ^{187}Re.

A third peak at a lower energy is necessary for a reliable calibration and to check the linearity. The linearity of a Re–Ge μ–calorimeter has been tested with a detector made with a 1 mm^3 rhenium crystal and a 1 mm^3 thermistor[7], the overall thermal capacity was then about 30 times bigger than the present detector. No deviation from linearity was observed within instrumentation limits at least up to 400 Kev. For the present detector an energy of 13 Kev will produce the same temperature increase, and we expect to have linearity up to this energy. In a much smaller detector deviation from linearity in the energy range of interest for the experiment must be carefully investigated.

No simple source is available to have direct calibration lines below 5 kev and it is necessary to revert to X–ray fluorescence.

An X–ray line of Chlorine at 2.7 Kev can be obtained by irradiating a sheet of PVC with a strong source of ^{55}Fe.

However, due to the small size of the detector a high intensity is required to obtain a good statistics in a reasonable calibration time and in these conditions it is not easy to avoid some heating of the detector environment, with a consequent drift of the operating conditions.

A system of thermal shields and collimators is being designed and tested. An annular ^{55}Fe source has been ordered.

To further improve the detector performance we plan, in the next future, to use a smaller thermistor (.1 X .1 X .25 mm^3), presently under test.

We hope, in this way, to improve the resolution by a factor about 5.

It was also observed[4],[5] that by applying a thin coating of a convenient material, Gold or Bismuth, to the Rhenium crystal a more efficient thermalization is obtained at the lowest temperatures. This effect that has to be more investigated could help us to operate a detector below $T_c/T_D = 2\ 10^{-4}$, with lower thermistor and parasitic heat capacity.

CONCLUSION

A Cryogenic μ–calorimeter with features adequate to set a meaningful limit to electron antineutrino mass studying the Re decay has been successfully tested, and preliminary data were obtained.

A viable technique to provide an efficient energy calibration procedure at low energy is being prepared, and some effort is needed to verify the detector linearity and energy resolution in the region below 3 Kev.

REFERENCES

(1) Limit on Mass from the observation of the β–decay of Molecular Tritium. R.G.H. Robertson, T.J.Bowles, G.J.Stephenson, jr., D.L.Wark, J.F.Wilkerson and D.A.Knapp: Physical Review Letters 67 (1991) pp 957–960.

(2) New upper bound on the electron anti–neutrino mass. H.Kawakami, S.Kato, T.Oshima, S.Shibata, K.Ukai, N.Morikawa, N.Nogawa, K.Haga, T.Nagafuchi, M.Shigeta, N.Y. Fukushima and T.Taniguchi: Physics Letters B256 (1991) pp 105–111.

(3) Measurement of the electron neutrino mass from tritium β–decay. E.Holzschul, M.Fritschi and W.Kùndig: Physics Letters B287 (1992) pp 381–388.

(4) Improved limit on the electron–antineutrino rest mass from tritium β–decay. Ch. Weinheimer, M.Przyrembel, H.Backe, H.Barth, J.Bonn, B.Degen, Th.Edling, H. Fischer, L.Fleischmann, J.U.Grooss, R.Haid, A.Hermanni, G.Kube, P.Leiderer, Th. Loeken, A.Molz, R.B.Moore, A.Osipo Wicz, E.W.Otten, A.Picard, M.Schrader and M.Steininger: Physics Letters B300 (1993) pp 210–216.

(5) First results of Troitsk experiment on the search for electron antineutrino rest mass in Tritium Beta–Decay. A.I.Belesev, A.I.Bleule, E.V.Geraskin, A.A.Golubev, N.A. Golubev, O.V.Kazachenko, E.P.Kiev, Yu.E.Kuznetsov, V.M.Lobashev, B.M. Ovchinnikov, V.I.Parfenov, I.V.Sekachev, A.P.Solodukhin, N.A.Titov, I.E.Yarykin, Yu.I.Zakharov and S.N.Balashov, P.E.Spivak: Pre–print INR–862/94–July 1994.

(6) Review of Particle Properties Physical Review D 50 1994.

(7) Environmental fine structure in low–energy –particle spectra. Steven E. Koonin: Nature Vol.354 pp 468–470 12 December 1991.

(8) Detection of ^{187}Re beta decay with a cryogenic microcalorimeter: preliminary results. E.Cosulich, G.Gallinaro, F.Gatti and S.Vitale: Physics Letters B295 (1992) pp 143–147.

(9) A Digital Processor for Nuclear spectroscopy with cryogenic detectors. E.Cosulich, F.Gatti: N.I.M. in Phys. Res. A321 (1992) pp 211–214.

(10) Alpha–, beta–, and gamma–ray detection with micro calorimeters made with a superconducting absorber, S.Vitale, G.Gallinaro, F.Gatti: EUV, X–Ray and Gamma–ray Instrumentation for astronomy III: Proceedings of SPIE Vol 1743, pp 368–379 (1992).

(11) Further results on micro calorimeters with superconducting absorber. S.Vitale, G.Gallinaro, F.Gatti: Journal of Low Temperature Physics Vol 93 n.3, pp 262, 268 (1993).