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CALIBRATION OF THE RESONANT GRAVITATIONAL WAVE DETECTORS EXPLORER AND NAUTILUS IN 2003 AND 2004 USING COSMIC RAYS

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Abstract

The cryogenic resonant gravitational wave detectors EXPLORER and NAUTILUS are able to detect cosmic ray showers. The experimental result leads to classify the responses in two categories: many small signals, in most cases with small multiplicity, obeying the thermo-acoustic model, and few large signals, usually associated to large multiplicity, which exceed the thermo-acoustic model by orders of magnitude, and whose understanding is still under investigation. Using the low multiplicity showers, we make a relative calibration of the apparatuses, comparing the response of EXPLORER with that of NAUTILUS. This comparison turns out useful when searching for coincidences between gravitational waves detectors.

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The cosmic ray showers (CRS), observed by the EXPLORER and NAUTILUS gravitational wave detectors, have already used for estimating the time uncertainty of the events employed for the search of coincidences [1]. Now we study the possibility to exploit the same measurements to calibrate the detectors in energy.

However, whilst for the time calibration the use of CRS leads to very accurate results, for the energy calibration we must face several problems as: the uncertainty in the effective area of the cosmic ray apparatuses, the evaluation of the energy deposited in the bar by the secondaries, the incomplete knowledge about the full nature of the CRS.

These uncertainties produce systematic errors in the estimation of the absolute energies. Nevertheless, the usefulness of the cosmic ray study in the gravitational wave apparatuses, even for the energies, comes from the fact that systematic errors do not interfere with the energy comparison among events detected by the gravitational wave detectors, making it possible to apply energy filters to the data for improving the signal-to-noise ratio.

We recall that, according to the thermo-acoustic model, a CRS interacting with a massive aluminum cylinder and producing a number Λ of secondaries, generates a signal with energy $E_{th} = \Lambda^2\ 4.7\ 10^{-10}\ K$. This has been verified in [2]. More recently, we made an experiment using an electron beam produced by the DaΦne facility in Frascati, verifying the thermo-acoustic model with good accuracy [3], with a small correction for Aluminum at the liquid helium temperatures, so that the above equation becomes

$$E_{th} = \Lambda^2\ 4.7\ 10^{-10} (1.15)^2\ K \tag{1}$$

We have found [4,5] that CRS generate in our GW detectors signals that can be classified in two categories: a) many small signals obeying the thermo-acoustic model in most cases with small multiplicity Λ, b) few large signals, usually associated to large Λ, which exceed the thermo-acoustic model by orders of magnitude.

For the response of the GW detectors to CRS we have

$$x(t) = s(t) + n \tag{2}$$

where s(t) is the signal due to the CRS and n is the stochastic noise.

The data have a sampling time of 3.2 ms. For each year (2003 and 2004, separately for EXPLORER and NAUTILUS) we have considered the CRS detected by the cosmic ray apparatuses and divided them in various categories according to the multiplicity Λ.

By averaging over the many CRS within each Λ category, we obtain

$$s^2 = \overline{x_i^2 - n^2 + 2sn} = \overline{x_i^2} - \overline{n^2} \tag{3}$$

Table 1: Time of data taking and T_{eff}. For EXPLORER 2003 the time begins on September 1^{st} .

	EXPLORER		NAUTILUS	
year	days	T_{eff} mK	days	T_{eff} mK
2003	95	2.39	171	4.19
2004	281	2.61	342	1.74

For each category we have used the EXPLORER and NAUTILUS cumulative filtered data centered at the time of each CRS and search for the maximum value in the time interval $\pm 17.6\ ms$ for taking care of the time uncertainty. We have

$$E_{max} = (\overline{x_i^2})_{max} - \overline{n^2} \tag{4}$$

The noise is $\overline{n^2} = T_{eff}$ (the effective temperature for delta-filtering) and its standard deviation is

$$\sigma = \sqrt{2}\frac{T_{eff}}{\sqrt{N}} \tag{5}$$

where N is the number of CRS within each Λ cathegory.

We must be aware that with this procedure, because of the time uncertainty, not all CRS maxima occur at exactly the same time. Therefore our estimation of $\overline{(x_i^2)}_{max}$ tends to be smaller than that we would have obtained if we made the average of all real maxima.

We give in the Table 1 the time of measurement and the noise T_{eff} of the two detectors. We remark that NAUTILUS underwent a hardware change from 2003 to 2004, with a different setting of the dcSQUID amplifier. The results of our analysis are given in the fig. 1.

We can see the two populations of the CRS response. This phenomenon is still matter of debate.

According to the result [5] obtained with the data recorded in 2001, we take into consideration the lowest Λ intervals, given in the Tables 2 and 3. We find a good linear correlation between measurements and theory, as shown in fig.2. The slopes are given in the Table 4.

We also considered a cumulative analysis of the four Λ intervals, as shown in fig.3. The maximum energies in this figure are reported in the Table 4.

We find that both the measured EXPLORER and NAUTILUS values of s^2 at small Λ values are correlated linearly with the theoretical expectations, although, because of the time uncertainty in the peak time estimation, as described above, the measured values are smaller than the theoretical ones.

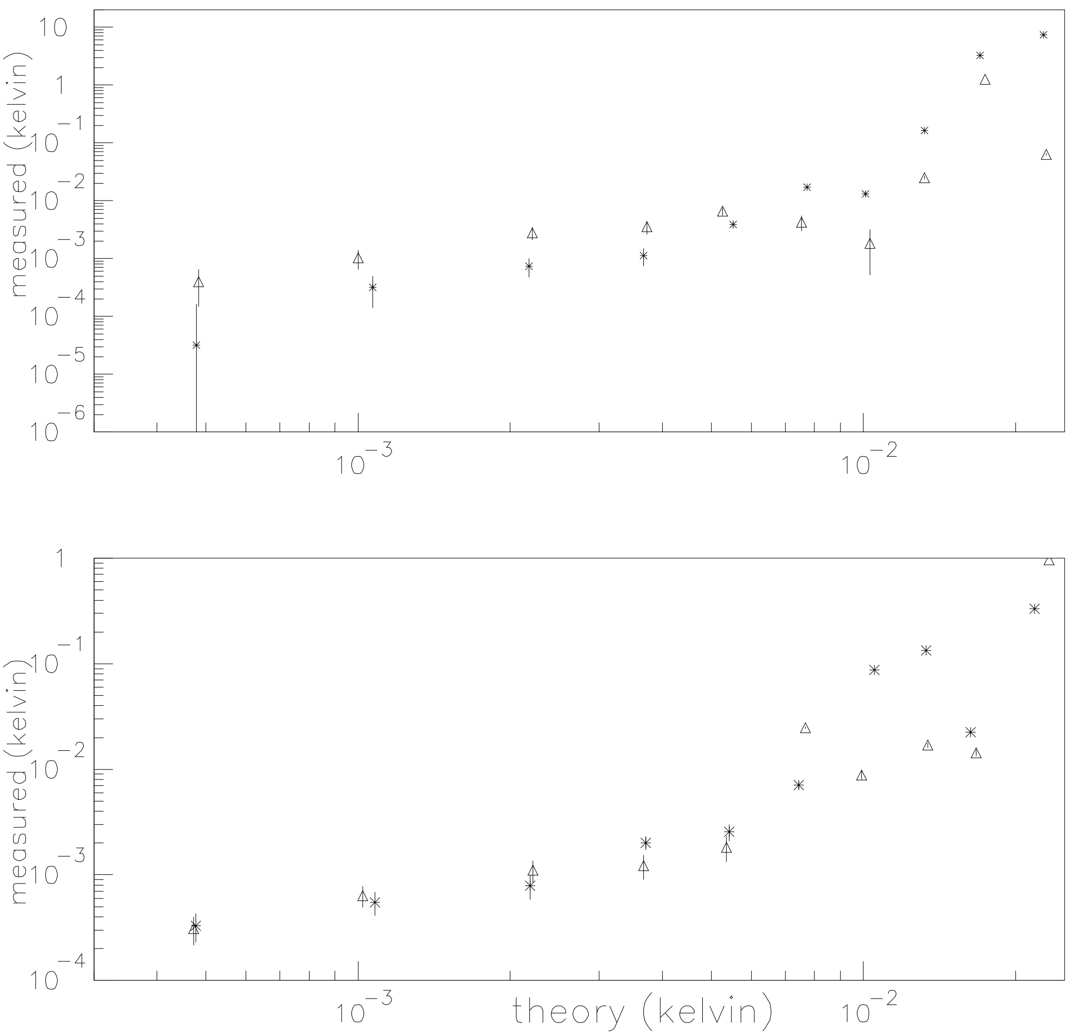

Figure 1: Measured energy signal s^2 versus the expectations according to the thermo-acoustic model for EXPLORER (asterisks) and NAUTILUS (triangles). The upper graph refers to the 2003 data, the lower one to 2004.

Table 2: 2003. Number of CRS, measured, standard deviation and calculated values of s^2 for various Λ. EXPLORER in the upper part, NAUTILUS in the lower part.

Λ	number	measured mK	standard dev. mK	calculated mK
400	669	0.03	0.13	0.48
600	357	0.32	0.18	1.07
900	161	0.74	0.27	2.18
1200	77	1.12	0.38	3.67
400	552	0.40	0.25	0.48
600	246	1.02	0.38	1.00
900	68	2.79	0.72	2.21
1200	43	3.54	0.90	3.73

Table 3: As in the Table 2 for 2004.

Λ	number	measured mK	standard dev. mK	calculated mK
400	1359	0.33	0.10	0.48
600	695	0.55	0.14	1.08
900	306	0.79	0.21	2.19
1200	148	2.01	0.30	3.71
400	737	0.31	0.09	0.47
600	297	0.63	0.14	1.02
900	93	1.11	0.26	2.22
1200	62	1.22	0.32	3.67

Table 4: The slopes are obtained from fig.2. The maxima from the data of fig.3.

detector	year	slope	bkg mK	maximum mK	theory mK
EXPLORER	2003	0.30	2.40	0.217	1.06
NAUTILUS	2003	1.03	4.20	0.646	0.905
EXPLORER	2004	0.49	2.61	0.385	1.05
NAUTILUS	2004	0.46	1.77	0.361	0.913

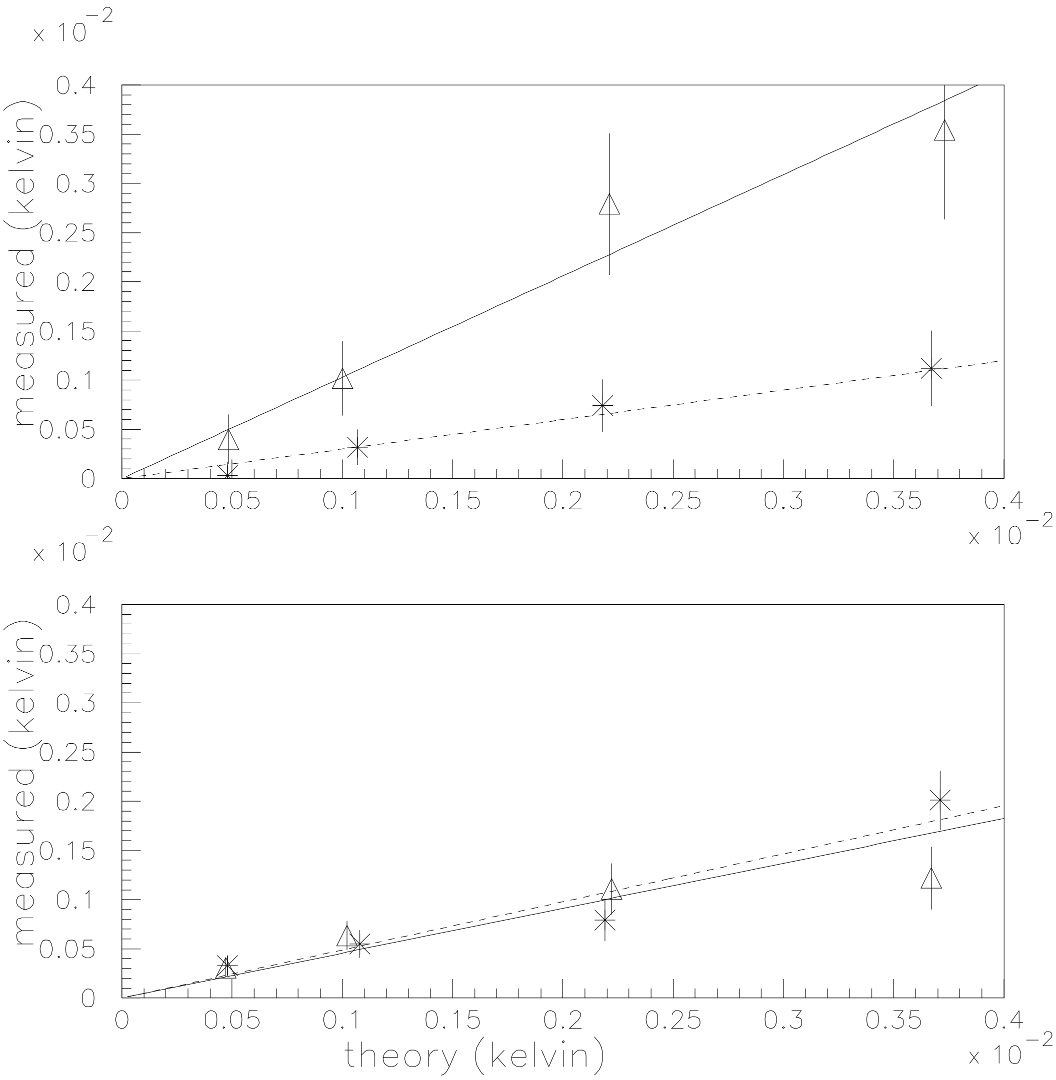

Figure 2: Upper graph for 2003. Lower graph for 2004. Measured energy signal s^2 versus the expectations according to the thermo-acoustic model for EXPLORER (asterisks) and NAUTILUS (triangles). The straight lines are weighted least square fits through the origin.

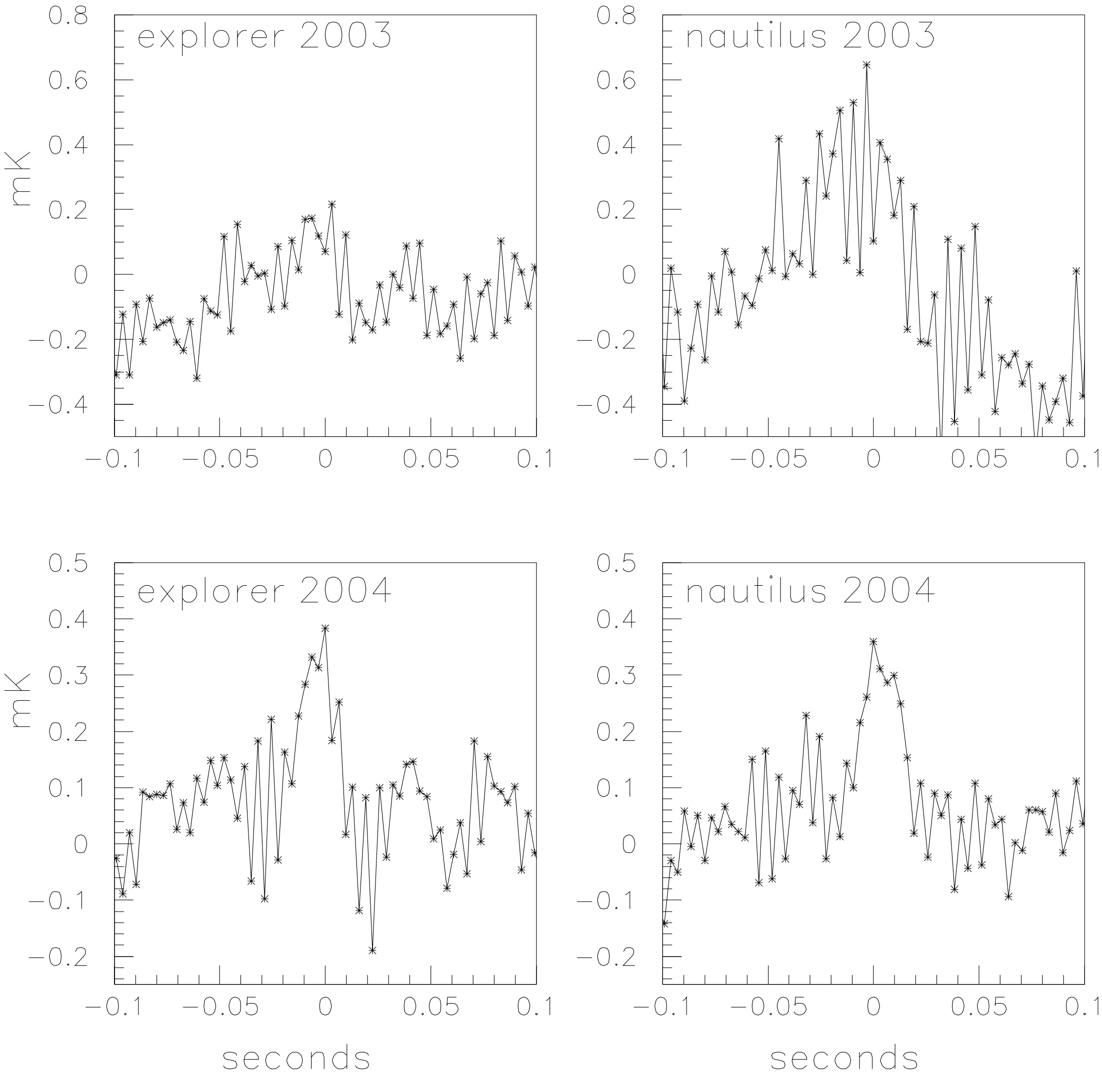

Figure 3: Cumulative response to CRS for the multiplicity interval $400 < \Lambda < 1500$. The background has been subtracted.

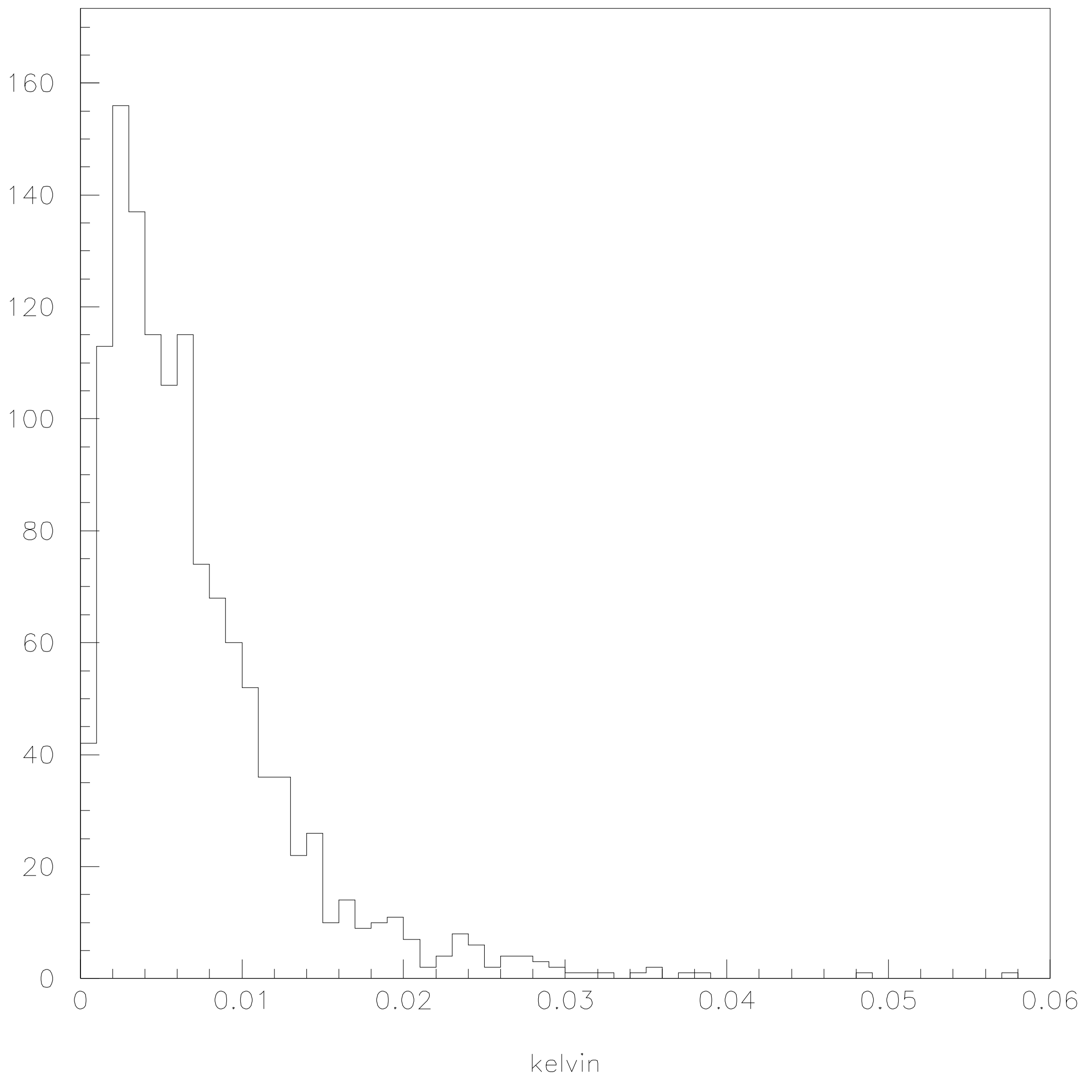

Figure 4: Distribution of the maxima in the four lowest Λ ranges for EXPLORER in 2003. We have eliminates 2 stretches (1 stretch in the lowest Λ range) with $E_{max} \geq 60\ mK$.

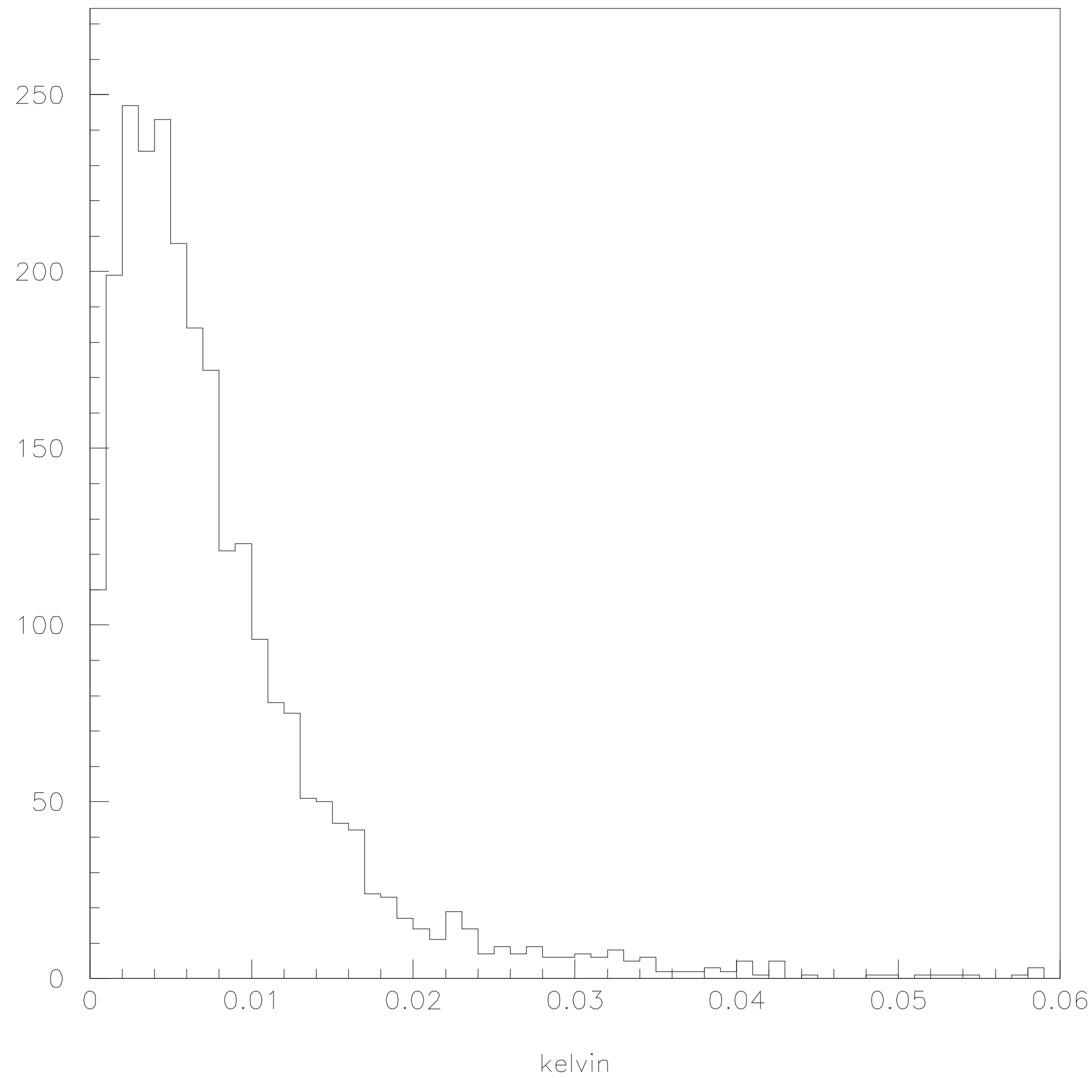

Figure 5: Distribution of the maxima in the four lowest Λ ranges for EXPLORER in 2004. We have eliminates 9 stretches (1 stretch in the lowest Λ range) with $E_{max} \geq 60\ mK$.

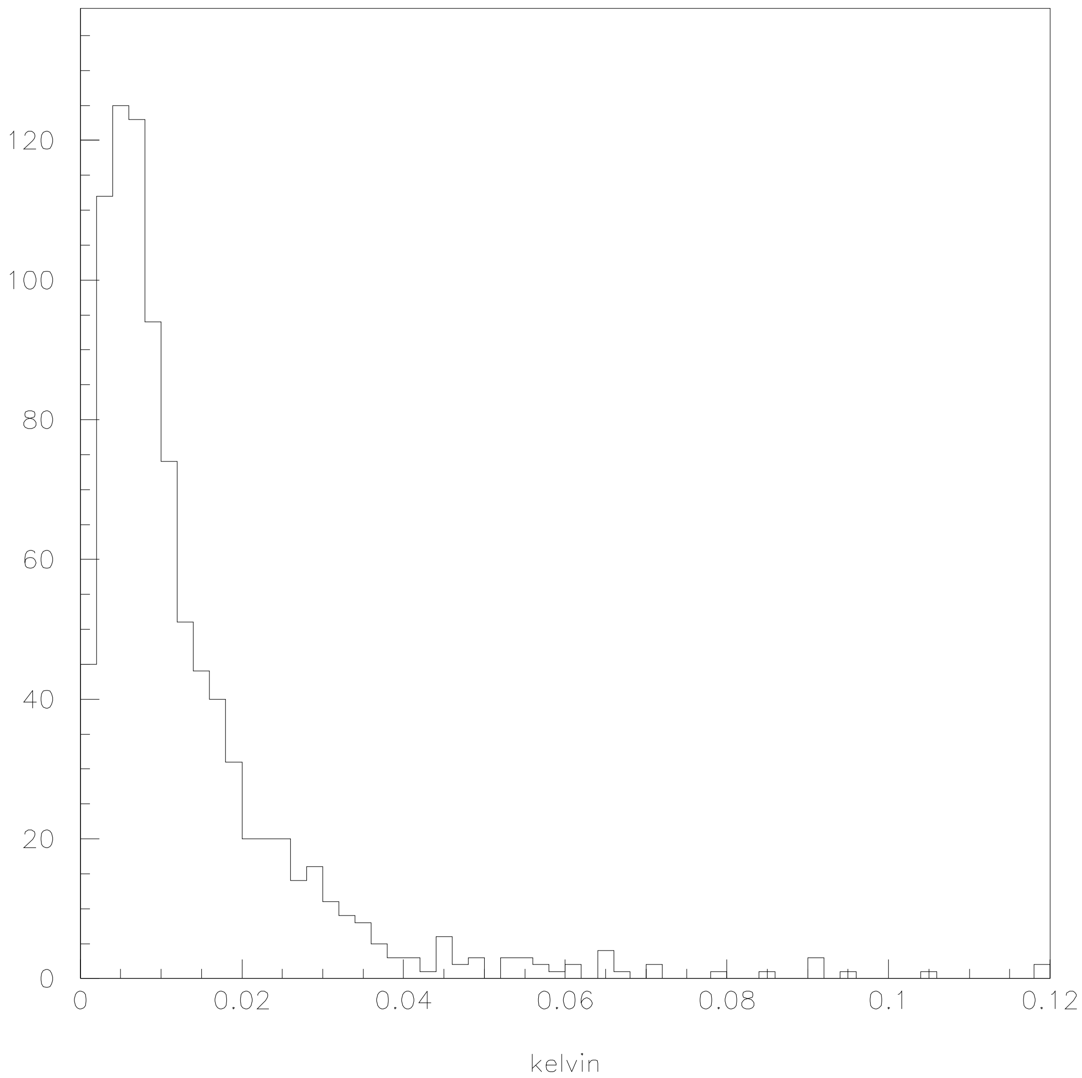

Figure 6: Distribution of the maxima in the four lowest Λ ranges for NAUTILUS in 2003. We have eliminates 2 stretches (1 stretch in the lowest Λ range) with $E_{max} \geq 120\ mK$.

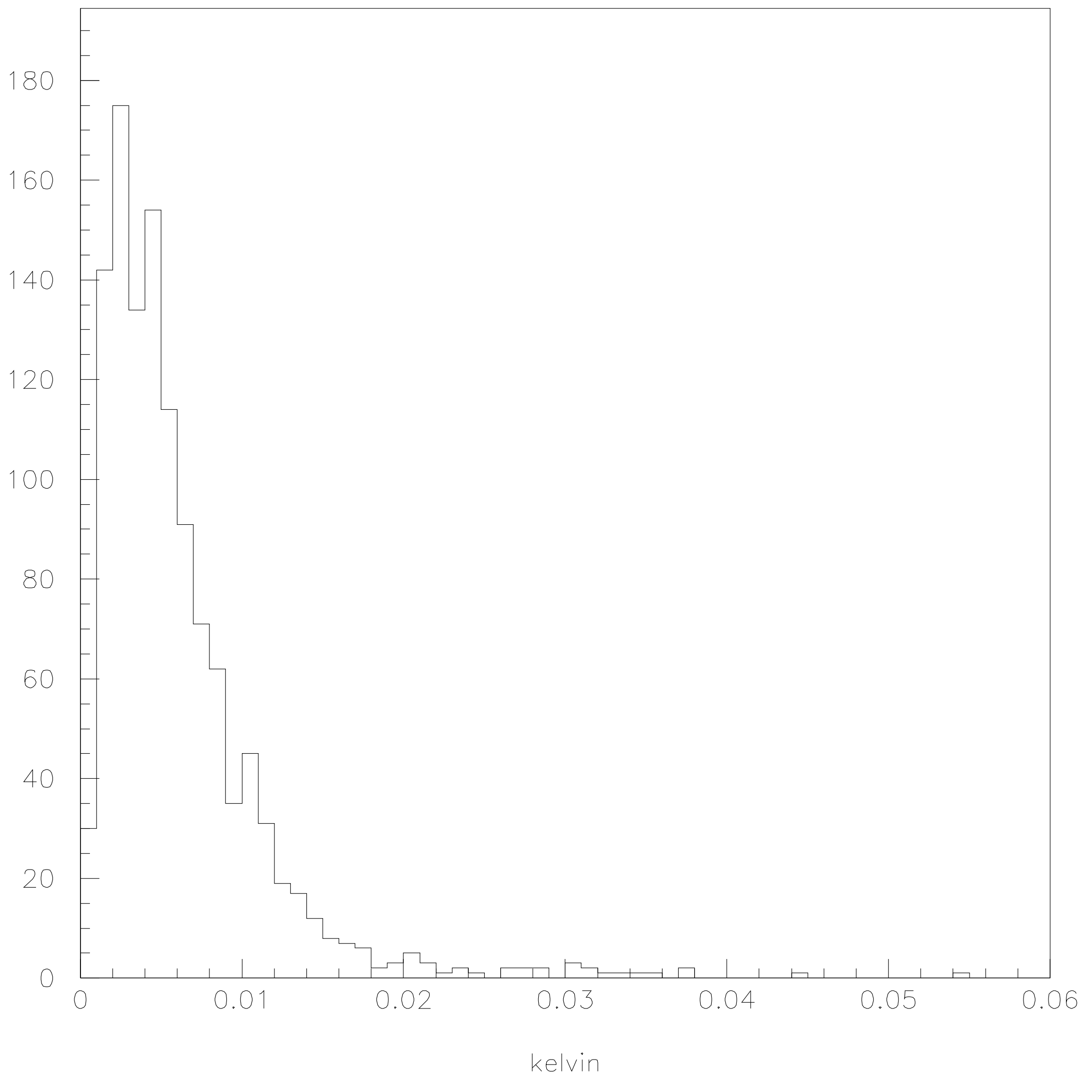

Figure 7: Distribution of the maxima in the four lowest Λ ranges for NAUTILUS in 2004. We have eliminates 4 stretches (1 stretch in the lowest Λ range) with $E_{max} \geq 60\ mK$.

From fig.2 and Table 4 we also notice that in 2004 both EXPLORER and NAUTILUS respond in the same way to CRS. In 2003, instead, the response of NAUTILUS is bigger in energy than that of EXPLORER.

No matter the interpretation of the experimental results, it turns out that for the same excitation EXPLORER and NAUTILUS in 2003 give responses differing by a factor, and this has to be taken into account when applying the energy filter to events in coincidence between EXPLORER and NAUTILUS.

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