Vibrational Excitation induced by electron beam and cosmic rays in Gravitational Wave bars

Summary

The unexpected large amplitude cosmic rays in the superconductive NAUTILUS Frascati bar GW detector

The interaction of the cosmic rays with a bar and the thermo-acoustical model in normal and superconductive aluminum

The RAP experiment (Rivelazione Acustica Particelle) on the Frascati linac to measure the vibrational amplitude at low temperatures

Conclusions


e-Print: arXiv:1105.4724 [gr-qc]
in press on Nuclear Instruments and Methods in Physics Research

F Ronga INFN LNF TAUP2011
Nautilus (the first cooled at 100 mK in 1998)

Al 2036 bar 2300
Cross section : 2 aluminum shields, container for helium 2000 liters, dilution
Mechanical suspension: shields are suspended in a chains and copper wire around the bar 260 db @ 1 Khz
A big surprise in 1998!!!
(Nautilus first detection of cosmic rays in a GW detector)

Rate much larger !!

The hadrons measured by Cascade should be an upper limit, because the bar should contain only \(~a few percent of the hadronic energy\)
Interaction of a particle with a bar: Thermo-Acoustical model

Ionization energy lost is converted in thermal heating and therefore pressure wave

\[ \delta T = \frac{\delta E}{\rho CV_0} \]

\[ \delta p = \gamma \frac{\delta E}{V_0} \]

\[ \gamma = \frac{3\alpha}{\rho kC_v} \]

\[ k = 3*(1-2*pois)/Y \]

\( \gamma \) Grunesein parameter

\( Y = \) Young module, \( C = \) specific heat, \( \alpha = \) linear thermal expansion coefficient

\( pois = \) Poisson module
Thermal acoustical conversion
(General case for a single particle)

\[
E_n = \frac{1}{2} \frac{l^2}{V} \frac{G_n^2}{\rho v^2} \gamma^2 \left( \frac{dE}{dX} \right)^2
\]


\( G_n \) cylinder form factor, first order in \( R/L \)

\[
T_{\text{eff}} = 2.75 \times 10^{-9} \left( \frac{dE}{dX} \right)^2 \left( \sin \left( \frac{\pi \ell_0 \cos \theta}{L} \right) \right)^2
\]

The thermo-acoustical model in a superconductive state

- In addition to the expansion due to the heating, we could have a release of additional energy if a local transition from the superconductive (s) state to a normal (n) state occur, due to the different energies of the s and n state. This effect has been demonstrated in the “superconductive strip” detector.

**So two possibilities:**

1) No local s - n transition: normal thermo-acoustical model with low temperature parameters.

2) s - n transition: overlapping of two effects:
   - thermo-acoustical with normal state parameters + s - n transition pressure wave.
   - The two effects could have different sign (“interference”).

\[
\frac{X}{W} = \left[ \frac{X}{W}_{\text{trans}} \right] + \left[ \frac{X}{W}_{\text{norm}} \right] = X \text{ amplitude } W \text{ energy}
\]

\[
\begin{bmatrix}
\mathcal{F}\left(H_c, \frac{\partial H_c}{\partial T}, \frac{\partial H_c}{\partial P}\right) + B\left(\frac{\alpha}{c_V}_{\text{norm}}\right)
\end{bmatrix}
\]

Very difficult to have a reliable prediction.
Rivelazione Acustica di Particelle

**Experimental Setup**

**Niobium Bar**
- 27.4\times10 \text{ cm}, 18.4 \text{ kg}
- \nu = 6373 \text{ Hz @ 290 K}
- annealed, purity > 99%
- 2 PZ24 ceramics in parallel glued to the bottom center
- \lambda \sim 10^6 \text{ V/m}

**Al 5056 Bar**
- 50\times18.1 \text{ cm}, 34.1 \text{ kg}
- \nu = 5096 \text{ Hz @ 296 K}
- 2 Pz24 ceramics in parallel embedded in the bar
- \lambda \sim 10^7 \text{ V/m}
Typical RAP results for $0.9 < T < 2K$ 
($T_c \approx 0.85K$)

Amplitude $B$ of the first longitudinal mode proportional to $W$
the energy delivered in the bar

$B/W = \text{constant}$
RAP results for $T < \text{critical temperature}$

- B/W not constant for $T < T_C$
  - the sign of B/W becomes negative for $T < T_C$
  - $\implies$ initial compression of the bar
  - apparently complicated behavior
RAP results for $T < \text{critical temperature}$

- the non linearity for $T < T_c$ and the complicated behavior is due to saturation effects. A typical electron produces a transition in a cylinder of $1\mu$ radius. With an electron beam having $10^9$ particles the cross section switched to normal is $30 \text{ cm}^2$ larger than the beam cross section ($20 \text{ cm}^2$)

- the sign of $B/W$ becomes negative because both effects (local heating and transition from s to n) are like a “compression”.

- this model suggest a relation of the kind:

$$\frac{B}{W} = a + (b(T) - a) \exp \left( \frac{-W}{p_0 \rho C_I(T)} \right)$$

$$b(T) = p_1 + p_2 T + p_3 T^2$$

- $a \approx 2.25 \times 10^{-10} \text{ mJ}^{-1}$ is the constant value of $B/W$ for $T > T_c$ and $b(T)$ the value of $B/W$ for $T < T_c$ and $W \to 0$

- $C_I$ is the integrated specific heat between $T$ and the critical temperature

- 4 free parameters $p$
RAP results for $T <$ critical temperature

\[ \frac{B}{W} = a + (b(T) - a) \exp \left( \frac{-W}{p_0 \rho C_1(T)} \right) \]

\[ b(T) = p_1 + p_2 T + p_3 T^2 \]

Fit result $\chi^2$/d.o.f. = 368/286 = 1.29

- the model of De Rujula Cabibbo et al. with the of two effects when $T < T_c$ is correct. But only for small value of the energy (as in the case of cosmic rays).
- The fit can be used to find $B/W$ when $W -> 0$
- measurements necessary due the approximations in the model and to the poor knowledge of low temperature parameter
Summary of the RAP measurements

The value at T<Tc are obtained from the fit for W (Energy)->0

Small disagreement also for T 1-4 K

Enhancement of ~ 4.9 for T ~0.1-0.2 K
Nautilus data at $T=0.14$ K and predictions using the RAP 4.9 enhancement

Figure 13: NAUTILUS 1998, at $T = 0.14$ K. The integral distribution of the event rate after the background unfolding, compared with the expected distribution (continuous line). The prediction is computed using the data of Table 4 and using the value $\delta_s = 5.7$ measured by RAP. The good agreement suggests the absence of anomalous components of cosmic rays or anomalous interactions of cosmic rays with a superconductive bar. Modified from Ref. 24.
• **Strange behavior** in superconductive aluminum: change of sign of the initial amplitude and enhancement of ~ 4.9 (in energy ~24)

• No **anomaly** found in the cosmic rays interaction with the bar.

• Cosmic rays are not an important noise at the moment. But **useful tool** to have a continuous monitor of very small amplitude signals (<1 mKelvin). Useful in “cumulative searches” like gamma ray bursts.

• **Application to exotic** particle searches (nuclearites..)

• Cosmic rays can be also **a noise in GW interferometers** (mirrors). Two mechanism: one similar to the bar, the other produces a pendulum oscillation. Not a problem for the next generation advanced detector, but the calculation for muons of Yamamoto et al., Phys. Rev. D 78 (2008) should be extended to include E.M. and hadronic showers.
Additional slides
Strange Quark Matter (nuclearites, strangelets)

- Aggregates of $u, d, s$ quarks + electrons of ~ equal number, density: $3.5 \times 10^{14}$ g cm$^{-3}$.
- Ground state of nuclear matter ($E/A < 930$ MeV).
- Stable for any baryon number $A$ (few $< A < 10^{57}$).

..a qualitative picture...

<table>
<thead>
<tr>
<th>$M$ (GeV)</th>
<th>$10^6$</th>
<th>$10^9$</th>
<th>$10^{12}$</th>
<th>$10^{15}$</th>
<th>$10^{18}$</th>
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- **Nuclearites**: core + electrons, neutral, $A > 10^6$ (CDM candidate)
- **Strangelets**: positively charged, $A < 10^6$ (Cosmic ray component)
Application: nuclearites searches in anti-coincidence with the CR detector

\[
\frac{dE}{dx} = 480 \text{GeV cm} \left[ \frac{\beta \theta(m)}{10^{-3}} \right]^2,
\]

where the mass dependence is

\[
\theta(m) = \begin{cases} 
1 & \text{if } m \leq 1.5 \text{ ng}, \\
\left( \frac{m}{1.5 \text{ ng}} \right)^{1/3} & \text{if } m \geq 1.5 \text{ ng}.
\end{cases}
\]

- limits are much higher than the one in other experiments (SLIM 1.4 $10^{-15}$ MACRO 3 $10^{-16}$)
- but some interest because the detection mechanism is quite simple, no threshold in $\beta$

\[\text{“calorimetric measurement”}\]

- for some masses limits < than DM matter limit

\[\text{multiply by 2 if } m < 0.1 \text{ gr and } \beta = 10^{-3}\]
With the today bar sensitivity events are due mainly to cosmic rays with a primary of energy $>\sim 10^{14}$ eV.
Application antenna monitoring and performances study: time resolution

Fig. 12. EXPLORER 2003-2006: Time difference (seconds) between cosmic rays with \( \Lambda \geq 100 \text{ particles m}^{-2} \) and the maximum of the filtered antenna signal, with a cut \( E \geq 35 \text{ TeV} \). The fit with a gaussian, with parameters \( p0=\text{peak}, p1=\text{mean}, p2=\sigma \) and a constant background \( p3 \), gives \( \sigma = 3.7 \text{ms} \). The value of the mean \((-1\pm0.35 \text{ ms})\) should be compared to the expected value of -0.6 ms due to the delay of the antenna electronic chain.