Gravitational Wave Astronomy
via
Hypersharp Neutrino Transitions

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Nuclear Resonance in Observation of Relativity Red Shifts

Red shift of photons at different Gravitational Potentials:

1. On the earth: $\Delta E/E = gh/c^2$
   $= 10^{-18}$ eV /cm vertical height diff.
   (g= acceleration due to earth gravity)

2. By Equivalence Principle red shift in lab Acceleration A
: $\Delta E/E = A/c^2$ h
   $= 10^{-21}$ eV /cm/s^2

Both Effects due *only* to Special Relativity (time dilation)

Both effects observed (~1960)

Both effects used the sharp widths of Nuclear Gamma Rays
by the detuning by the red shifts in resonance absorption
in a resonator (absorber) tuned to the source emission

Resonance Absorption of γ-rays emitted by isomeric nuclear states

Energy width—decided by lifetime of the state
$\Delta E = h/2\pi\tau$ → longer the τ (isomeric level)
→ sharper the $\Delta E/E$ of the emitted γ-ray

- Red Shifts are extremely SMALL→ Sharp γ-rays Nuclear Recoil Problem
- → Recoil eliminated in crystals if $E_R << \theta_D$ → Mδssbauer Effect

- Typical Figs. Of Merit:
- Classic Nuclear resonance: 14.4 keV γ of ^{57}Fe
- Lifetime: $\tau = 100$ ns → $\Delta E/E \sim 10^{-12}$

1. Red Shift on earth measured in 22m height difference
2. Red Shift in Acc. Sys measured at tip of fast rotor

Special Relativity OK!!

Effect of GR on nuclear resonance

So far unsuspected!

•GR creates space distortion→length *scale* is changed

→Typical Length Strain $\mathbf{h} = \Delta\ell/\ell \;\; \mathbf{10^{-21}}$

→Detectable via Michelson-Morley→ LIGO, LISA

•GW also changes wavelength/ frequency / energy of photons/neutrinos since number of waves/unit length changes when length scale changes

→Detunes very sharp nuclear resonances

→Can be detected by a suitably sharp resonance

→New Approach to GW astronomy

SR vs GR Effect on Nuclear Resonance

- GR effect even with source and absorber are at the same grav. potential or in unaccelerated systems (No effect in SR)
- No Effect in the absence of GW—GW only known way to distort space in the Lab Scale on Earth
- Effect on Nuclear Resonance only in the presence of GW
- Resonance effect if resonance $\Delta E/E \sim \Delta\ell/\ell \sim 10^{-21}$ or less
- GW Strain from typical sources is periodic (also transient….)

→Resonance effect is ***modulation*** of photon/neutrino energy
Not resonance detuning by a constant energy shift as in SR

Signatures & Sensitivity

GW effect→ Energy *modulation* of radiation
Modulation depends on Strain and Frequency of GW
Anisotropy of GW → Directional dependence of modulation
→ *locate source* of GW
→GW Astronomy

→Typical effect $\Delta E/E \sim 10^{-21}$→ need resonance sharpness of same order
→Best γ-resonances so far: $\Delta E/E$ ~**5×10^{-13}**; (^{57}Fe), **10^{-15}** (^{67}Zn)
→Need new "HYPERSHARP" nuclear Resonance for GW

→Discovery of possibility of ***Neutrino*** Resonance with

$\Delta E/E \sim 10^{-29}$ → HYPERSHARP !

Hypersharp Resonances—Neutrinos !

---how to reach < 10^{-20} ? → Longer γ-ray lifetimes?

But long lifetimes result from high EM multipolarity—high conversion of atomic electrons → fewphotons

→ Beta decay—weak interaction guarantees long lifetimes

But…3-body beta decay → continuous spectrum…. not lines!!

e.g., tritium decay $^3H \rightarrow {}^3He + e^- + \tilde{\nu}_e$

Need new ideas

"Bound State" or 2-body β-decay—J Bahcall(1962)

→ Beta electron is captured in an atomic orbit instead of into the continuum

→ ^3H →neutral ^3He (with e^- in 1s orbit) + $\tilde{\nu}_e$ → 2-body decay

→ Monoenergetic Neutrino LINES!

→ BB decay branching in T decay = *0.54%*

→ Line NEUTRINO →resonance transitions like γ-rays.

→ Neutrinos from tritium $(\tau \sim 17\ years)$ will be Hypersharp

--if *all other relevant aspects are in place !*

Detecting the Tritium Antineutrino line $\tilde{\nu}_e$

Induced Orbital Electron Capture (Mikaelyan 1968)

Reverse of BB decay:

$\tilde{\nu}_e + {}^3He + e^- (\text{ 1s orbital}) \rightarrow T$

→Resonance capture of T antineutrinos

→Really low threshold → E_ν min = 18.6 keV

Basic neutrino emission & capture scheme

$T \leftrightarrow {}^3He + \tilde{\nu}_e$

Emitted neutrino exactly in resonance (if no recoil).

$E_{\nu\,emit}(BB) = Q + B$; $E_{abs}(EC) = Q - B$

Binding energy B added in emission

is exactly enough for additional energy needed for EC.

→ Condition for Resonance Capture satisfied

LINEWIDTH

→Determines the line sharpness

→Resonance cross section via the resonance density of incident beam

→ $\sigma = \sigma_o / (\Delta E/\Gamma)$ Γ- natural width ($\sim 10^{-24}$ eV).

For hypersharp, i.e. with natural linewidth $\Delta E = \Gamma$

$\sigma = \sigma_o$ → "geometrical cross section" (independent of radiation, energy etc) $\sim 10^{-17}$ cm^2

→HUGE for neutrinos (typically 10^{-45} cm^2 at this energy)

LW → Prime moverss for the quest for natural linewidth in resonance transitions.

LINE BROADENING

Resonance lines broadened beyond Γ by solid state interactions—fluctuations of energy (homogeneous broadening) and distributed (non-unique) energies (inhomogeneous) broadening

Linewidth estimates for short lived (usual) ME cases taken from other techniques—generally fluctuation times ~kHz to MHz inhomegenity of similar enerrgy spread appliled to microsecond ME levels.

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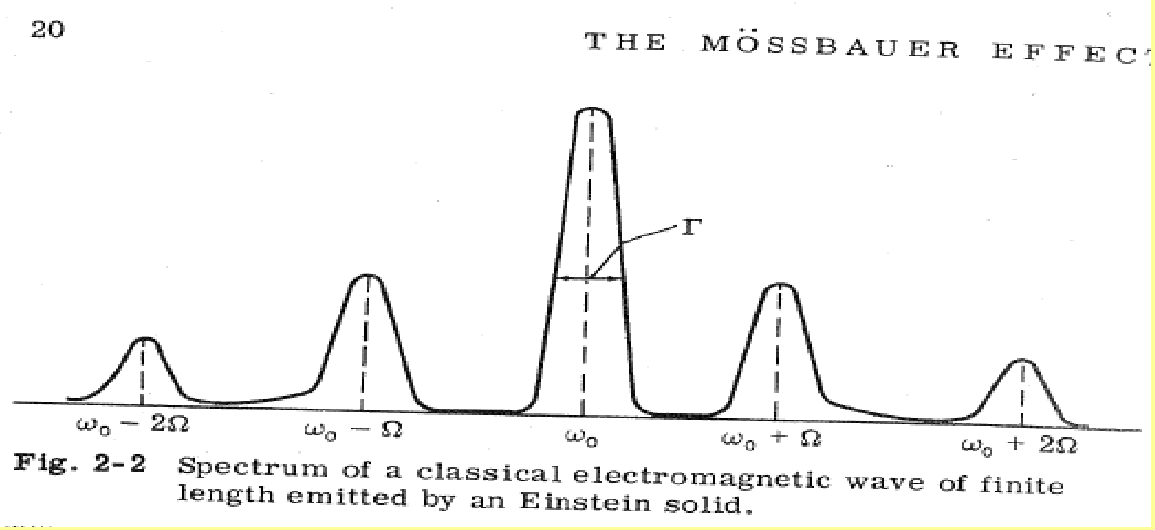
--Couold the linewidth physics be different for long life times?

Normally, i.e. with ME experience, the answer is NO

Linewidth ↔Nuclear Lifetime Connection?—YES!
Motional averaging! Lesson from theory of ME itself



20 THE MÖSSBAUER EFFEC

Fig. 2-2 Spectrum of a classical electromagnetic wave of finite length emitted by an Einstein solid.

Lattice vibrations modulate the energy of γ-ray (Shapiro1960).
Central unshifted line (ME line) emitted with natural width Γ
Sidebands $E_o \pm n\Omega$ (also with Γ); Ω are the phonon frequencies.
Condition for ME: → $\Gamma \ll \Omega$ i.e. lifetime of emitting level longer than typical lattice vibrational time $1/\Omega \sim 10^{-14}$ sec
→solid state interactions also MOTIONALLY averaged if the level llifetime $\tau \gg$ fluctuation times→ **Hypersharp lines**

FM Approach to Motionally Averaged linewidth

Theoretical treatment of ME lineshape that explicitly includes role of the nuclear lifetime: ---_(Salkola & Stenholm)_

The line shape is an FM series :

$$A \propto \frac{1}{\Gamma} \Sigma_{k=-\infty}^{k=+\infty} J_k{}^2(\eta) \frac{1}{[(\delta/\Gamma)-k\xi]^2+1}$$

Jk(x) are Bessel functions,

$\eta = \Omega o/\Omega$ [Ωo is the energy spread of fluctuation Ω= frequency

$\xi = \Omega/\Gamma$, δ is the external detuning for scanning the line shape.

→ Central line and \sidebands of index ±k, all with the natural width.

Broadening arises from overlap of k= ± 1 peaks separated by ξ linewidths from central line. →k= ± 1 overlap small if ξ is LARGE → Ω/Γ is large

→*Line approches natural width as Γ becomes very small (as in T)*

→ Long lived states naturally emit HYPERSHARP radiation with natural linewidth

→ Counterintuitive from normal ME experience with short lived states

Generalized Hypersharp Fraction

Motional averaging—pervasive; includes the basic ME itself

→ Efficiency of motionally averaged sharp line emission can be generalized to include the ME.

A hypersharp fraction (not just recoilless fraction):

$$\mathbf{H = J_0^2\,(<x>/\,\lambda)\,\prod_K J_0^2\,(\Delta_K/\,\Omega_K)}$$

where K runs over the different types of fluctuations with width Δ_K and rate Ω_K specific hypersharp fraction $J_0^2\,(\Delta_K/\,\Omega_K)$. The recoilless fraction $f = J_0^2\,(<x>/\,\lambda)$ is just the first term

Resonance Energy Self-compensation

Perturbing interactions create energy SHIFTS specific to T, He $E_T \neq E_{He}$ Atomic (B's already considered)

- Chemical bonding (T and He chemically different)
- Lattice → vibrational energy, at T≠ 0
  - → second order Doppler shift (SOD)
  - → Zero Point Energy ZPE
- Dipolar interaction in rigid lattice of spins
- Magnetic shielding-- Site dependent "chemical" /other shifts
- Gravitational broadening in the lattice—source vs absorber
- Earths field effect in source absorber
- *Spin ½ of T and 3He → Q =0 → random electric interactions absent*
- Motional averaging via vibrating r affects also the net shifts → hypersharp $\pm \Delta(E_T - E_{He})$.

- Energy gain in Emission is COMPENSATED EXACTLY in absorption

Technology--- Embedding T and He in solids -- "Tritium Trick"

T and He are gases--How to embed T and He in solids →Metal tritides

→ Tritium gas reacts with metals and alloys and forms metal tritides – (PdT, TiT, NbT...)

→ embeds T in lattice uniformly in the bulk

→ Tritium decays and He grows—distributed uniforml →(Tritium Trick (TT))

T and He lattice Sites in TT—

Unique? Identical for T, He? –YES if Nb is the matrix

→Unique Discovery!

Recoil free fractions in local Potential Wells

In Nb TIS the sizes of T and He result in local deformations that create potential wells in which T and He oscillate.

→ Simple picture—T and He ignore the general lattice.

- → Recoil free fractions from local excited vibrational states E_i , not general lattice excitations outside well. (No Debye Model !)
- → Then $f = \exp\text{-}[E_R\ (=62\ \text{meV})(\Sigma 1/E_i\ )]$
- → f = f(T)f(He) ~1.5%.
- → The dynamics of T and He in their potential wells implies that all random interactions with the rest of the lattice are bypassed– IMPORTANT feature

Detection of $\tilde{\nu}_e$ Resonance by $\tilde{\nu}_e$ Activation

Source T and absorber ^{3}He made by tritium trick.

Resonance signal is the $\tilde{\nu}_e$ induced activity of betas (Rβ).

The TT method implies T content in the absorber will create a background (Tβ). A chief design goal is to maximize Rβ/Tβ. The background due to T in absorber can be minimized by replacing T with H via efficient xchange process.

The source and absorber are set in the same cryogenic bath at temperatures << 200K.

The resonance activation signal, Rβ of 18.6 keV betas grows with time m ($\propto$ t /τ_) while the background Tβ decays ($\propto$ exp-t/τ) , thus the rate deviation from the exponential decay is the signature of the resonance.

T	^{3}He	Rβ	Tβ
10 Ci	0.3 pg	165 Hz Δt =100 d	38 Hz

Detection of GW

1. The GW perodically The GW produces a *periodic* strain that *modulates* the ṽe line energy by ± *h*E, at a rate f with the frequency f of the GW source.
2. The line energy is thus averaged in the same way as by motional averaging in the lattice.. The line splits into a central line and sidebands by the modulation parameters η = [*h*Ev /f] and ξ = [f / Γ].
3. The fractional intensities are given by the J_o^2 (η) for the central line (resonance signal) and J_1^2 (η) for the first sideband at ±δ = ±ξ linewidths.
4. The dependence on η in particular, sets the conditions of **detectability** of GW. Most of the GW sources produce space time strains 10-23 < *h* < 10-20 with frequencies 10-4 < f < 103 Hz1.
5. Qualitatively, high frequency GW (η→ 0) tend to average out the GW effect (as with lattice vibrations) and result in the *unperturbed* maximum. This sets the limits on **sensitivity** on the other side

Quantitative Detection by Countermodulation

- Since the GW perturbatiion is a modulation of the neutrino energy, quantitative detection can be based on a **countermodulating** drive on each absorber which creates variable acceleration (in frequency and ***phase****)* that can lock on in anti-resonance to the ṽe resonance signal rate in that absorber.

- The signal rate varies from the background to fully retuned resonance, measuring J_o^4 (Ev*h/f)*= J_o^4 (3x1019 *h*/f) (taking into account the source+absorber in the final resonance signal).

- In addition, one can scan for the first *sideband* intensity J_1^4 (3x1019 *h*/f) and its position δ given by ξ= *(f / Γ) = (6.6x108 f)* linewidths (with Γ ~10-24 eV) The measured data on η and ξ can lead to a determination of *h* and f independently

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Invent the Future

Figures of merit for GW sensitivity

1. The minimum detectable resonance effect is set by the *(3σ)* statistical precision *~10^{-3}* of the background Tβ in a live time of1 day.
2. At the high η end, J_o^4 (3x1019 (*h/f*)) = J_o^4 (10) ~4x10-3, thus, the limit 3×10^{10} (*h/f*) < 10 → *h*/f <3×10^{-19} applies for a detectable signal.
3. In a multidetector array which is sensitive to different relative directions the limit figures apply to the absorber that sees the maximum strain; the off-axis absorbers see less strain,
4. As η→0 the resonance signal approaches 1, the full value and the resonance line is ***decoupled from the GW*.**
5. A qualitative "*detunability*" can be set with η ~0.3 for which J_o^4 ~0.9, thus (3×10^{19} h/f)>0.3 or *h*/f >$10^{-20.}$. At *h* ~ 10^{-20}. the GW will begin to detune the ṽe resonance if f < 1 Hz.
6. GW sources with smaller strains can be detected by detuning only if the frequency is lower.
7. These limits of detectability and detunability demarcate the optimal range as:

$$f< 1\text{Hz and } h/f < 3\times10^{-19}$$

Summary

1. A novel approach to GW astronomy based on hypersharp $\tilde{\nu}$e resonance may be possible.
2. A GW telescope with a central source of T and a multi-detector He absorber array is proposed.
3. The method is suited to sources in the range of strain/frequency ratios 10-20 <*h*/f <3x10-19 which covers low frequency objects presently targeted by LISA18.
4. A Hulse-Taylor like binary source[i] with *h*/f ~10^{-22} / 10^{-4} but **1000 times farther away** (the GW weakens as $h \propto 1/r$) can be detected even if f ~10^{-5} Hz.
5. These ideas thus lay the foundation for a new laboratory-scale all-sky, all-live, telescopic observatory for detecting and characterizing GW sources farther than ever.

Ref. for Hypersharp Neutrinos.

R. S. Raghavan, Phys. Rev. Lett. **102**, 091804 (2009)