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Workshop Towards Neutrino Technologies

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Hypersharp Neutrinos

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Hypersharp Neutrinos I

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July 16, 09

Hypersharp neutrinos- Some Milestones

Resonant Nu Capture--Technology: Neutrino Osc. on the Table Top

Recoilless resonant capture of antineutrinos, hep-ph/0511191 (early (>25 y old) ideas: Kells & Schiffer, Phys. Rev. **C28** (1983) 2162 **–conclude technology unlikely!**

Recoilless resonant capture of antineutrinos from tritium *decay*, hep-ph/0601079 --first experimental design with reasonable potential-(hydrogen storage tech.)

Assumes ("WIDE") linewidth ideas from "Moessbauer" Experience

Linewidth in Nu Capture—Conceptual Advance:

Hypersharp Neutrino Lines, 0805.4155

Hypersharp Resonant Capture of Anti-Neutrinos, 0806.0839---New Ideas on line narrowing!

Final paper : Much refined.

Hypersharp Resonant Capture of Neutrinos as a Laboratory Probe of the Planck length (Phys. Rev. Letters,)

TEU and quantum mechanics

Hep-ph 0907.0878 (July 09)

Quest for resonance reaction of neutrinos from Tritium

Analagy to γ-ray resonance (Moessbauer Effect)

Step 1

Make **monoenergetic neutrinos in beta decay of T-**- normally with continuous beta emission-- need nu LINES for resonance

→ **"Bound State" β-decay—John** Bahcall (1962) ; Electron appears in an atomic orbit (2-body decay) instead of into the continuum -- Monoenergetic Neutrino LINES! ---branching in T decay = *0.54% to 1s state—OK since it has a vacancy for one more electron*

T → neutral ^{3}He (with e^- in 1s orbit) + $\tilde{\nu}_e$ (18.6 keV)

Step 2

Detection of 18.6 keV $\tilde{\nu}_e$

$\tilde{\nu}_e$ capture by inverse beta sets capture threshold at 1.022 MeV to create positron → $\tilde{\nu}_e + {}^3He \rightarrow T + e^+$ →**threshold too high**

Induced Orbital Electron Capture (Mikaelyan 1968) induced by antineutrnos from tritium

Reverse of BB decay: $\tilde{\nu}_e + {}^3He + e^-$ (1s orbital) → T

→**Resonance capture of T antineutrinos**

→**Really low threshold → E_ν min = 18.6 keV**

Enegy Balance

Nuclear decay energy = Q

Ev emit(BB) = Q + B; (electron inserted in shell)
Eabs (EC) = Q - B (electron removed from shell)
Self compensation of final state energies (orbital Binding energy B
(part of general self compensation mechanism for final state energies)

Condition for Resonance Capture satisfied
Basic Resonance Idea Complete :

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

a pair of time-reversed processes

Moessbauer Neutrinos →Hypersharp Neutrinos →LINEWIDTH

Line widths determine the resonance cross section inversely → $\sigma = \sigma_o / (\Delta E/\Gamma)$ Γ- natural width (~10^{-24} eV in tritium).

e.g. linewidth for T from NMR data for broadened lines ~ 13 kHz

→ $\sigma \sim 10^{-33}$ cm^2

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

$\sigma = \sigma_o$ → "geometrical" cross section ~10^{-17} cm^2

→ Very High σ and very small ΔE Prime mover for the quest for natural linewidth in resonance transitions.

Linewidths in Short lived & long lived states

Linewidth estimates for short lived (usual) ME cases taken from other techniques—generally fluctuation times ~kHz to MHz in microsecond ME levels. First pass assumption in previous work (R. S. R *hep-ph/06 1079 (2006)* → T = 13kHz → $\sigma \sim 10^{-33}$ cm^2

Further work→ examine the correctness of this practice for LONG LIVED LEVELS.

--Is the linewidth physics basically different for long life times?

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

Linewidth ↔Lifetime Connection?

But….Early hint for “yes”---from theory of ME itself.

Lattice vibrations modulate the energy of γ-ray (Shapiro 1960).
Fig shows energy spectrum with central unshifted line (ME line) with natural width and sidebands $E_o \pm n\Omega$ (also of natural width) where Ω is the phonon frequency (single freq as example).

Condition for ME: non overlapping first bands → Γ<< i.e. lifetime of emitting level longer than typical lattice vibrational time 1/Ω ~ 10^{-14} sec **(explicitly remarked – H. Frauenfelder, 1962).**

This condition always satisfied in every ME isotope so far(>10^{10}s) , thus ignored.
But the important outcome is that there is a nuclear lifetime-linewidth connection

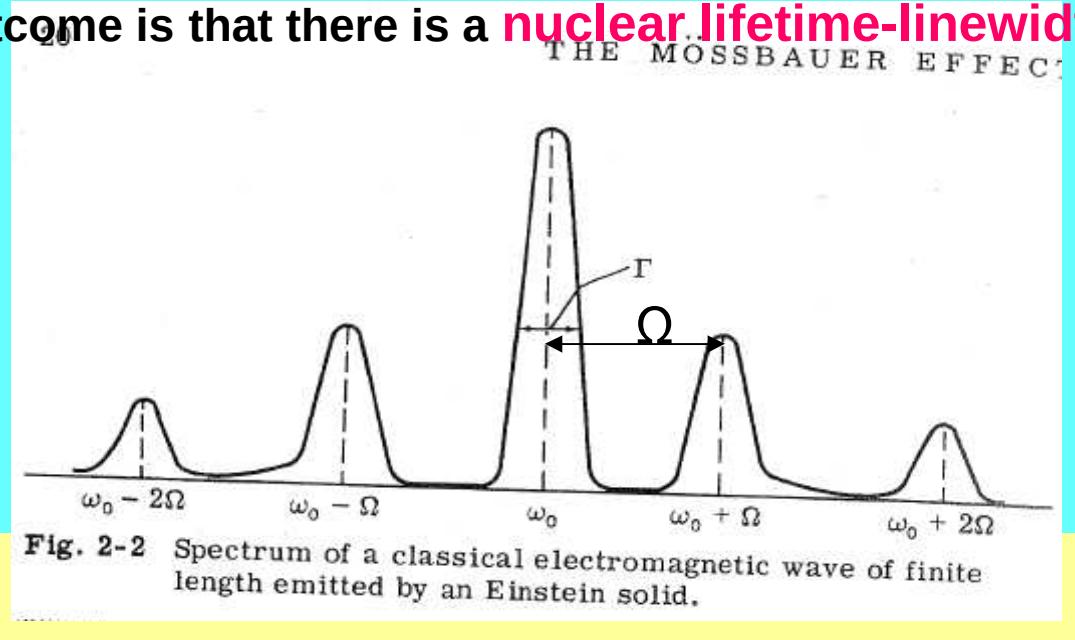


Fig. 2-2 Spectrum of a classical electromagnetic wave of finite length emitted by an Einstein solid.

Quantitative linewidth in long lived states

Theoretical treatment of ME lineshape that explicitly includes role of the nuclear lifetime: --- (Salkola, S. Stenholm 1990-extension of Shapiro theory)

Considered in another context—lifetime connection not remarked upon)

- **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,

η = Ωo/Ω [Ωo is the energy spread of fluctuation

Ω= frequency of fluctuation

ξ = Ω/ Γ , δ is the external detuning for scanning the line shape.

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

Crucial Feature: Broadening arises from overlap of k= ± 1 peaks. They are ξ linewidths separated from central line.

→k= ± 1 overlap small if separation ξ is LARGE or Ω/ Γ is large

→ ***Line approches natural width as Γ becomes v. small i.e. when τ becomes longer than 1/Ω i.e. >> 1msec for normal kHz type relaxation processes in simple metals***

→ **For T decay (τ = yrs) the $\tilde{\nu}_e$ linewidth is *necessarily = Γ !***

Line "narrowing" ubiquitous in physics

Direct estimate of narrowing effect of vibrating dipoles in the vicinity

Dipolar field H = μ /r3

Surrounding magnetic moments at different distances r

fluctuate because lattice vibrational displacements change r, thus changing H by $\Delta H/H = -3 (dr/r)$

r ~4 A lattice constant

Get dr from Debye Waller Factor

$f = \exp[-\langle dr\rangle^2/[(h/2\pi)\, c/E_\nu]^2 \sim 0.1 \rightarrow \Delta H \sim 0.02$ gauss

- **Spin relaxation time $T_2 \sim [\gamma^2 (\Delta H)^2 \tau]^{-1}$ (Slichter)**
- **$\gamma = \mu/I = 2\times10^{-11}$ eV/gauss; τ = fluctuation time = h/(ZPE = 0.1 eV)**

$T_2 \sim 4.2\times10^8$ s $\sim \tau$ (^{3}H) = 5×10^8 s

- **The tritium $\tilde{\nu}_e$ line is motionally averaged to a width comparable nuclear natural width**
- **Argument applies to motional averaging of *all r-dependent* interaction—not just dipolar fields**

Stochastic fluctuations

The Effect of Collisions upon the Doppler Width of Spectral Lines

R. H. Dicke
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received September 17, 1952)

Quantum mechanically the Doppler effect results from the recoil momentum changing the translational energy of the radiating atom. The assumption that the recoil momentum is given to the radiating atom is shown to be incorrect if collisions are taking place. If the collisions do not cause broadening by affecting the internal state of the radiator, they result in a substantial narrowing of the Doppler broadened line.

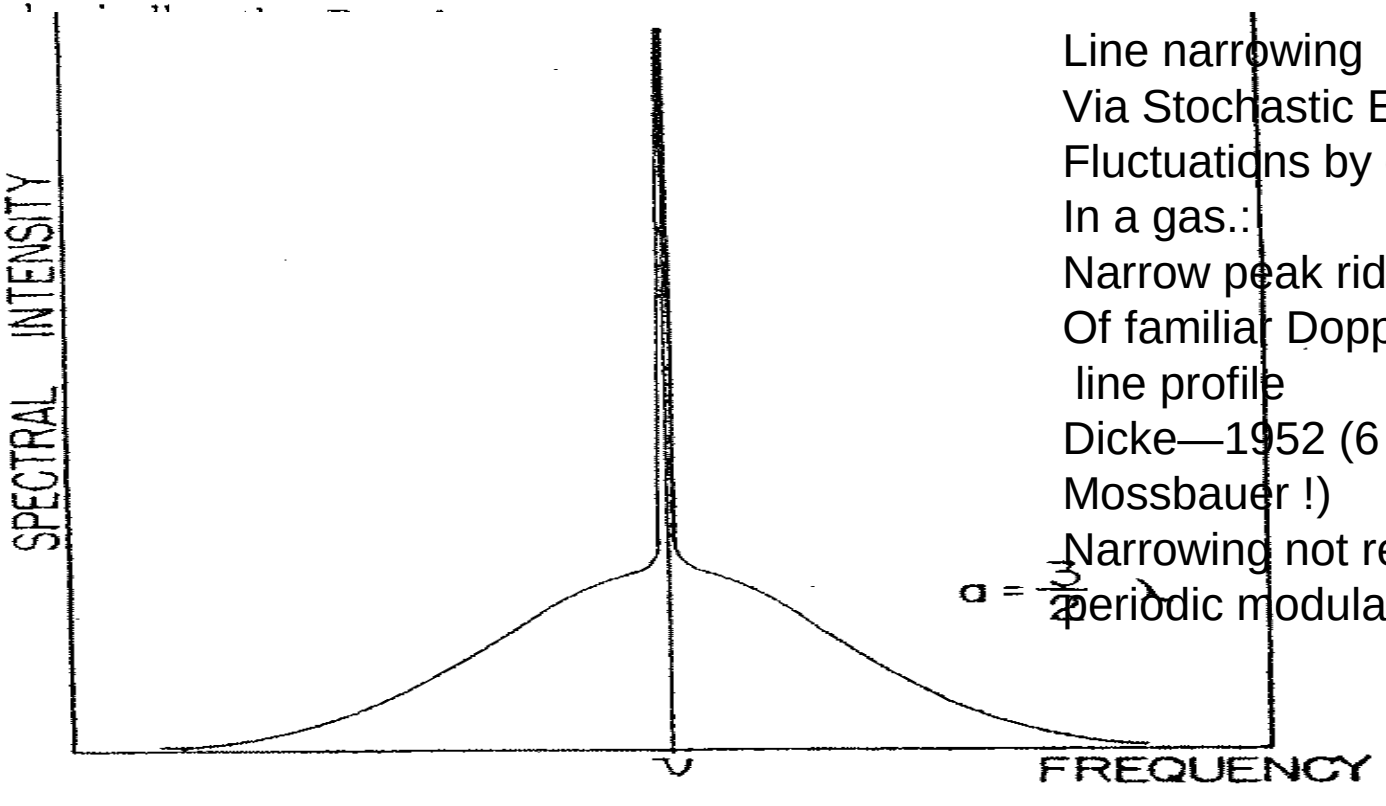


FIG. 2. Doppler broadened line of a gas in a one-dimensional box.

Line narrowing
Via Stochastic Energy
Fluctuations by collisions
In a gas.:
Narrow peak riding on top
Of familiar Doppler broadened
line profile
Dicke—1952 (6 years before
Mossbauer !)
Narrowing not restricted to
periodic modulation

Other examples

Perturbations of intermediate States in Nuclear Cascades (Abragam & Pound (1953)

Unequal population initiated by cascade angular momentum balance (Angular Correlations) can be perturbed by relaxation and other perturbations in the intermediate state.

For paramagnetic. Relax. (Example for Stochastic perturbations)

- **Perturbation factor $G_k = 1/(1+\lambda_k \tau_N)$**
- **$\lambda_k \propto \tau_s \omega_s^2$ (relax. Time, relax. Width)**
- **τ_N nuclear lifetime**
- **$G_k \rightarrow 0$ as $\tau_N \rightarrow$ long.**

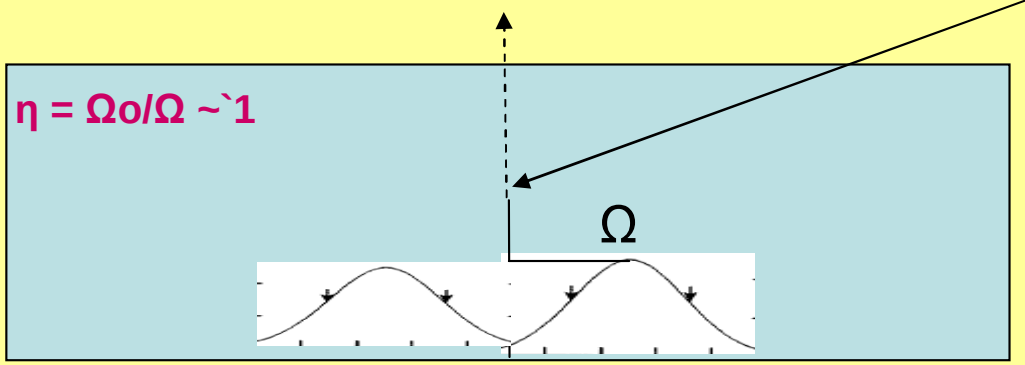
→ **In long lifetime states Perturbation *averaged to zero* so initial correlations are destroyed.**

→ **Another general example of explicit role of nuclear lifetime in stochastic Perturbations**

Other examples—NMR
Line Narrowing by stochastic
Magnetic Relaxation, exchange narrowing Stochastic fluctuation of magnetic moments (paramagnetic relaxation)

Simple way to look at what happens in ME.
Take the Fourier Transform of random fluctuation
→Gaussian form with Ω width of the relaxation time Ω_o mean value of field
(Anderson 1953—exchange/relaxation narrowing of NMR lines)

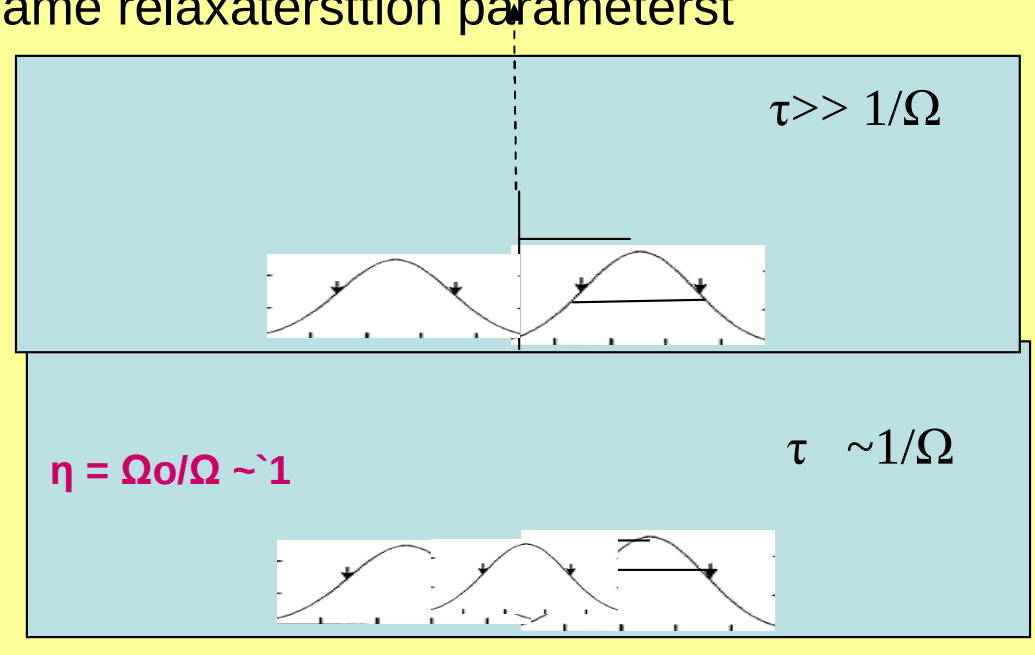
If we tomagraphically take very narrow slices they can represent lines of
A modulating frequency spectrum instead of a line of the periodic freq:
Then the modulated spectrum looks like:



Line remains hypersharp
Many orders of magnitude (~10^{11} taller)
But intensity is reduced by
J_o^2 ~ 0.4 60% traqnsferred to side bands
overall reduction Jo^4

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

Line Broadeng in Long and Short lived levels under same relaxatersttion parameterst



Simple FM picture works best when e there is no overlap (τ long)
As lines ovelap (τ ~ relaxation time Ω)
more powerful correlaion methods needed

Generalized Hypersharp Fraction of Emitted Neutrinos

Motional averaging concept—pervasive; includes the basic ME itself

In the FM approach, the efficiency of motionally averaged sharp line emission can be generalized to include the ME.

A hypersharp fraction can be defined as

$$H = J_0^2 (\langle x \rangle / \lambda) \prod_K J_0^2 (\Delta_K / \Omega_K)$$

where K runs over the different types of fluctuations with width Δ_K and rate Ω_K with the specific hypersharp fraction $J_0^2 (\Delta_K / \Omega_K)$. The familiar recoilless fraction $f = J_0^2 (\langle x \rangle / \lambda)$, the first term above, is now just one of factors that set the overall hypersharp line intensity.

Emitter-Target Energy Balance

Perturbing interactions create energy SHIFTS

E_T and E_{He} specific to the T and the He, in general, different.

- **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 (considered)**
- **Magnetic shielding-- Site dependent "chemical" /other shifts**
- **Gravitational broadening in the lattice—source vs absorber-external avg design**
- **Earths field effect in source absorber (external avg—careful design**
- **Spin ½ of T and 3He → Q =0 → random electric interactions *absent***
- **Motional averaging via vibrating r affects also the net shifts → hypersharp ± $(E_T - E_{He})$.**
- **Energy gain in Emission is COMPENSATED in absorption**
- **Compensation is PRECISE because each shift is averaged to unique sharp values**

Experimental---Basic Embedding Technique
Tritides and the "Tritium Trick"

He is a noble gas. Tricky problem to embed in a solid.

How to embed T and He in solids

→ Metal tritides —Best approach visible

→ 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 uniformly

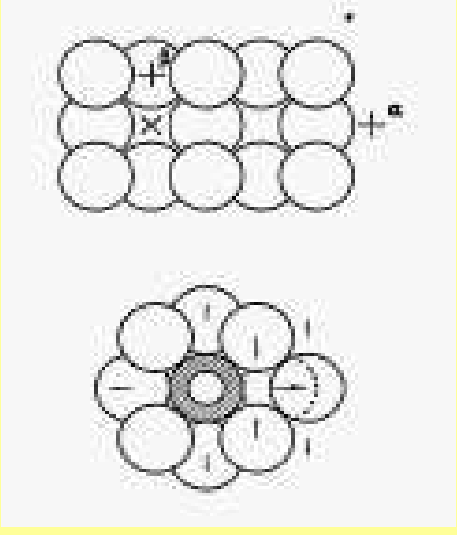
(Tritium Trick (TT))

→Problems:

1. **T and He lattice Sites in TT—Unique? Identical for T, He?**
2. **Must Remove T from absorber to improve S/N –replace T by H**

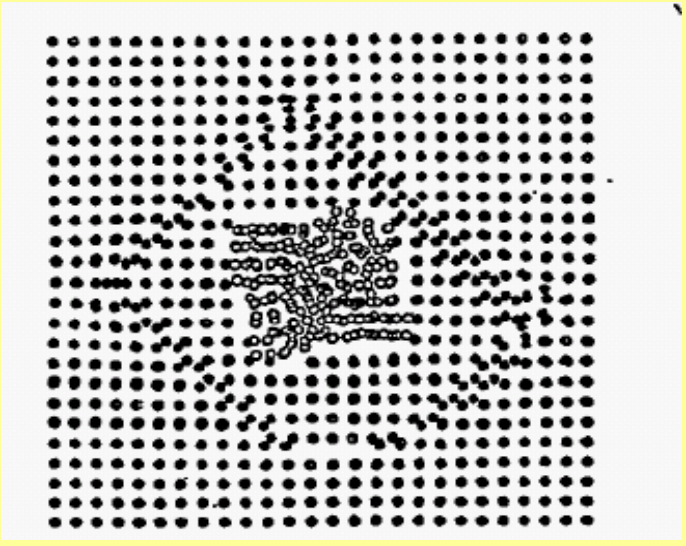
Tritium and He sites in metals

T



T→Interstitial Sites
Octahedral – fcc metals
Tetrahedral—bcc metals

He

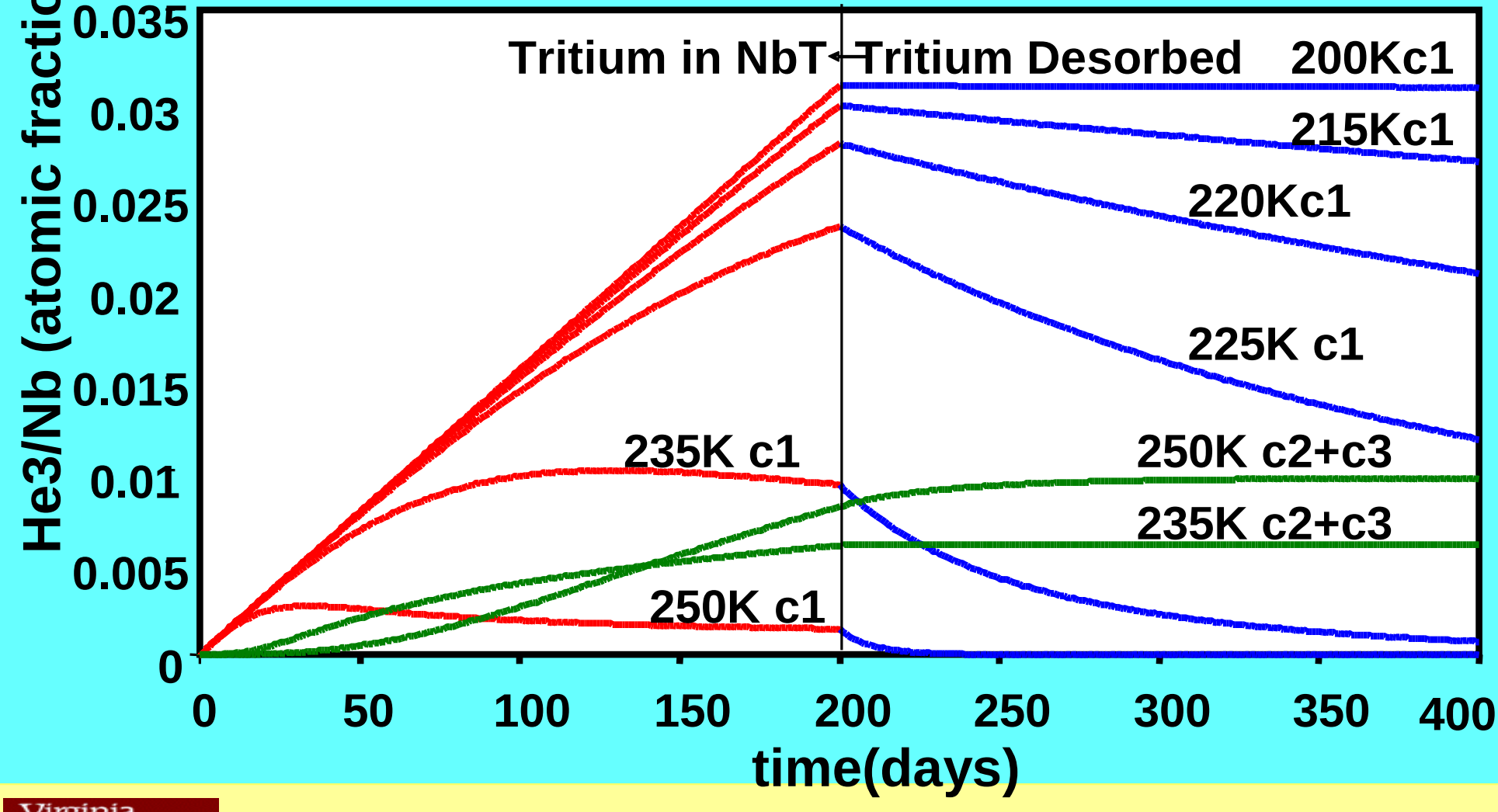


He→Microbubbles:
1-2nm diam; 4000 atoms
Solid under pressure ~10 GPa at <100K
He atoms closer than in IS sites

Quest for matrix and conditions where
IS sites dominant –not bubbles
T and He should occupy same type of INTERSTITIAL site
→ Search for metal matrix and conditions

How to make Unique, Identical IS for He Niobium !

- He transport in Nb : T in Nb for 200 days
- Remove T and monitor He for 200 d



Niobium- Unique Discovery

Niobium as Matrix choice:

- **Calculations show that at <200K He is ONLY in TIS sites**
- **No bubbles are formed indefinitely**
- **The EST of Tetra and Octa sites are nearly degenerate**
- **→ He sits randomly in either site==67% in TIS**
- ***→ Uniqueness and identical site requirement satisfied***
- **→Nb is unique in providing these features**
- **Most significant advance in 25 years since Kells Schiffer**

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 !)**
- → **E_i have been measured via n-inelastic scttering.**
- → **Exact calculations**
- → **Then f = exp-[E_R (=62 meV)(Σ1/E_i)] =0.125 with E_i =72 and 2x 101 meV→ f = 0.15**
- → **f = f(T)f(He) ~1.5%.**
- → **The dynamics of T and He in their potential wells implies that random interactions with the rest of the lattice are bypassed– IMPORTANT feature**

Detection of $\tilde{\nu}_e$ Resonance– $\tilde{\nu}_e$ Activation Analysis

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

The background due to T in absorber can be minimized by replacing T with H via efficient exchange process.

Resonance signal is the $\tilde{\nu}_e$ induced activity of betas (Rβ). The TT method implies some T content in the absorber which will create a background (Tβ). A chief design goal is to maximize Rβ/Tβ.

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 ($\propto t/\tau$_) while the background Tβ decays ($\propto \exp -t/\tau$) , thus the rate deviation from the exponential decay is the signature of the resonance.

TABLE III. T-^{3}He hypersharp $\tilde{\nu}_e$ capture rates (worst case, line 1, and best cases, lines 2, 3; see text). Δt is the delay after start of activation. TT is the tritium trick.

Absorber	Baseline	T	^{3}He	$R\beta/d$	$T\beta/d$
TT	1 cm	1 kCi	1 pg	2×10^6 ($\Delta t = 100$ d)	3.7×10^9
T desorbed	1 cm	1 mCi	1 pg	2 ($\Delta t = 0$ d)	~0
T desorbed	10 cm	1 kCi	1 pg	2 ($\Delta t = 0$ d)	~0

Summary

- Arguments from several perspectives of motional averaging suggest that the resonance linewidth depends on the nuclear lifetime.
- Motional averaging also makes energy shifts hypersharp so that can be precisely self compensated in the emission+ absorption
- Identical interstitial sites are possible for T and He in Niobium below 200K—a key experimental discovery
- The sites create local potential wells which isolate the dynamics of T and He from the rest of the lattice and "shielding" them from inhomogeneous interactions.
- The cross section is "geometrical" ~10^{-17} cm^2-->practicality