Summer Student Seminar
Wed. May 24, 2006, 9:30 a.m.

Laser Traps for Beta Decay Experiments

John Behr, TRIUMF

TRIUMF’s neutral atom trap captures radioactive atoms in a 1 mm-sized cloud in a vacuum chamber. The atomic nuclei undergo beta decay, which produces three decay products: a $\beta$, a $\nu$, and the daughter recoiling nucleus. The daughter nucleus has very little energy and would stop in a nanometer of material, but it freely escapes the trap. By measuring its momentum in coincidence with the $\beta$, the $\nu$ direction with respect to the $\beta$ can be deduced more directly than in previous experiments.

As far as we know, the Standard Model weak interaction is mediated by “heavy light”, “vector” bosons with spin 1 which are heavy partners of the photon. We see a $\beta$-$\nu$ correlation consistent with the Standard Model, and constrain the existence of other exchange bosons with spin 0. We also spin-polarize the nuclei with circularly polarized light, to test whether parity is fully violated in the weak interaction. We will wave our hands about a possible search for keV-mass $\nu$’s.

The mathematical proof that these traps cannot work will be presented, along with its experimental dodges. No laser pointers will be harmed during this presentation. If you can’t read the t-shirt, you’re sitting too far away.
I. Laser Cooling and Trapping
   Why Laser traps Can’t Work

II. Demonstrated Capabilities:
   $\beta^+$–recoil coincidence $\Rightarrow \nu$ momentum
   Best Limits on scalar interactions
   Search for keV-mass $\nu_x$?

III. Promise: high known polarization:
   How to polarize a nucleus with a laser
   Search for right-handed $\nu$’s: need $P > 99\%$
**TRIUMF Neutral-Atom Trapping “TRINAT”**

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<th>Simon Fraser U.</th>
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<th>Tel Aviv</th>
<th>Undergrad</th>
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| Supported by Canadian NSERC, Canadian NRC through TRIUMF, WestGrid, Israeli Science Foundation |

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Laser Cooling

Radiation Pressure:

\[ \Delta \vec{p} = \hbar \vec{k}_\gamma \]
\[ \vec{F} = \frac{d\vec{p}}{dt} = (\hbar \vec{k}_\gamma) \] (scattering rate)

Equal intensity plane waves, redshifted, 1-D

\[ F = \frac{\hbar k_\gamma (\Gamma/2 I/I_0)}{1+4(\frac{\delta-kv}{\Gamma})^2} - \frac{\hbar k_\gamma (\Gamma/2 I/I_0)}{1+4(\frac{\delta+kv}{\Gamma})^2} \]

\[ \delta = k v \]
\[ \delta = -k v \]

\[ F_{\text{SUM}} \]

- slows efficiently for \( v < v_{\text{capture}} \)
- \( 10^4 \) photons to slow room \( T \)
- no spatial dependence (yet)
‘Optical molasses’
“Why Optical Traps Can’t Work”

Earnshaw Theorem:

\[ \nabla \cdot \vec{E} = 0 \]

\[ \Rightarrow \text{no electrostatic potential minimum for charge-free region} \]

“Optical Earnshaw Theorem” (Ashkin + Gordon 1983):

Using Poynting’s theorem:

\[ \nabla \cdot \vec{S} = \frac{c}{4\pi} \nabla \cdot (\vec{E} \times \vec{B}) = -\vec{J} \cdot \vec{E} - \frac{\partial u}{\partial t} = 0 \]

\[ \Rightarrow \text{no 3-D traps from spontaneous light forces with static light fields} \]

Dodges!

- Dipole Force traps (“optical tweezers”)
- Modify internal structure of atom with external fields
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Zeeman Optical Trap (MOT)  

Raab et al. PRL 59 2631 (1987)

Damped harmonic oscillator

\[ \varepsilon = \mathbf{s} \cdot \mathbf{k} \]
Zeeman Optical Trap (MOT)

Raab et al. PRL 59 2631 (1987)

Damped harmonic oscillator

\[ \varepsilon = \hat{S} \cdot \hat{k} \]

Bquad weak: recoils unperturbed

Velocities negligible

Vector polarization \( \sim 0 \)

(Tensor alignment maybe)

Turn MOT off to polarize

\[ J=0 \]

\[ m=-1 \quad 0 \quad 1 \]

\[ \sigma^- \quad \sigma^+ \]

\[ J=1 \]

\[ m=-1 \quad 0 \quad 1 \]

\[ \sigma^- \quad \sigma^+ \]
3000 atoms $^{38m}$K $t_{1/2} = 1$ sec
laser power changes cloud size

not enough

too much atoms heat up

stop!

1 mm just right

no $\nu$ s = bad $\nu$ s
What elements can be laser-cooled/trapped?

Need quasi-closed E1 transition ($J_e = J_g + 1$, $\pi_e = -\pi_g$)

Here Be Dragons

Trapped in MOT  Radioactives trapped  Long-lived Rad.  Plans
What elements can be laser-cooled/trapped?

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Trapped in MOT ☐ Radioactives trapped ☐ Long-lived Rad. ☐ Plans
Electroweak Interactions: what we “know”

- E&M unified with Weak interactions
  \[ \gamma \leftrightarrow Z^0, W^+, W^- \]

1) Only spin-1 “vector” exchange bosons
2) Only left-handed \( \nu \)'s: “parity is maximally violated” “V-A”

- What we can test:
  1) Are there spin-0 **Scalar** Bosons ?
     \[ I^\pi = 0^+ \rightarrow 0^+ \beta^+ - \nu \sigma \approx 0.5\% \text{ is useful} \]
  2) Right-handed \( \nu \)'s ? “V+A”? 
     Polarized observables with \( \sigma \approx 0.1\% \) needed.
Vector and Scalar bosons and the $\beta$-$\nu$ angular distribution

For $^{38mK}$, $0^+ \rightarrow 0^+$ decay:

$$W[\theta_{\beta\nu}] = 1 + b \frac{m}{E} + a \frac{v_{\beta}}{c} \cos \theta_{\beta\nu}$$

$a = +1$

For scalar exchange, lepton helicities are same: $a = -1$
TRIUMF’s Neutral Atom Trap
- Isotope/Isomer selective
- Evade 1000x untrapped atom background by → 2nd MOT
- 75% transfer (must avoid backgrounds!)
- 0.7 mm cloud for $\beta$-Ar$^+$ → $\nu$ momentum → $\beta$-$\nu$ correlation
- >97% polarized, known atomically
$^{38\text{m}}\text{K}$ $0^+ \rightarrow 0^+$
$\beta-\nu$ correlation

Recoil TOF$[T_\beta]$, C.L. of total fit 52%

Gorelov PRL Apr 2005
$\tilde{a}=0.9981 \pm 0.0030\text{(stat)} \pm 0.0037\text{(syst)}$
Best general constraints on scalars coupling to 1st generation
Upgrade approved: Goal 3x better
$\tilde{a}=a/(1 + bm_\beta/\langle E_\beta \rangle)$

Complementary to $\pi \rightarrow e\nu$ (B. Campbell et al. NPB 709 419 (2005))
(Adelberger $^{32}\text{Ar}$ $\beta$-delayed proton emission PRL 1999
$\tilde{a}=0.9989 \pm 0.0052 \pm 0.0039$ still under re-analysis)
$\cos[\theta_{\beta\nu}]$ From Other Observables

$\chi^2/(N-3) = 0.69$

agrees with other analysis
New: Geometry with $e^-$ detector

For E1070:

- High-statistics
- free of $\beta$ bias
- expect collection for all $e^-$’s < 100 eV

Also with higher statistics:

$^{80}$Rb tensor search by recoil singles: Lots of data Dec 05

$^{37}$K $A_{recoil}$ gives Fermi/GT interference, right-handed currents; $A_\beta$

$^{36}$K isospin mixing becomes practical: $A_{recoil}, A_\beta$

$^{74}$Rb Q-value
keV sterile $\nu$'s \[ |\nu_e\rangle = \cos\theta \, |\nu_{m=0}\rangle + \sin\theta \, |\nu_x\rangle \]

- dark matter, pulsar kicks... Dodelson PRL 1994 Biermann PRL 2006
- Admixture $\sim 10^{-8}$ Abazajian PRD 2005
  ‘like rare K decay’ $\rightarrow$ Need $\sim$zero background

- $10^{-5}$ admixture conceivable at 20 keV (‘do you care?’):

**Electron Capture**

$^{131}\text{Cs} + e^- \rightarrow \nu + ^{131}\text{Xe}$ \hspace{1cm} (or $^{82}\text{Sr}$ or $^7\text{Be}$)

$p' \approx p \left(1 - m_{\nu_x}^2/2Q^2\right) \Rightarrow \delta p/p \sim 0.001$

**Must measure momenta of all shakeoff e$^-$’s to 10% and K X-ray direction**
Gelmini PRL 93 80312 (2004) "low reheating" T<<100 MeV
Projected:
- $^{131}$Cs EC
- $^{82}$Sr EC
- ‘1 week counting’

Boyarsky
astro-ph/512509
plots
$\Omega_s \sin^2 2\theta$
Laser Traps for Beta Decay Experiments

[Refs.: Nobel Prize Lectures: Rev. Mod. Phys. 70 Jul 1998; and J.A.B. NIMB204 526 (2003)]

- MOT provides a localized, backing-free source ideal for $\beta^+$-recoil coincidence studies
- Neutral atom trap technology provides (?) highly polarized nuclei with known polarization