Probing the Quantum Nature of the Neutrino Using Two-Particle Interferometry

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Two contemporary questions in neutrino physics

- Neutrino oscillation experiments have demonstrated that neutrinos have mass:
- What is the absolute mass scale of the neutrino?
- What is the quantum nature of the neutrino? Majorana ($\nu=\bar{\nu}$) or Dirac ($\nu\neq\bar{\nu}$)?

These questions are currently being addressed through a growing industry of neutrinoless double beta decay ($0\nu\beta\beta$) experiments

- Existence of $0\nu\beta\beta$ indicates ν is Majorana

- Lifetime of decay ($\tau > 10^{24}$ years) sets absolute mass scale (< 1 eV)

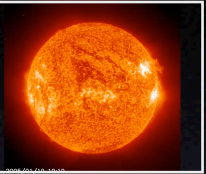
Can two-particle interferometry provide any insights into the problem?

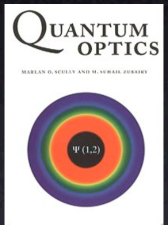
Theoretically, yes.
Experimentally, not now.

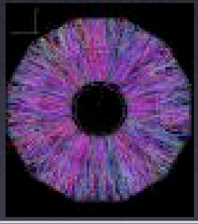
What is two-particle interferometry? A brief history.

- A second order (intensity) interference technique pioneered by Robert Hanbury Brown and Richard Twiss (HBT) in the 1950's
  - Originally used to measure the angular size of stars in radio astronomy
- The quantum formalism of HBT was expanded and applied to photons by Glauber, Mandel, Loudon et al. leading to the birth of modern quantum optics
- In 1960 Goldhaber, Goldhaber, Lee, and Pais (GGLP) independently applied these principles to pions in proton-proton collisions
  - Femtoscopy is used extensively today in high energy heavy ion and particle physics to characterize the space-time distributions of tiny particle sources
- Not just for bosons: Two-particle interferometry has also been observed with fermions such as neutrons, protons, and electrons (in nuclear, high energy, and condensed matter systems)

A Test Of A New Type Of Stellar Interferometer On Sirius
Hanbury Brown
Nature 178 (1956) 1046

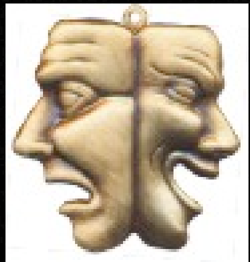






Femtoscopy in Relativistic Heavy Ion Collisions: Two Decades of Progress
Lisa, Pratt, Soltz, Wiedemann
nucl-ex/0505014

Systematic Investigations of Femtoscopic Radii in Heavy Ion Collisions
Ron Soltz APS/JPS DNP Monday the 19th 2005



Introduction to the physics of two-particle interferometry

Correlation Function

<u>Desnity matrix</u>

- source geometry
- source dynamics
- pairwise interactions

$$C_2 \propto \frac{\mathrm{P}(1,2)}{\mathrm{P}(1)\mathrm{P}(2)}$$

<u>operators</u>
quantum statistics

$$\frac{\mathrm{Tr}(\hat{\rho}\hat{a}_k^\dagger \hat{a}_q^\dagger \hat{a}_k \hat{a}_q)}{\mathrm{Tr}(\hat{\rho}\hat{a}_k^\dagger \hat{a}_k)\mathrm{Tr}(\hat{\rho}\hat{a}_q^\dagger \hat{a}_q)} \propto \frac{\frac{d^6\sigma}{dk^3 dq^3}}{\frac{d^3\sigma}{dk^3}\frac{d^3\sigma}{dq^3}}$$

- Incoherently generated pairs of bosons (fermions) clump (anti-clump) while close in phase space
- Insensitive to random source fluctuations
- Can be applied in different spaces: Δt, Δd, Δp, etc.

Koonin-Pratt Equation

two-particle correlation function in variable ζ

normalized source pair distribution in variable x

two-particle wavefunction in variable x and parameter ζ

$$C_2(\zeta) = \int \rho(x)\left|\psi_{12}(x,\zeta)\right|^2 dx$$

I. Anatomy of neutrino correlation function: identical, massless case

m=0

One favor

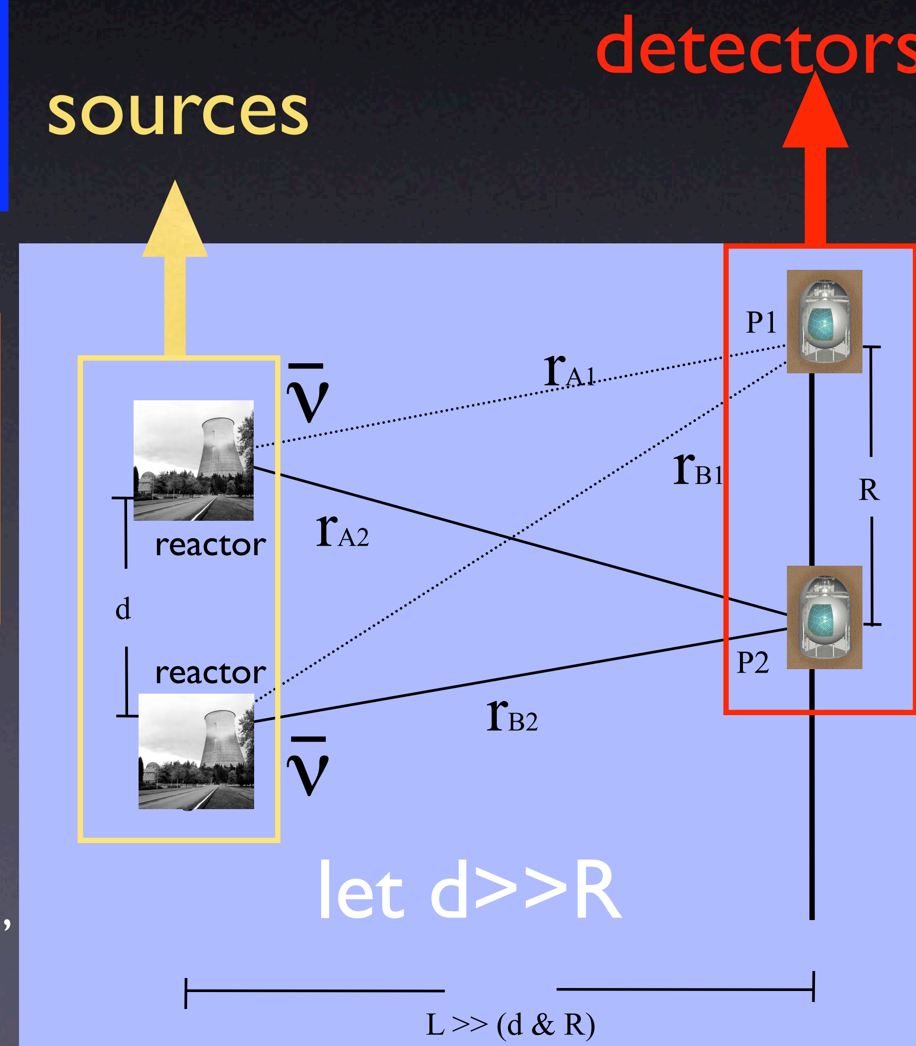
The two particle wave function is antisymmetric

$$C_2^{\nu_D \nu_D}(R) = C_2^{\bar{\nu}_D \bar{\nu}_D}(R) = C_2^{\nu_M \nu_M}(R) =$$
$$1 - \cos(R\theta/\lambda)$$

This is essentially the neutrino version of "classic" HBT

Two incoherent sources of indistinguishable neutrinos

Are they:
2 Dirac (anti)neutrinos
or
2 Majorana neutrinos of identical handedness



If you didn't know the quantum statistics a priori:

1. Fix neutrino energy
2. Fix known angular source geometry
3. Correlate signals at a pair of detectors
4. Vary R (could just use the fiducial volume of a single detector)
5. Look for anticorrelation at small values of R (for fermions)

Can't yet distinguish between Dirac and Majorana objects.
Consistent with Boris Kaiser's "Practical Dirac-Majorana Confusion Theorem"

II. Anatomy of neutrino correlation function: non-identical, massless case

m=0

One favor

Two incoherent sources of distinguishable neutrinos

Dirac neutrino and a Dirac anti-neutrino
<u>or</u>
2 Majorana neutrinos of <u>opposite</u> handedness

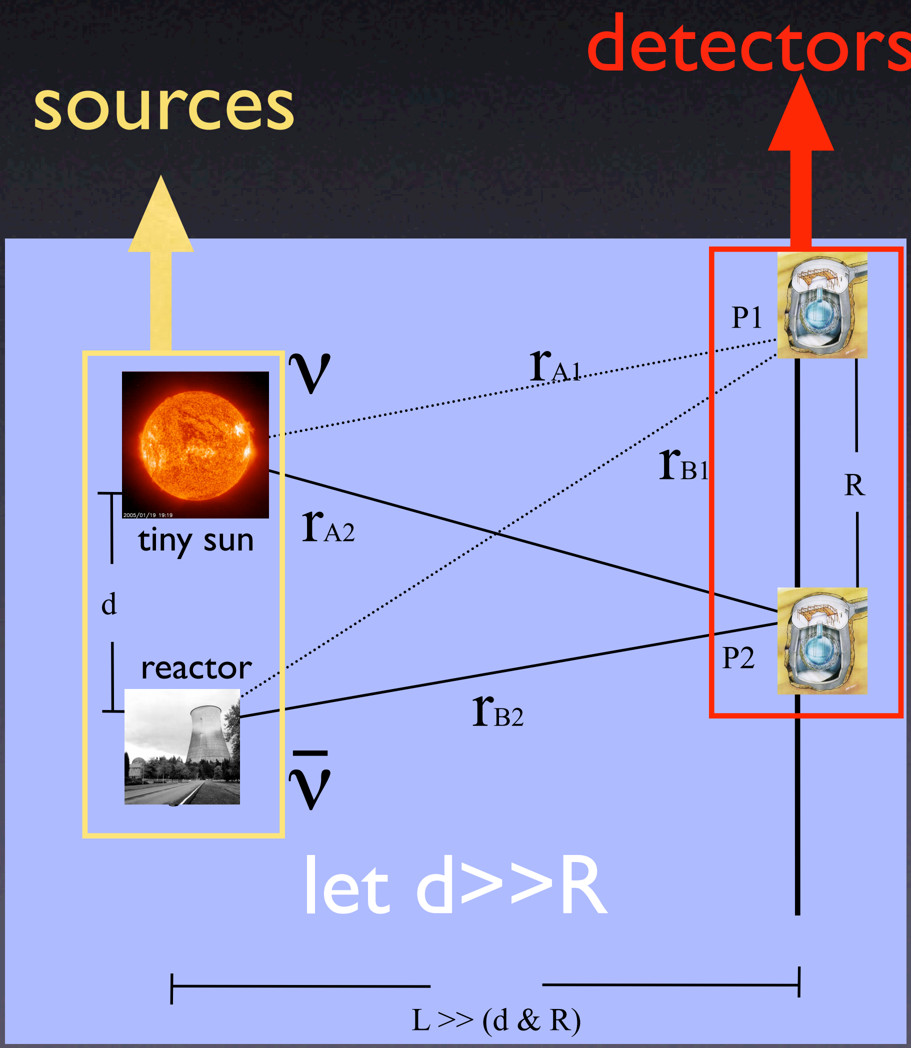
$$C_2^{\nu_D \bar{\nu}_D}(R) = C_2^{\nu_M^L \nu_M^R}(R) = 1$$

The two-particle correlation function is <u>constant</u> for incoherent sources of non-identical objects

Why? The wavefunction <u>factorizes</u> and the particles are not entangled

Although we often colloquially say the Majorana neutrino "is it's own antiparticle," the weak source currents will still create them with a handedness as if they were Dirac particles

Majorana neutrinos of opposite handedness are quantum mechanically distinguishable



III. Anatomy of neutrino correlation function: non-identical, massive case

m≠0

One favor

Two incoherent sources of objects usually called neutrinos and antineutrinos. Are they...

a Dirac neutrino and a Dirac antineutrino

2 Majorana neutrinos of unknown handedness

Chirality and helicity are not the same anymore

Source currents of fixed chirality (e.g. left) can now emit and absorb neutrinos of the “wrong” helicity

This occurs with amplitude ~ (m/E) for m<<E

If Dirac

mostly $\Lambda=-1$ neutrinos, some $\Lambda=+1$ neutrinos

If Majorana

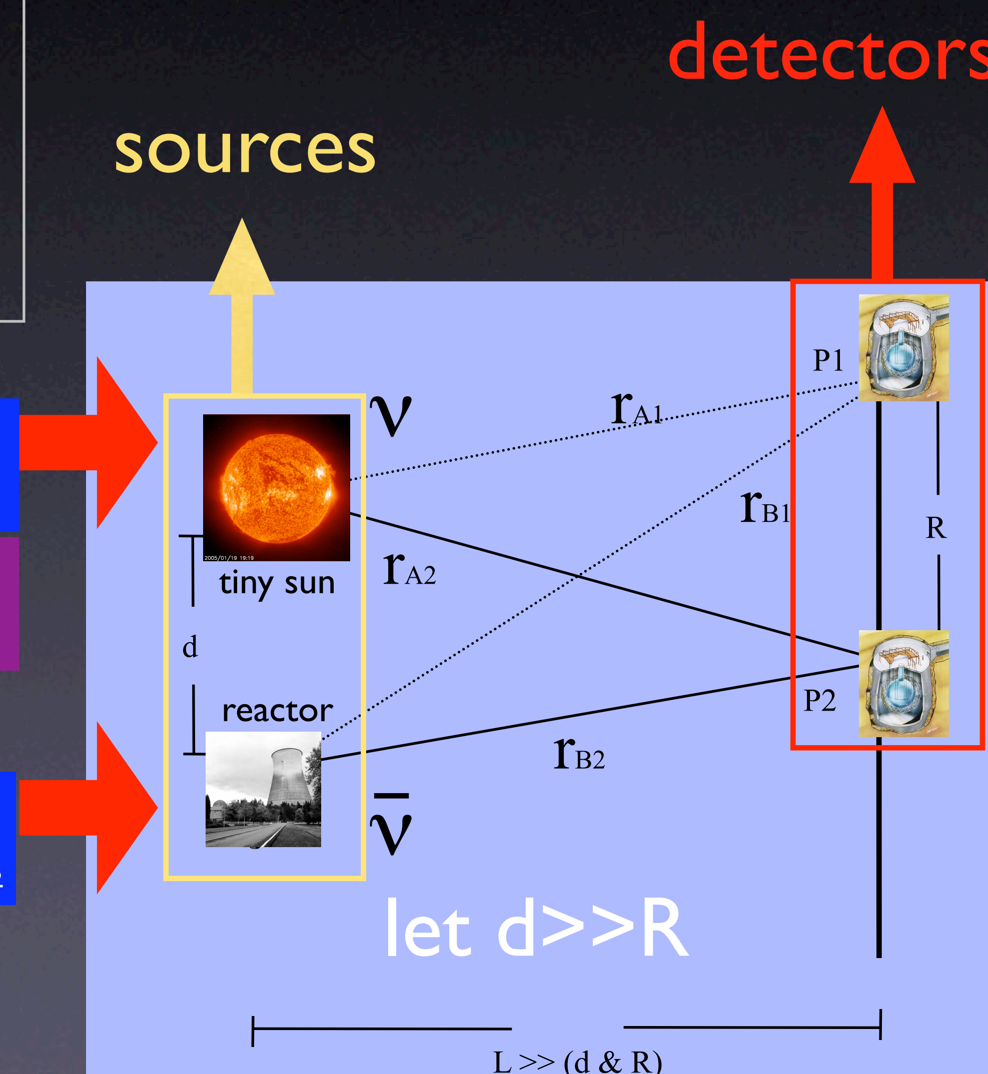
mostly $\Lambda=-1$ neutrinos, some $\Lambda=+1$ neutrinos

If Dirac

mostly $\Lambda=+1$ anti-neutrinos, some $\Lambda=-1$ anti-neutrinos

If Majorana

mostly $\Lambda=+1$ neutrinos, some $\Lambda=-1$ neutrinos



Closer look at the non-identical source, massive neutrino case

Dirac

$$C_2^{\nu_D^a \bar{\nu}_D^b}(R) =< C_2^{\nu_D \bar{\nu}_D}(R) >_\Lambda = 1$$

Dirac particles have an extra quantum number (lepton number) that always makes them distinguishable under these conditions (massive particles, non-identical sources)

Majorana

$$C_2^{\nu_M^a \nu_M^b}(R)\big|_{a\neq b} = 1 \longrightarrow$$

Filter on different helicities (a,b) kills C_2

$$C_2^{\nu_M^a \nu_M^a}(R) = 1 - \cos(R\theta/\lambda) \longrightarrow$$

Filter on identical helicities (a,a) maxes C_2

$$< C_2^{\nu_M \nu_M}(R) >_\Lambda = 1 - \xi \cos(R\theta/\lambda) \longrightarrow$$

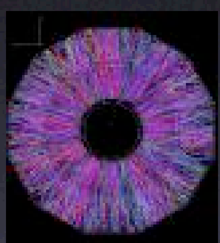
Helicity averaging has the effect of introducing contamination such that $\xi \sim \vartheta(m^2/E^2)$

Distinguishes Majorana and Dirac

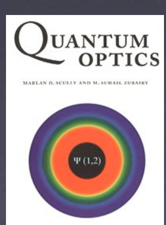
Can extract a mass scale

Current Experimental Limitations

- Energy resolution vs. coherence time $\Delta E \Delta t \sim \text{eV} \cdot \text{fs}$
  - For counting rates of modern experiments (1-3000 counts/day), an essentially infinite energy resolution is required to permit neutrinos arriving so far-separated in time to be correlated quantum mechanically
  - Technically achievable energy resolutions (1eV to 1keV) still demand femto-to-attosecond neutrino measurement detection capability or something approaching macroscopic currents of neutrinos



- <u>Momentum space</u>: For neutrino femtoscopy (e.g. in high energy particle physics) one must be able to measure neutrinos at roughly the same degree of efficiency as pions in pp collisions circa 1960 or later
  - ≥ 2 inclusive identified ν's per event, 10k-100M events, ~MeV ν energy-momentum resolution for 1 fm to 6 fm systems



- <u>Time domain</u>: Quantum anti-bunching measurement of neutrinos in a beam also requires extraordinary detection rates/efficiencies or energy resolution

Alas, its currently in the realm of science fiction...

Conclusions

- As a gedanken experiment, two-particle interferometry can extract both the neutrino's quantum nature and mass scale with a single observable C_2
- Practical considerations make the approach prohibitive with current technology
- As discussed elsewhere, $0\nu\beta\beta$ isn't the "only way" but is still the most effective way to extract both the mass and neutrino nature (if that nature happens to be Majorana...)
- Nevertheless, a fun exercise to combine my physics interests and backgrounds

Many thanks to my colleagues in heavy ion and neutrino physics, especially those in the INPA and RNC groups at LBL, for helpful and inspiring discussions