The GSI Time Anomaly: Facts and Fiction

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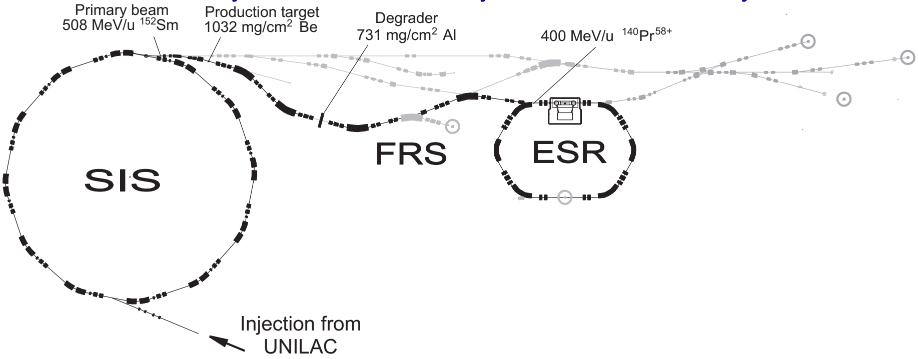
Padova, 5 June 2008

Outline

- The GSI Anomaly
- Neutrino Mixing?
- Interference: Double-Slit Analogy
- Causality
- arXiv:0801.1465 and arXiv:0805.0435
- arXiv:0801.2121 – arXiv:0801.3262
- Quantum Beats?
- Conclusions

The GSI Experiment

Schematic layout of the secondary nuclear beam facility at GSI



{Litvinov et al, nucl-ex/0509019}

SIS: Heavy Ion Synchrotron

FRS: FRagment Separator

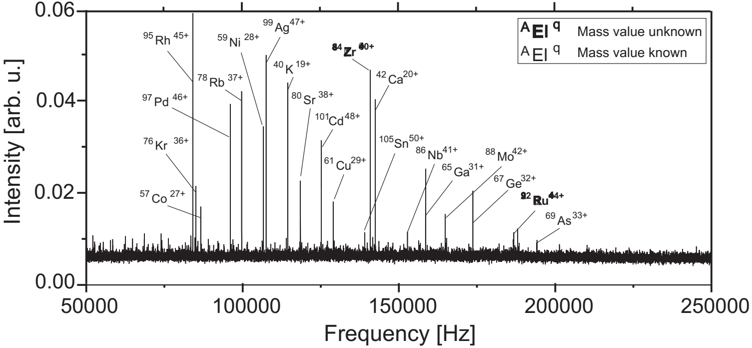
ESR: Experiment Storage Ring

Schottky Mass Spectrometry

- Stored ions circulate in ESR with revolution frequencies $\sim$ 2 MHz
- At each turn they induce mirror charges on two electrodes
- Revolution frequency spectra provide information about q/m:

$$\mathrm{f} = \frac{\omega}{2\pi} = \frac{qB}{2\pi m \gamma}$$

- Area of each frequency peak is proportional to number of stored ions



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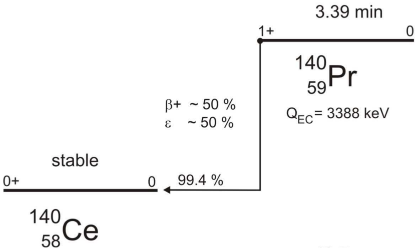
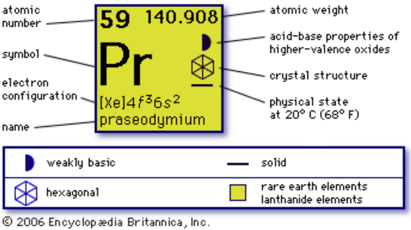


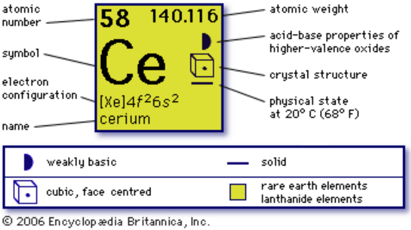
{Litvinov et al, arXiv:0801.2079v1 [nucl-ex]}

Praseodymium

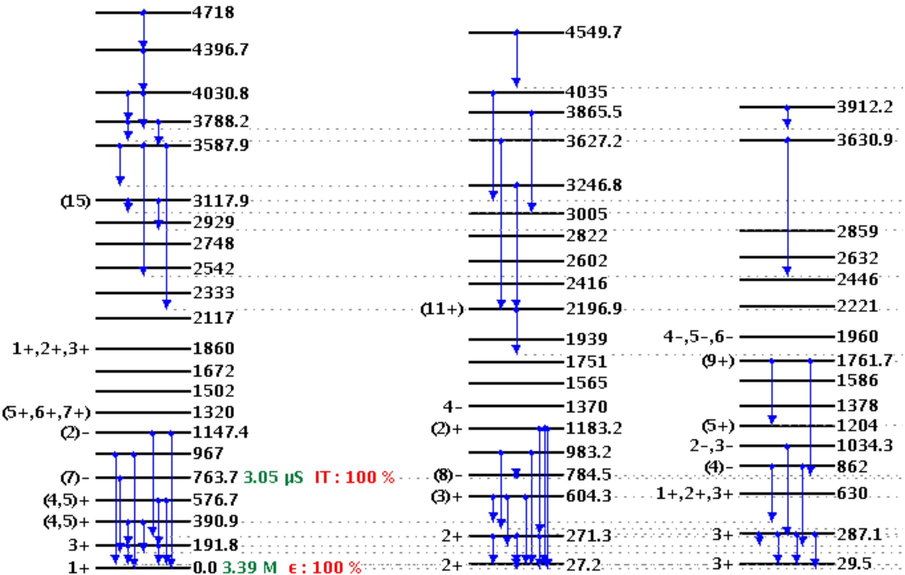


$$ {}^{140}_{59}\mathrm{Pr}^{58+} \to {}^{140}_{58}\mathrm{Ce}^{58+} + \nu_e $$

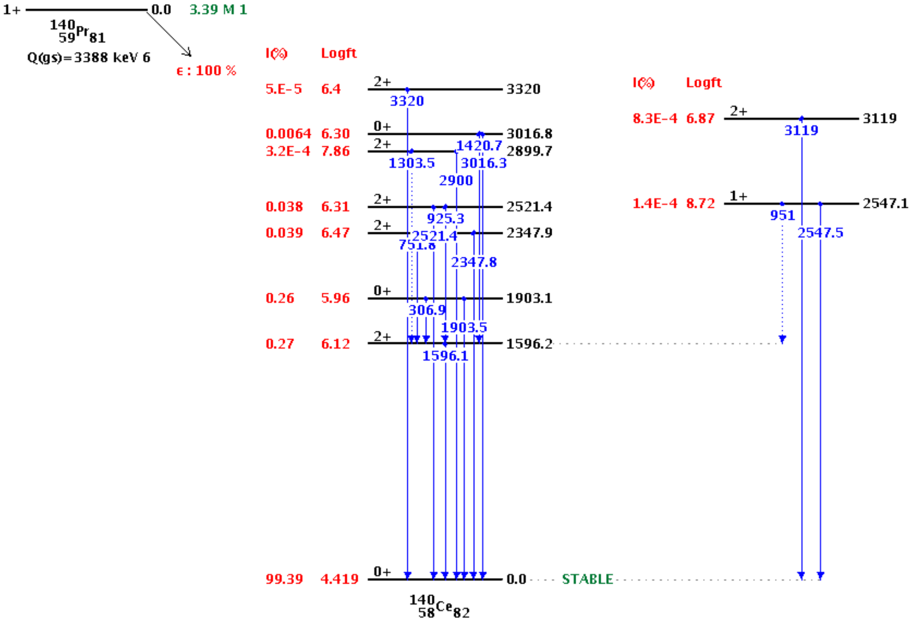
Cerium



Praseodymium ($^{140}_{59}\mathrm{Pr}_{81}$)



{NuDat, http://www.nndc.bnl.gov/nudat/}



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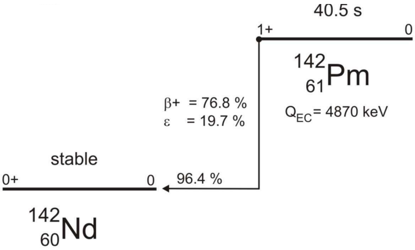

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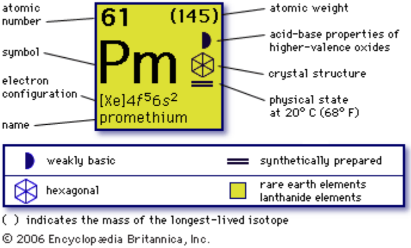
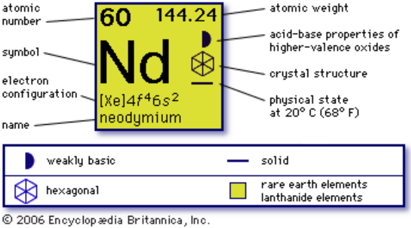
Promethium

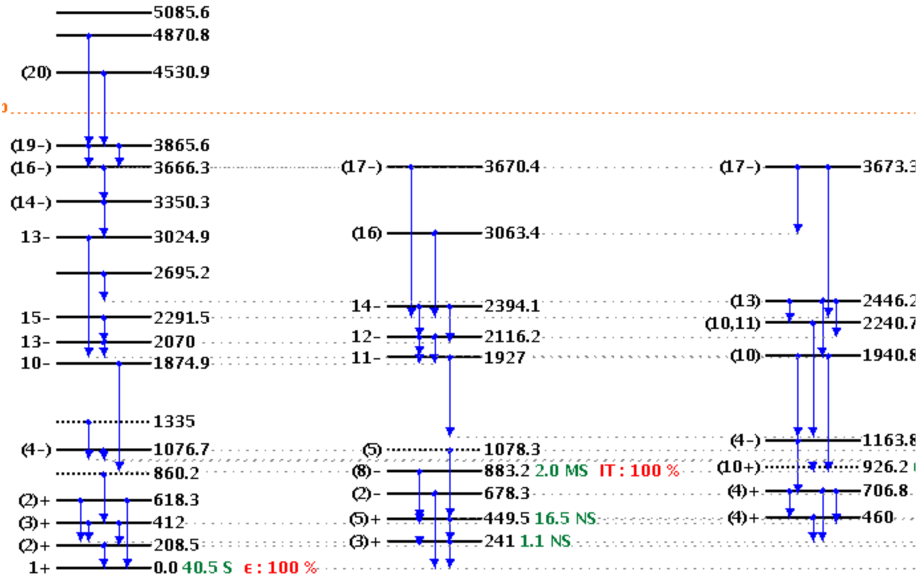


$$^{142}_{61}\mathrm{Pm}^{60+} \to {}^{142}_{60}\,\mathrm{Nd}^{60+} + \nu_e$$

Neodymium



Promethium ($^{142}_{61}Pm_{81}$)



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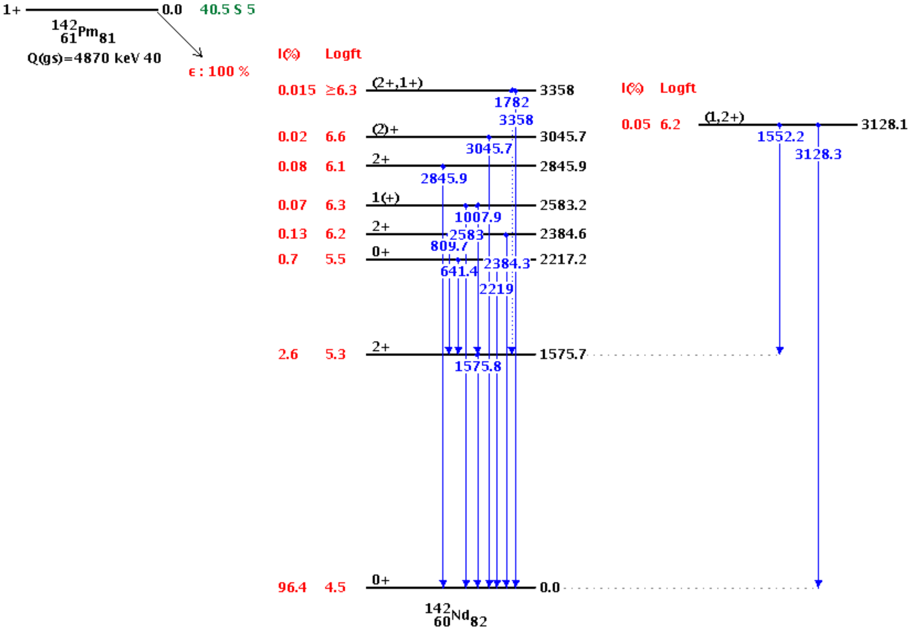

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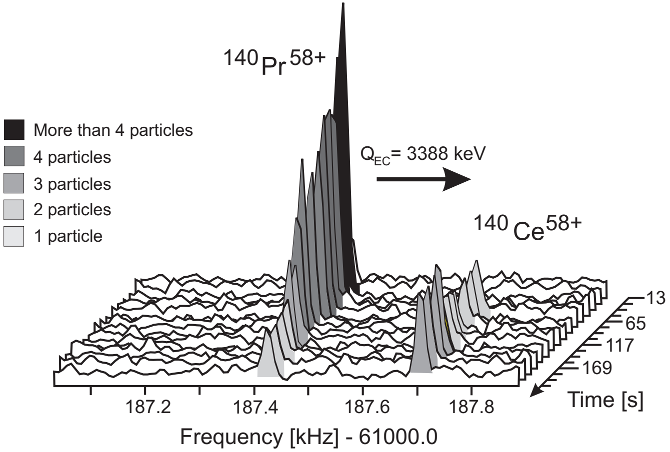
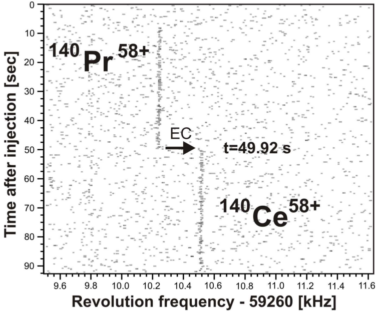
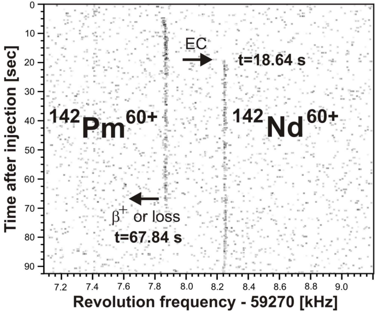


- About six initial $^{140}_{59}\mathrm{Pr}^{58+}$ ions ($\mathrm{f} = qB/2\pi m\gamma$)
- Two decayed via nuclear electron capture into $^{140}_{58}\mathrm{Ce}^{58+}$
- Seen because $\Delta q = 0 \Rightarrow \Delta\mathrm{f}/\mathrm{f} = -\Delta m/m$ (small)
- Other decayed via β^+ decay ($\Delta q = -1 \Rightarrow \Delta\mathrm{f} \sim -150\,\mathrm{kHz}$) or were lost (interactions with residual gas)



$$ {}^{140}_{59}\mathrm{Pr}^{58+} \to {}^{140}_{58}\mathrm{Ce}^{58+} + \nu_e $$



$$ {}^{142}_{61}\mathrm{Pm}^{60+} \to {}^{142}_{60}\mathrm{Nd}^{60+} + \nu_e $$

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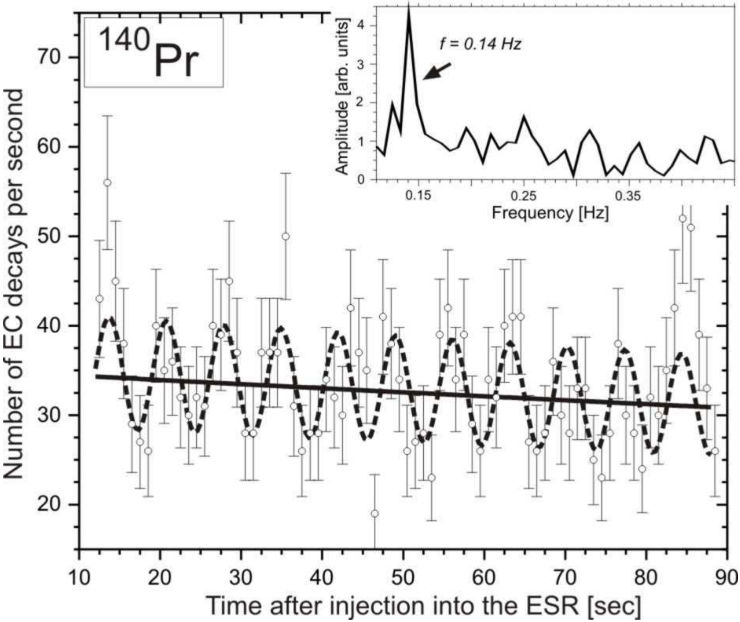

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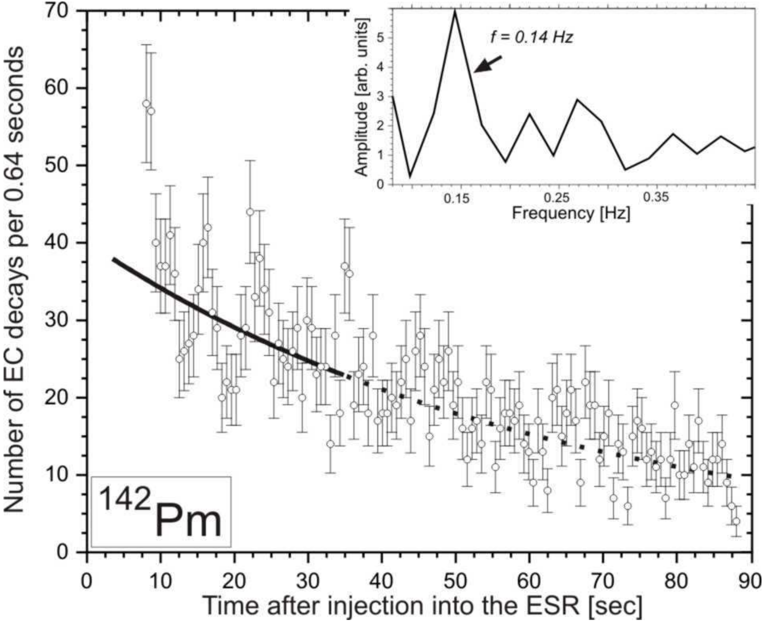

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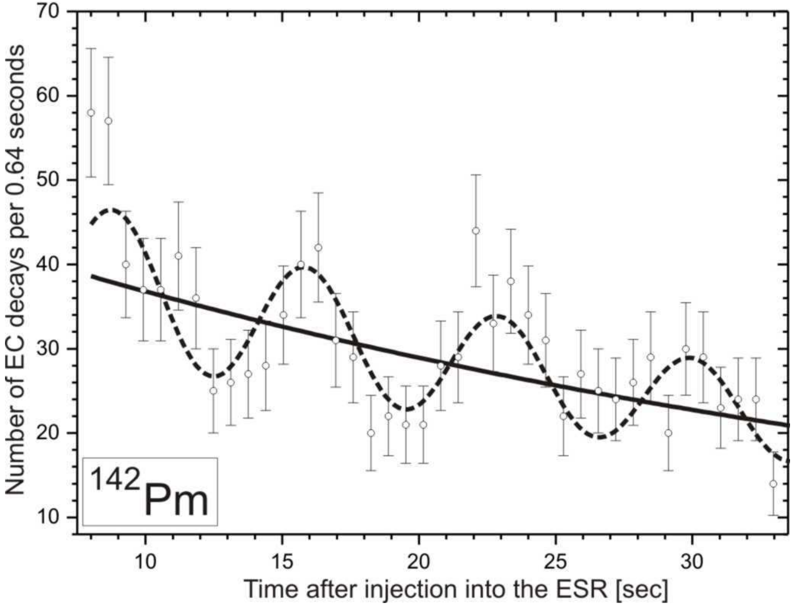


{Litvinov et al, arXiv:0801.2079v1 [nucl-ex]}

$$(1) \qquad \frac{dN_{EC}(t)}{dt} = \lambda_{EC}\, N(t) = \lambda_{EC}\, N(0)\, e^{-\lambda t}$$

$$(2) \qquad \frac{dN_{EC}(t)}{dt} = \tilde{\lambda}_{EC}(t)\, N(t) = \tilde{\lambda}_{EC}(t)\, N(0)\, e^{-\lambda t}$$

$$\lambda = \lambda_{EC} + \lambda_{\beta^+} + \lambda_{loss} \qquad \tilde{\lambda}_{EC}(t) = \lambda_{EC}\,[1 + a\cos(\omega t + \phi)]$$

Fit parameters of $^{140}_{59}$Pr data					
Eq.	$N_0\lambda_{EC}$	λ	a	ω	χ^2/DoF
(1)	34.9(18)	0.00138(10)	-	-	107.2/73
(2)	35.4(18)	0.00147(10)	0.18(3)	0.89(1)	67.18/70
Fit parameters of $^{142}_{61}$Pm data					
Eq.	$N_0\lambda_{EC}$	λ	a	ω	χ^2/DoF
(1)	46.8(40)	0.0240(42)	-	-	63.77/38
(2)	46.0(39)	0.0224(41)	0.23(4)	0.89(3)	31.82/35

$$T(^{140}_{59}\mathrm{Pr}^{58+}) = 7.06 \pm 0.08\,\mathrm{s} \qquad T(^{142}_{61}\mathrm{Pm}^{60+}) = 7.10 \pm 0.22\,\mathrm{s}$$

$$\langle a \rangle = 0.20 \pm 0.02$$

{Litvinov et al, arXiv:0801.2079v1 [nucl-ex]}

Neutrino Mixing?

{Litvinov et al, arXiv:0801.2079v1 [nucl-ex]}

$I_i \to I_f + \nu_e$ $\qquad$ $|\nu_e\rangle = \cos\vartheta|\nu_1\rangle + \sin\vartheta|\nu_2\rangle$

Initial Ion: Momentum $\vec{P} = 0$, Energy E

Massive ν_k: Momentum $\vec{p}_k$, Energy $E_k = \sqrt{p_k^2 + m_k^2}$

Final Ion: Momentum $-\vec{p}_k$, Energy $M + p_k^2/2M$

$E_1 + M + p_1^2/2M = E$ $\qquad$ $E_2 + M + p_2^2/2M = E$

$$\Delta E \equiv E_2 - E_1 \simeq \frac{\Delta m^2}{2M} \qquad \Delta m^2 \equiv m_2^2 - m_1^2$$

$$\Delta E \equiv E_2 - E_1 \simeq \frac{\Delta m^2}{2M}$$

$$\Delta m^2 = \Delta m^2_{\odot} \simeq 8 \times 10^{-5}\,\mathrm{eV}^2 \qquad M \simeq 140\,\mathrm{amu} \simeq 130\,\mathrm{GeV}$$

$$\Delta E \simeq 3.1 \times 10^{-16}\,\mathrm{eV}$$

$$T = \frac{2\pi}{\Delta E}\,\gamma \simeq 19.1\,\mathrm{s} \qquad \gamma = 1.43$$

about 3 times larger than $T_{\mathrm{GSI}} \simeq 7\,\mathrm{s}$

ΔE is the massive neutrino energy difference!

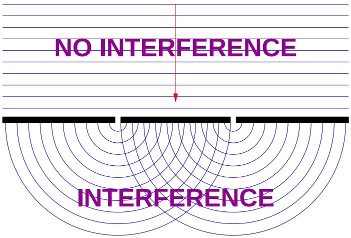
Can the GSI Time Anomaly

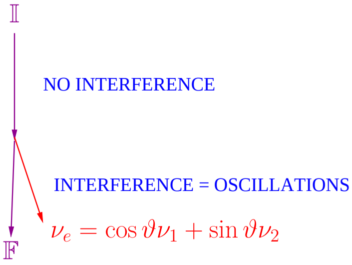
be due to

Neutrino Mixing?

NO

Interference: Double-Slit Analogy





- Decay rate of $\mathbb{I}$ corresponds to fraction of intensity of incoming wave which crosses the barrier
- Fraction of intensity of the incoming wave which crosses the barrier depends on the sizes of the holes
- It does not depend on interference effects which occur after the wave has passed through the barrier
- Analogy: decay rate of $\mathbb{I}$ cannot depend on interference of ν_1 and ν_2 which occurs after decay has happened

Causality

INTERFERENCE OF ν_1 AND ν_2

OCCURRING AFTER THE DECAY

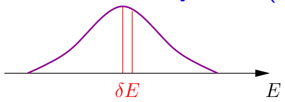
CANNOT AFFECT THE DECAY RATE

arXiv:0801.1465 and arXiv:0805.0435

H.J. Lipkin

- Causality is violated explicitly
- arXiv:0801.1465: The difference in momentum δp_ν between the two neutrino eigenstates with the same energy produces a small initial momentum change δP ...
- arXiv:0805.0435: Since the time dependence depends only on the propagation of the initial state, it is independent of the final state, which is created only at the decay point. Thus there is no violation of causality.
- But in calculation of effect: The phase difference at a time t between states produced by the neutrino mass difference on the motion of the initial ion in the laboratory frame with velocity $V = (P/E)$ is

$$\delta\phi \approx -\delta E \cdot t = \Delta m^2/2E$$



arXiv:0801.2121 – arXiv:0801.3262

A. N. Ivanov, R. Reda, P. Kienle – M. Faber

- $\mathbb{I} \to \mathbb{F} + \nu$ decay rate in time-dependent perturbation theory

  with final neutrino state $|\nu\rangle = \sum_k |\nu_k\rangle$

- Not even properly normalized to describe one particle:

$$\langle \nu_j | \nu_k \rangle = \delta_{jk} \quad \Longrightarrow \quad \langle \nu | \nu \rangle = 3$$

- Different from standard electron neutrino state

$$|\nu_e\rangle = \sum_k U_{ek}^* |\nu_k\rangle$$

Time-Dependent Perturbation Theory

$$P_{\mathbb{I}\to\mathbb{F}+\nu}(t) = \left| \int_0^t \mathrm{d}\tau \, \langle \nu, \mathbb{F} | \mathcal{H}_W(\tau) | \mathbb{I} \rangle \right|^2 = \left| \sum_k \int_0^t \mathrm{d}\tau \, \langle \nu_k, \mathbb{F} | \mathcal{H}_W(\tau) | \mathbb{I} \rangle \right|^2$$

$$\mathcal{H}_W(t) = \int \mathrm{d}^3x \, \mathscr{H}_W(x)$$

Effective Four-Fermion Interaction Hamiltonian

$$\begin{aligned}
\mathscr{H}_W(x) &= \frac{G_F}{\sqrt{2}} \cos\theta_C \bar{\nu}_e(x) \gamma_\rho (1-\gamma^5) e(x) \bar{n}(x) \gamma^\rho (1 - g_A \gamma^5) p(x) \\
&= \frac{G_F}{\sqrt{2}} \cos\theta_C \sum_k U_{ek}^* \bar{\nu}_k(x) \gamma_\rho (1-\gamma^5) e(x) \bar{n}(x) \gamma^\rho (1 - g_A \gamma^5) p(x)
\end{aligned}$$

$$\langle \nu_k, \mathbb{F} | \mathcal{H}_W(\tau) | \mathbb{I} \rangle = U_{ek}^* \, e^{i\Delta E_k t} \, T_k \qquad \text{with} \qquad \Delta E_k = E_k + E_{\mathbb{F}} - E_{\mathbb{I}}$$

$$\int_0^t \mathrm{d}\tau \, e^{i\Delta E_k t} = e^{i\Delta E_k t/2} \, \frac{\sin(\Delta E_k t/2)}{\Delta E_k/2} \xrightarrow[\Delta E_k t \gg 1]{} 2\pi \, \delta(\Delta E_k) \, e^{i\Delta E_k t/2}$$

$$P_{\mathbb{I}\to\mathbb{F}+\nu}(t) = 4\pi^2 \left| \sum_k U_{ek}^* \, e^{i\Delta E_k t} \, \delta(\Delta E_k) \; T_k \right|^2$$

$T_k \simeq T_j$ $\delta(\Delta E_k)$ satisfied by wave packet

$$P_{\mathbb{I}\to\mathbb{F}+\nu}(t) \propto \left| \sum_k U_{ek}^* \, e^{i\Delta E_k t} \right|^2$$

Two-Neutrino Mixing

$$P_{\mathbb{I}\to\mathbb{F}+\nu}(t) \propto \left| \cos\vartheta \, e^{i\Delta E_1 t} + \sin\vartheta \, e^{i\Delta E_2 t} \right|^2 = 1 + \sin 2\vartheta \, \cos\left(\frac{\Delta E t}{2}\right)$$

$$= 1 + \sin 2\vartheta \, \cos\left(\frac{\Delta m^2 t}{4M}\right)$$

$$\Delta E = \Delta E_2 - \Delta E_1 = E_2 - E_1 = \frac{\Delta m^2}{2M}$$

- Standard QFT: $P_{\mathbb{I}\to\mathbb{F}+\nu} = |\langle\nu,\mathbb{F}|\mathsf{S}|\mathbb{I}\rangle|^2 = \left|\sum_k \langle\nu_k,\mathbb{F}|\mathsf{S}|\mathbb{I}\rangle\right|^2$
- S-matrix operator at first order in perturbation theory:

$$\mathsf{S} = 1 - i\int \mathrm{d}^4x\, \mathscr{H}_W(x)$$

- Effective four-fermion interaction Hamiltonian:

$$\begin{aligned}\mathscr{H}_W(x) &= \frac{G_F}{\sqrt{2}}\cos\theta_C\,\bar{\nu}_e(x)\gamma_\rho(1-\gamma^5)e(x)\bar{n}(x)\gamma^\rho(1-g_A\gamma^5)p(x)\\ &= \frac{G_F}{\sqrt{2}}\cos\theta_C\sum_k U_{ek}^*\bar{\nu}_k(x)\gamma_\rho(1-\gamma^5)e(x)\bar{n}(x)\gamma^\rho(1-g_A\gamma^5)p(x)\end{aligned}$$

- $\langle\nu_k,\mathbb{F}|\mathsf{S}|\mathbb{I}\rangle = U_{ek}^*\mathcal{M}_k$ with

$$\mathcal{M}_k = -i\frac{G_F}{\sqrt{2}}\cos\theta_C\int \mathrm{d}^4x\langle\nu_k,\mathbb{F}|\bar{\nu}_k(x)\gamma_\rho(1-\gamma^5)e(x)\bar{n}(x)\gamma^\rho(1-g_A\gamma^5)p(x)|\mathbb{I}\rangle$$

- $P_{\mathbb{I}\to\mathbb{F}+\nu} = \left|\sum_k U_{ek}^*\mathcal{M}_k\right|^2$ different from standard $P = \sum_k |U_{ek}|^2\,|\mathcal{M}_k|^2$

- Check: in the limit of massless neutrinos decay probability should reduce to the Standard Model decay probability

$$P_{\text{SM}} = |\mathcal{M}_{\text{SM}}|^2$$

with

$$\mathcal{M}_{\text{SM}} = -i\frac{G_F}{\sqrt{2}}\cos\theta_{\text{C}}\int \mathrm{d}^4x \langle \nu_e, \mathbb{F}|\bar{\nu}_e(x)\gamma_\rho(1-\gamma^5)e(x)\bar{n}(x)\gamma^\rho(1-g_A\gamma^5)p(x)|\mathbb{I}\rangle$$

where ν_e is the Standard Model massless electron neutrino

$$\mathcal{M}_k = -i\frac{G_F}{\sqrt{2}}\cos\theta_{\text{C}}\int \mathrm{d}^4x \langle \nu_k, \mathbb{F}|\bar{\nu}_k(x)\gamma_\rho(1-\gamma^5)e(x)\bar{n}(x)\gamma^\rho(1-g_A\gamma^5)p(x)|\mathbb{I}\rangle$$

$$\mathcal{M}_k \xrightarrow[m_k \to 0]{} \mathcal{M}_{\text{SM}}$$

$$P_{\mathbb{I}\to\mathbb{F}+\nu} = \left|\sum_k U_{ek}^* \mathcal{M}_k\right|^2 \xrightarrow[m_k \to 0]{} |\mathcal{M}_{\text{SM}}|^2 \left|\sum_k U_{ek}^*\right|^2 \neq P_{\text{SM}}$$

WRONG!

- Correct normalized final neutrino state ($\langle\nu_e|\nu_e\rangle = 1$):

$$|\nu_e\rangle = \left(\sum_j |\langle\nu_j, \mathbb{F}|\mathsf{S}|\mathbb{I}\rangle|^2\right)^{-1/2} \sum_k |\nu_k\rangle \langle\nu_k, \mathbb{F}|\mathsf{S}|\mathbb{I}\rangle$$

$$= \left(\sum_j |U_{ej}|^2 |\mathcal{M}_j|^2\right)^{-1/2} \sum_k U_{ek}^* \mathcal{M}_k |\nu_k\rangle$$

- Standard decay probability:

$$P_{\mathbb{I}\to\mathbb{F}+\nu_e} = |\langle\nu_e, \mathbb{F}|\mathsf{S}|\mathbb{I}\rangle|^2 = \sum_k |\langle\nu_k, \mathbb{F}|\mathsf{S}|\mathbb{I}\rangle|^2 = \sum_k |U_{ek}|^2 |\mathcal{M}_k|^2$$

$$P_{\mathbb{I}\to\mathbb{F}+\nu_e} \xrightarrow[m_k\to 0]{} P_{\mathsf{SM}}$$

- In experiments which are not sensitive to the differences of the neutrino masses, as neutrino oscillation experiments,

$$\mathcal{M}_k \simeq \overline{\mathcal{M}} \quad \Longrightarrow \quad |\nu_e\rangle = \sum_k U_{ek}^* |\nu_k\rangle$$

Time-Dependent Perturbation Theory

$$A_k(t) = \int_0^t \mathrm{d}\tau \langle \nu_k, \mathbb{F} | \mathcal{H}_W(\tau) | \mathbb{I} \rangle$$

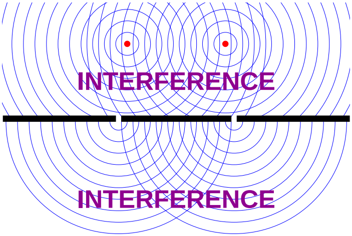
$$|\nu_e(t)\rangle = \left(\sum_j |A_j(t)|^2 \right)^{-1/2} \sum_k A_k(t) \, |\nu_k\rangle$$

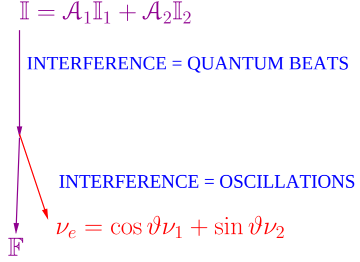
$$P_{\mathbb{I}\to\mathbb{F}+\nu_e} = \left| \left(\sum_j |A_j(t)|^2 \right)^{-1/2} \sum_k A_k^*(t) \int_0^t \mathrm{d}\tau \langle I_f, \nu_k | H_\mathrm{W}(\tau) | I_i \rangle \right|^2$$

$$\boxed{P_{\mathbb{I}\to\mathbb{F}+\nu_e} = \sum_k |A_k(t)|^2}$$

Quantum Beats?

- GSI time anomaly can be due to interference effects in initial state
- Two coherent energy states of the decaying ion $\Longrightarrow$ Quantum Beats





- Incoming waves interfere at holes in barrier
- Causality: interference due to different phases of incoming waves developed during propagation before reaching the barrier

- Quantum beats in GSI experiment can be due to interference of two coherent energy states of the decaying ion which develop different phases before the decay

- Coherence is preserved for a long time if measuring apparatus which monitors the ions with frequency ~ 2 MHz does not distinguish between the two states

- $|\mathbb{I}(t=0)\rangle = \mathcal{A}_1 \, |\mathbb{I}_1\rangle + \mathcal{A}_2 \, |\mathbb{I}_2\rangle \qquad\qquad (|\mathcal{A}_1|^2 + |\mathcal{A}_2|^2 = 1)$

$$\Gamma = \Gamma_1 \simeq \Gamma_2 \quad \Longrightarrow \quad |\mathbb{I}(t)\rangle = \left(\mathcal{A}_1 \, e^{-iE_1 t} \, |\mathbb{I}_1\rangle + \mathcal{A}_2 \, e^{-iE_2 t} \, |\mathbb{I}_2\rangle \right) e^{-\Gamma t/2}$$

$$P_{\mathrm{EC}}(t) = |\langle \nu_e, \mathbb{F} | \mathsf{S} | \mathbb{I}(t) \rangle|^2 = [1 + A \cos(\Delta E t + \varphi)] \, \overline{P}_{\mathrm{EC}} \, e^{-\Gamma t}$$

$$A \equiv 2|\mathcal{A}_1||\mathcal{A}_2| \, , \quad \Delta E \equiv E_2 - E_1 \, , \quad \overline{P}_{\mathrm{EC}} = |\langle \nu_e, \mathbb{F} | \mathsf{S} | \mathbb{I}_1 \rangle|^2 \simeq |\langle \nu_e, \mathbb{F} | \mathsf{S} | \mathbb{I}_2 \rangle|^2$$

$$\frac{\mathrm{d} N_{\mathrm{EC}}(t)}{\mathrm{d} t} = N(0) \, [1 + A \cos(\Delta E t + \varphi)] \, \overline{\Gamma}_{\mathrm{EC}} \, e^{-\Gamma t}$$

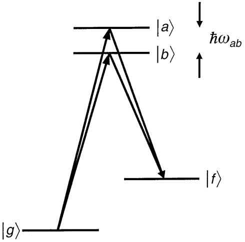


Fig. 1 Diagram of the four level system. A photon is absorbed by the ground state $|b\rangle$ and excites a superposition of states $|a\rangle$ and $|b\rangle$ whose energy separation is $\Delta E = \hbar\omega_{ab}$. Emission of a second photon leaves the system in the final state $|f\rangle$.

$$I_{\mathrm{fl}}(t) \propto |\mu_{ag}|^2|\mu_{fa}|^2 \mathrm{e}^{-\gamma_a t} + |\mu_{bg}|^2|\mu_{fb}|^2 \mathrm{e}^{-\gamma_b t} + |\mu_{ag}\mu_{bg}\mu_{fa}\mu_{fb}| \mathrm{e}^{-(\gamma_a+\gamma_b)t/2} \cos(\omega_{ab}t + \theta). \quad (4)$$

Examination of this expression shows that it consists of two parts, one incoherent term (first two terms) describing the independent decays of the two states $|a\rangle$ and $|b\rangle$ and one coherent or cross term (last term) which decays at the average rate of the two states and, most importantly, is modulated at the angular frequency ω_{ab}. The modulation frequency is the difference of the two angular frequencies in eqn. (2), *i.e.* $\omega_{ab} = |\omega_a - \omega_b|$, and the coherent term in eqn. (4) is therefore termed the quantum beat. The angle θ is included in eqn. (4) to describe the phase of the quantum beat, which depends on a number of factors such as the excitation and detection polarisations and transitions. When the transition moments and decay rates are equal, as is often the case, a particularly simple expression is derived for the four level system. In this case eqn. (4) becomes

$$I_{\mathrm{fl}}(t) \propto [1 + \cos(\omega_{ab}t + \theta)]\mathrm{e}^{-\gamma t}, \quad (5)$$

clearly illustrating the contributions of the incoherent and coherent terms to the fluorescence decay. In this special case the quantum beat is 100% modulated. It is important to point out

{Carter, Huber, Quantum beat spectroscopy in chemistry, Chem. Soc. Rev., 29 (2000) 305}

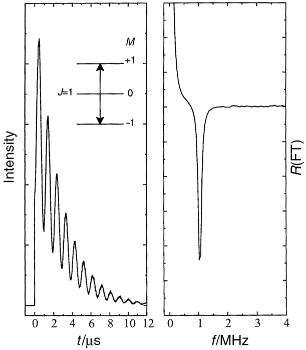


Fig. 2 Zeeman quantum beat recorded for the $R(0)$ line of the 17U transition in CS_2 in an external field of ~15 Gauss. The laser polarisation was perpendicular to the magnetic field direction and prepares a coherence between the $M = \pm 1$ sublevels as shown in the level diagram. This is manifested by a single quantum beat on the fluorescence decay; the real part of the Fourier transform is also shown. The less than 100% modulation, which is observed in virtually all quantum beat measurements in molecules, is due to incoherent emission from the excited states.

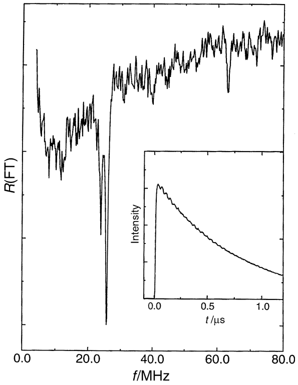


Fig. 6 Nuclear hyperfine quantum beats recorded for the $P_{21}/Q_1(3/2)$ line in a vibrational band of the $A^2\Sigma^+ - X^2\Pi$ transition in the Ar·OD van der Waals complex. The inset shows the fluorescence decay which exhibits weakly modulated quantum beats. Following Fourier transformation the beat frequencies between hyperfine levels in the $A^2\Sigma^+$ state are clearly visible.

{Carter, Huber, Quantum beat spectroscopy in chemistry, Chem. Soc. Rev., 29 (2000) 305}

$$\frac{\mathrm{d}N_{\mathrm{EC}}(t)}{\mathrm{d}t} = N(0)\,[1 + A\,\cos(\Delta E t + \varphi)]\,\overline{\Gamma}_{\mathrm{EC}}\,e^{-\Gamma t}$$

$$\Delta E({}^{140}_{59}\mathrm{Pr}^{58+}) = (5.86 \pm 0.07) \times 10^{-16}\,\mathrm{eV}\,, \qquad A({}^{140}_{59}\mathrm{Pr}^{58+}) = 0.18 \pm 0.03$$

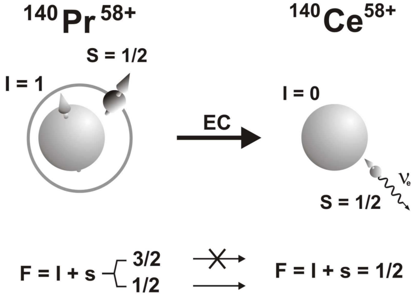
$$\Delta E({}^{142}_{61}\mathrm{Pm}^{60+}) = (5.82 \pm 0.18) \times 10^{-16}\,\mathrm{eV}\,, \qquad A({}^{142}_{61}\mathrm{Pm}^{60+}) = 0.23 \pm 0.04$$

$$A \equiv 2|\mathcal{A}_1||\mathcal{A}_2|$$

- Energy splitting is extremely small
- $|\mathcal{A}_1|^2/|\mathcal{A}_2|^2 \sim 1/99$ or $|\mathcal{A}_2|^2/|\mathcal{A}_1|^2 \sim 1/99$
- It is difficult to find an appropriate mechanism

Hyperfine Splitting

smallest known energy splitting



{Litvinov et al, PRL 99 (2007) 262501, arXiv:0711.3709}

$\Delta E \sim 10^{-6}\,\text{eV} \quad \Longrightarrow \quad T \sim 10^{-9}\,\text{s} \quad \text{f} \sim \text{GHz}$

too large to explain the GSI anomaly

$T_{\text{GSI}} \simeq 7\,\text{s} \qquad \text{f}_{\text{GSI}} \simeq 0.14\text{Hz} \qquad \Delta E_{\text{GSI}} = 2\pi/T_{\text{GSI}} \simeq 6 \times 10^{-16}\,\text{eV}$

Conclusions

- Interference: due to phase difference of two incoming waves
- Causality: there cannot be interference of waves before they exist
- The GSI ion lifetime anomaly cannot be due to interference of decay product before the decay product start to exist (neutrino mixing in the final state)
- The GSI ion lifetime anomaly can be due to interference of two energy states of the decaying ion: Quantum Beats
- No known mechanism, because
  - Energy splitting of the two energy states: $\Delta E \sim 6 \times 10^{-16}\,\mathrm{eV}$
  - Ratio of probabilities of the two energy states: $1/99$