Possible Tests of the Unruh effect*

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N. Rad and D. Singleton, Eur. Phys. J. D66** (2012) 258; arXiv:1110.1099*

Outline

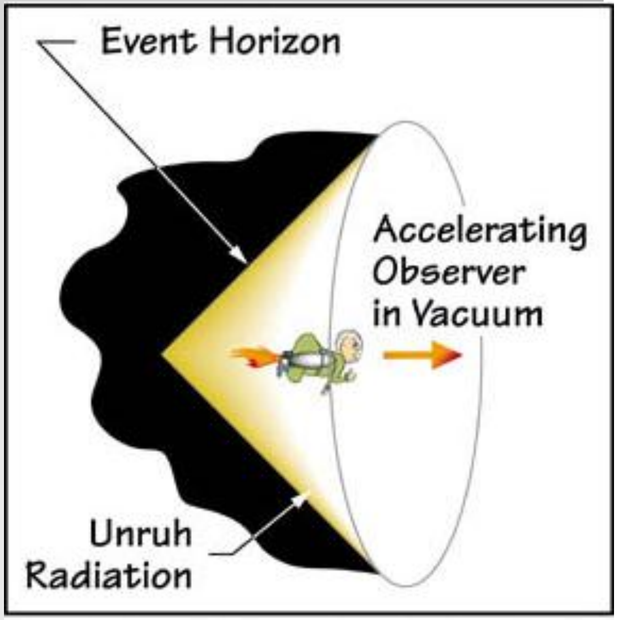
- Unruh radiation
- Unruh-Dewitt detector
- Experimental tests of Unruh effect
- Summary/conclusions

Unruh radiation

- An observer accelerating (with *a)* through empty space-time will register an thermal bath at temperature, T (W. Unruh, *PRD* ***16****, 870 (1976)*).

$$k_B T_U = \frac{\hbar a}{2\pi c}$$

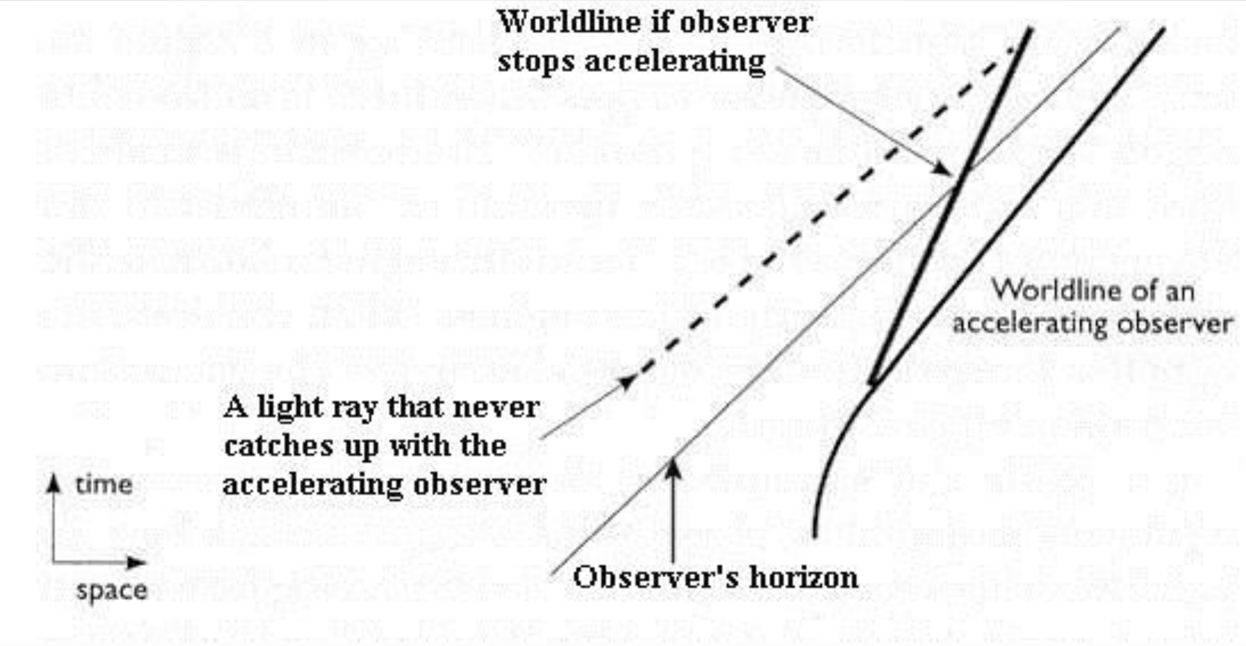
- This is a QFT effect. It is generally small. T~1 K for a~10^{20} m/s^2



An accelerating observer in vacuum would see a similar Hawking-like radiation called Unruh radiation.

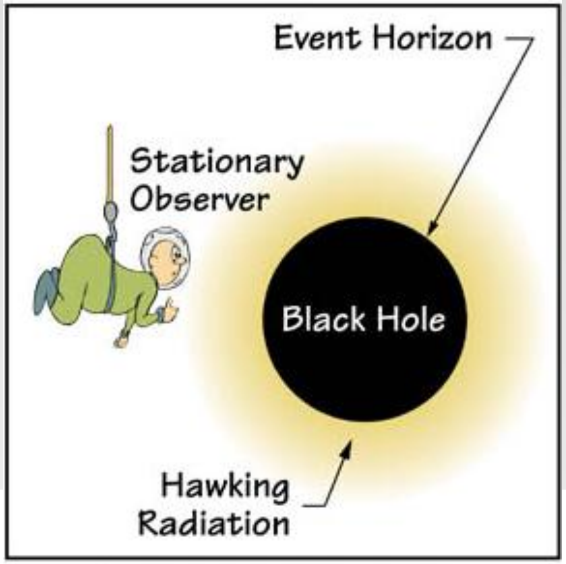
Unruh radiation

- The origin of Unruh radiation can be traced to the existence of a horizon in Rindler space-time.
- The horizon is a barrier and one can think of the radiation as "quantum tunneling" through the barrier.



Unruh radiation

- Via the equivalence principle Unruh radiation is connected with Hawking radiation from black holes $k_B T_H = \frac{\hbar c^3}{8\pi G M}$.
- There is also a horizon in this case and the effect is again small for large black holes T~10^{-8} K for M=solar mass



A stationary observer outside the black hole would see the thermal Hawking radiation.

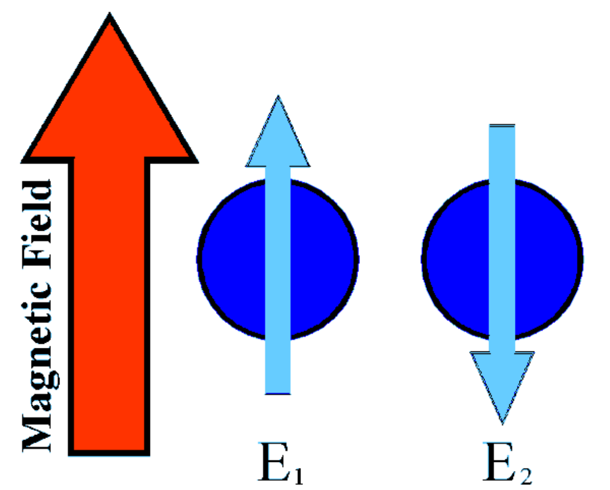
Unruh-DeWitt detector

- A two–level detector for measuring “temperature” of vacuum
- Wightman function G[x(t-τ/2), x(t+τ/2)], a space-time path x(t) and a scalar field φ(x).

$$G[x(t-\tau/2),x(t+\tau/2)]=\left\langle 0\middle|\phi[x(t-\tau/2)]\phi[x(t+\tau/2)]\middle|0\right\rangle$$

- Excitations (-) de-excitation (+) of response function of the detector.

$$w_{\pm}\propto\int_{-\infty}^{\infty}d\tau e^{\mp i\Delta E\tau}G[x(t-\tau/2),x(t+\tau/2)]$$



Unruh-DeWitt detector

- For linear acceleration one measures a thermal heat bath (linear Unruh effect)

$$w_- \propto \left[\frac{\Delta E}{e^{2\pi \Delta E / a} - 1} \right] \rightarrow k_B T_U = \frac{\hbar a}{2\pi c}$$

- For a detector outside a black hole

$$w_- \propto \left[\frac{\Delta E}{e^{\Delta E / k_B T_H} - 1} \right] \rightarrow k_B T_H = \frac{\hbar c^3}{8\pi GM\sqrt{1 - 2GM/rc^2}}$$

A test for the Unruh effect

- For linear acceleration it is hard to achieve $a \sim 10^{20}$ m/s^2 or larger.
- For circular acceleration this is possible (e.g. storage rings at LEP have $a \sim 10^{23}$ m/s^2 so T~1000 K).
- One must redo the above calculation for circular motion

$$w_- \propto a e^{-\sqrt{12}\frac{\Delta E}{a}} \quad \rightarrow \quad k_B T_c \approx \frac{\hbar a}{2\sqrt{3}\pi}$$

Spectrum for circular Unruh effect*

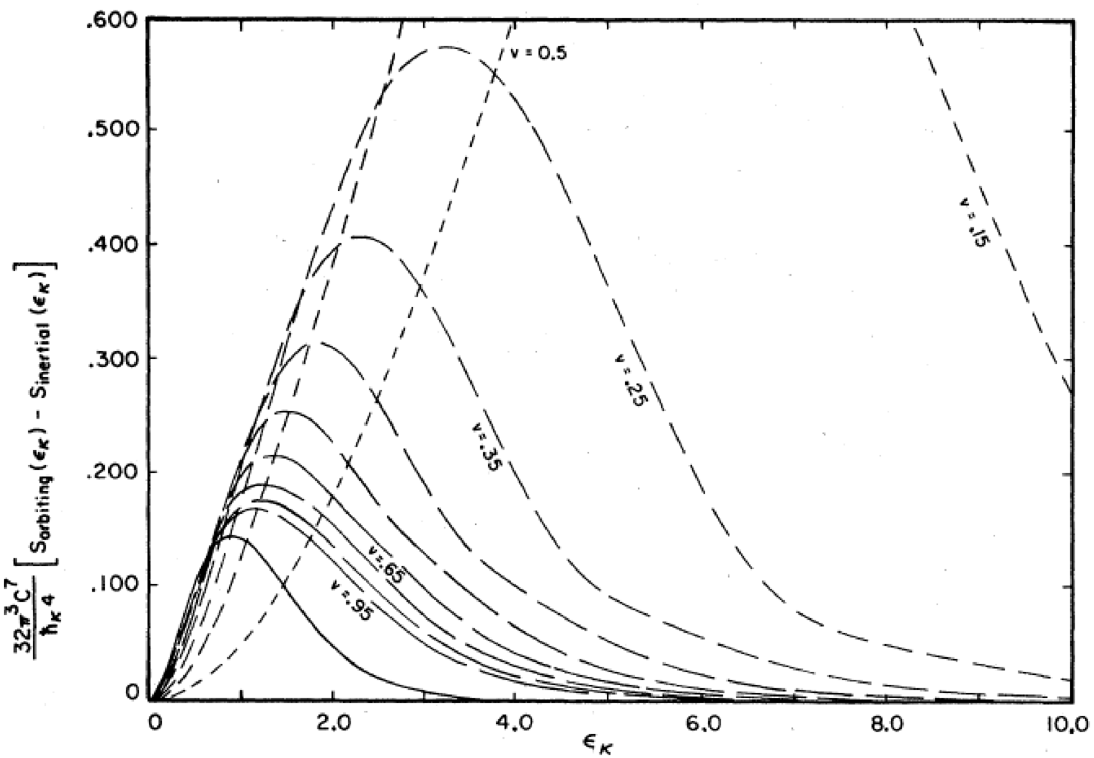


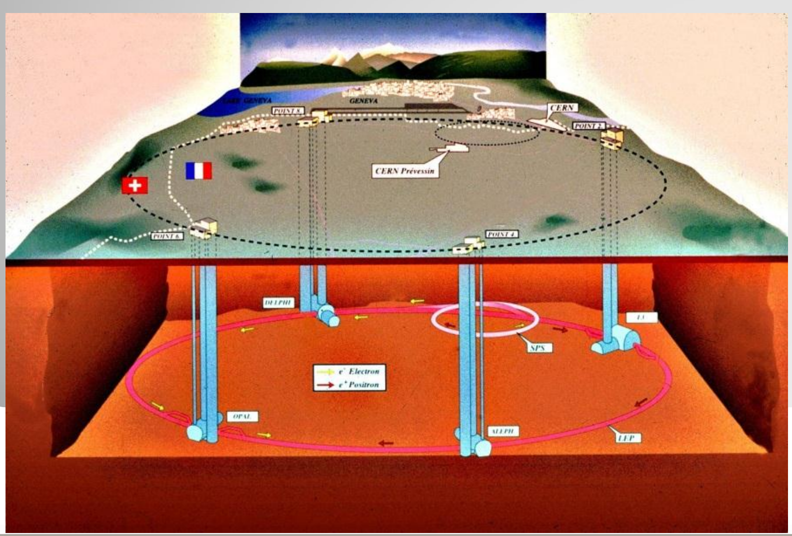
FIG. 2. Vacuum fluctuation spectra at constant acceleration. The solid line represents a uniformly accelerated observer. The dashed lines represent orbiting observers with velocities ranging from $0.05c$ to $0.95c$ in steps of $0.1c$.

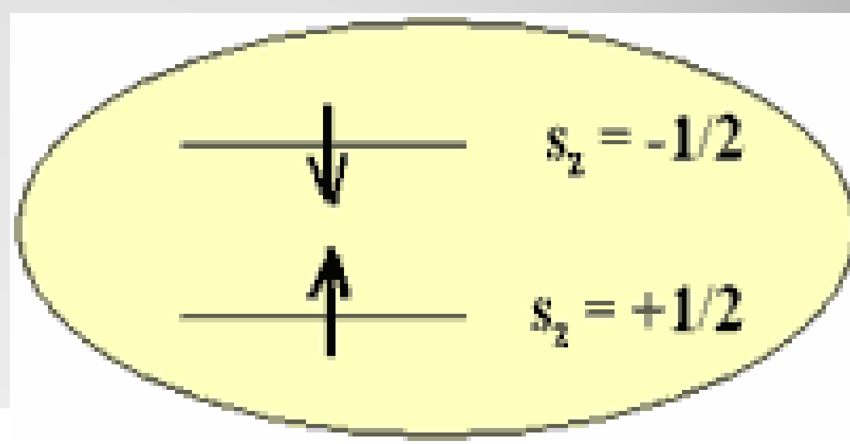
* J. Letaw and J. Pfautsch. *PRD 22, 1345 (1981)*

A test for the Unruh effect

- Bell and Leinaas (*NPB* ***212****, 131 (1983))* proposed that this would lead to a measurable de-polarization of electrons in storage rings like LEP.

- This 8% de-polarization is seen (Sokolov and Ternov, *Sov.-Phys. Dokl.,* ***8*** *1203 (1964))*





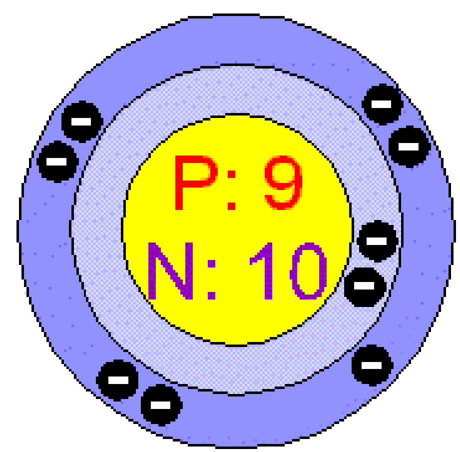
Another test for the Unruh effect: atomic electrons

- Some atoms (fluorine, oxygen) have electrons with centripetal accelerations of this order

- Centripetal potential, force and acceleration

$$V_C(r) = \frac{l(l+1)\hbar^2}{2mr^2} \qquad a_c(r) = \frac{F_c}{m} = \frac{-\nabla V_c}{m} = \frac{l(l+1)\hbar^2}{m^2 r^3}$$

- Fluorine → radius $=0.4\text{x}10^{-10}$ m; acceleration $a_c=4.2\text{x}10^{23}$ m/s^2 ; estimated temperature $T \sim a/2\pi = 1700$ K



Acceleration and Unruh temperature

TABLE I: Radius, centripetal acceleration and Unruh temperature of the outer shell electrons

Atom	radius [a]	centripetal acceleration	Unruh temperature
Oxygen	$0.45 \times 10^{-10}\ m$	$2.94 \times 10^{23}\ m/s^2$	1200 K
Fluorine	$0.40 \times 10^{-10}\ m$	$4.19 \times 10^{23}\ m/s^2$	1700 K

[a] The radius is defined by the peak of the calculated charge density of the outer orbital [22]

Energy levels

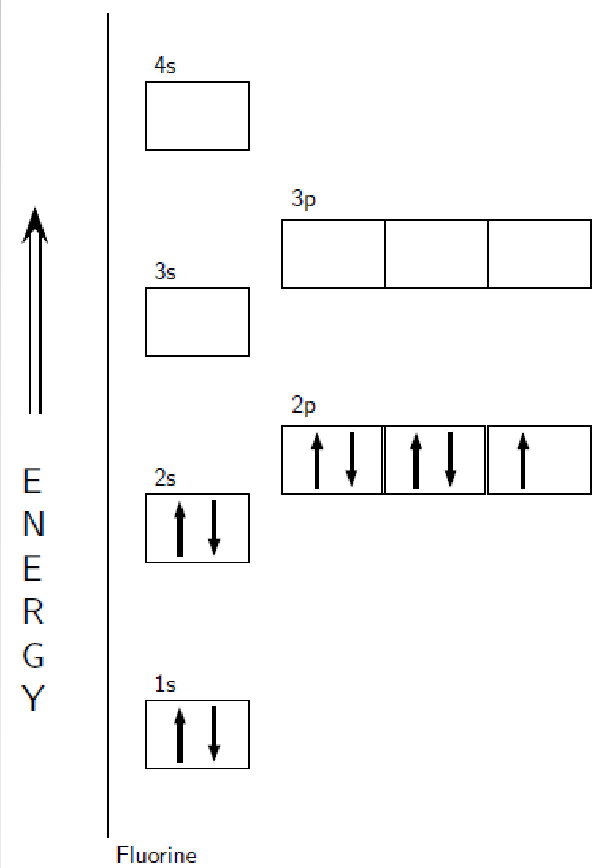
TABLE II: Energy of the low lying, excited energy levels above the lowest level, equivalent temperatures, and spectroscopic notation.

Atom	spec. notation	$\Delta E_{i1} = E_i - E_1$ [a]	$T = \Delta E_{i1}/k_B$
Oxygen	$^3P_1$; $^3P_0$	0.02 eV ; 0.03 eV	232 K ; 348 K
Fluorine	$^2P_{1/2}$	0.05 eV	580 K

Low lying energy levels

- Fluorine has a low lying excited state ΔE_{01}=0.05eV

Ground state: $^2P_{3/2}$
1st excited state: $^2P_{1/2}$



- A temperature of 1700 K ~0.14 eV should populate this level to a significant degree. Via density matrix

$$f(E_1, T) \approx \frac{1}{\exp\left(\frac{\Delta E_{01}}{k_b T}\right) + 1}$$

f(T=1700 K)~0.42 (Unruh temperature)
f(T=100 K)~0.003 (low temperature)

- Prediction: Look at the population of E_1 of fluorine at low temperature. A larger than expected population indicates Unruh effect

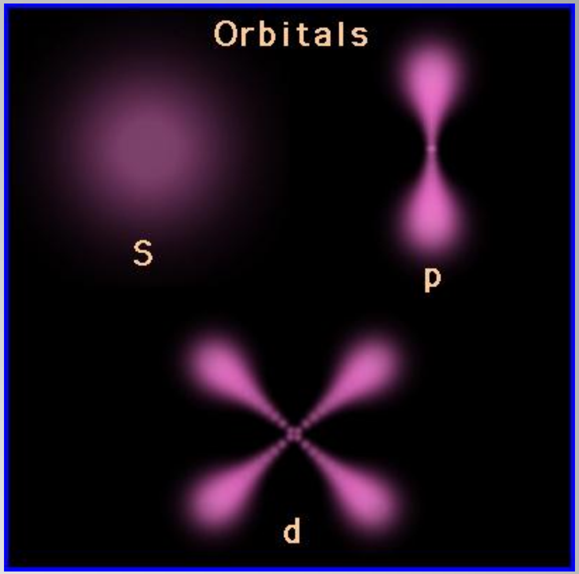
Population of low lying levels

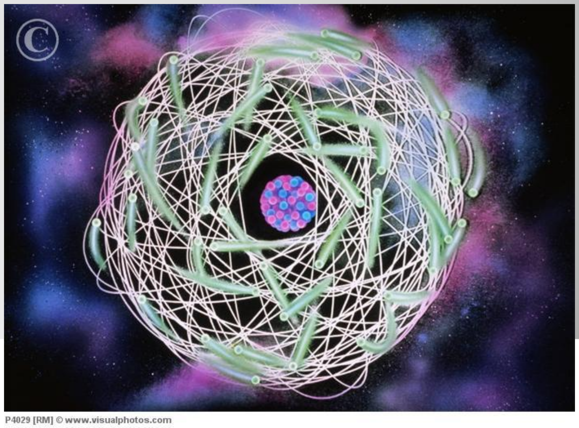
TABLE III: The fraction of electrons populating the low lying excited levels from table II assuming these levels are populated by thermal excitations of a background temperature versus the effective Unruh temperature

Atom	configuration	$f(T = 100K)$	$f(T = 300K)$	$f(T_{Unruh})$
Oxygen	$^3P_1$; $^3P_0$	0.07 ; 0.03	0.22 ; 0.21	0.30 ; 0.31
Fluorine	$^2P_{1/2}$	0.003	0.13	0.42

Path Integral motivation for temperature

- **Orbital approach** – electrons (with *l≠0*) can have a large centripetal acceleration but they do not follow a "path"
- **Path integral approach** – electrons **do** follow every possible path weighted by exp[i*Action]
- The hydrogen atom was solved in the path integral approach in (Ho and Inomata, *PRL,* 48, 231 (1982))
- Observing this effect might provide a way to distinguish the path integral vs. the standard approach to QM.





Classical vs. quantum acceleration

- Electrons in collider storage rings (e.g. LEP) experience a *classical centripetal acceleration* and effective temperature → unexpected population of upper level.

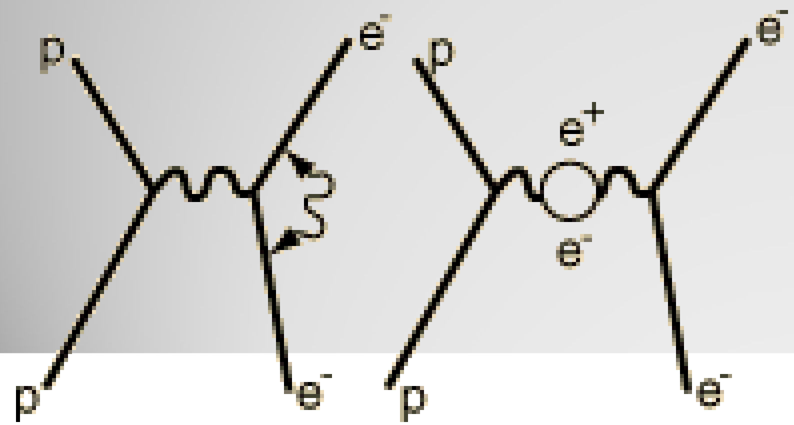
- Electrons in fluorine/oxygen experience a *quantum centripetal acceleration* and (maybe) an effective temperature → (maybe) unexpected population of upper level.

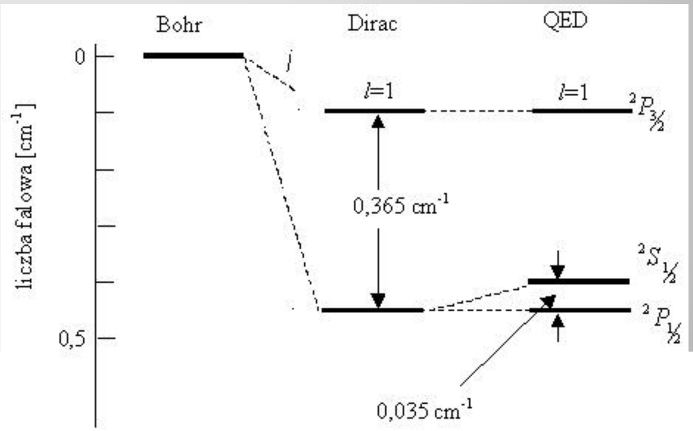
An external quantum field theory effect

- This is not related to old arguments about classical radiation and instability of the Rutherford atom → for Hydrogen in the ground state *l=0.* Also electrons do not emit radiation.

- Related to Lamb Shift –a shift of electron energy due to electron's interaction with its *own quantized* E&M field.

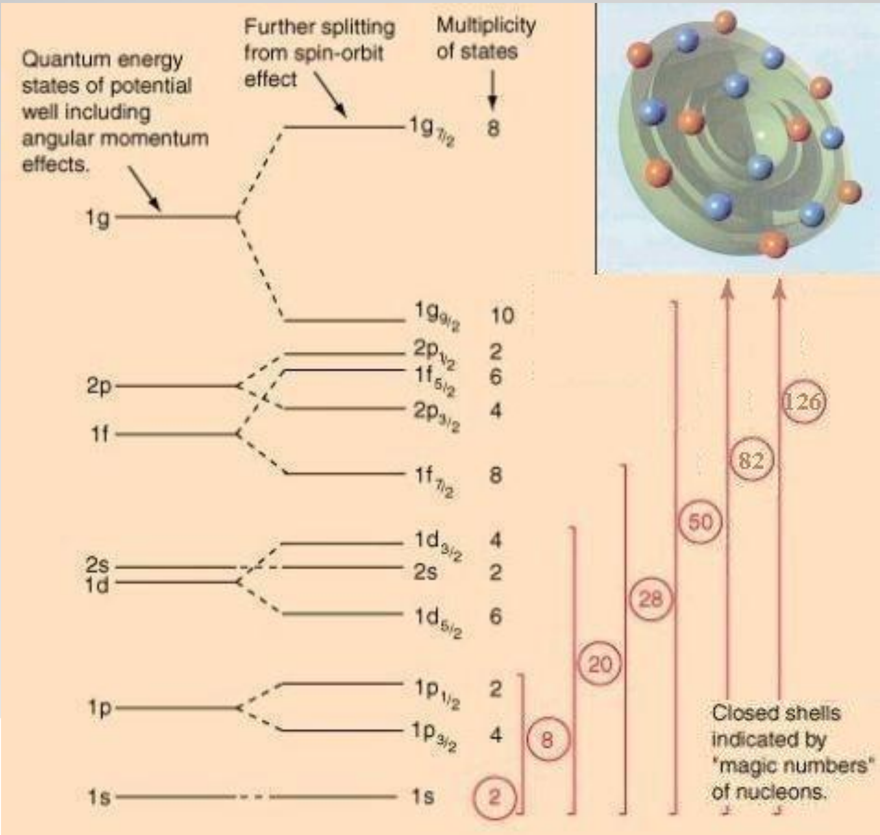
- Possible shift in population of energy levels due to the electron's interaction with the *external vacuum quantized* E&M field.





Circular Unruh effect for nuclei

- Nuclei can be described by the **Nuclear Shell Model**
- The above process might work for nuclei



Circular Unruh effect for nuclei

- For nuclei r is smaller (~10^{-15} m). Good. Mass of nucleon is 2000 X that of the electron. Bad. Energy levels splitting are larger. Bad.

- Nuclear acceleration $a = \frac{l(l+1)\hbar^2}{(m_p)^2 r^3} \approx 8 \times 10^{30} m/s^2$

  assuming *l=1* and r~10^{-15} m.

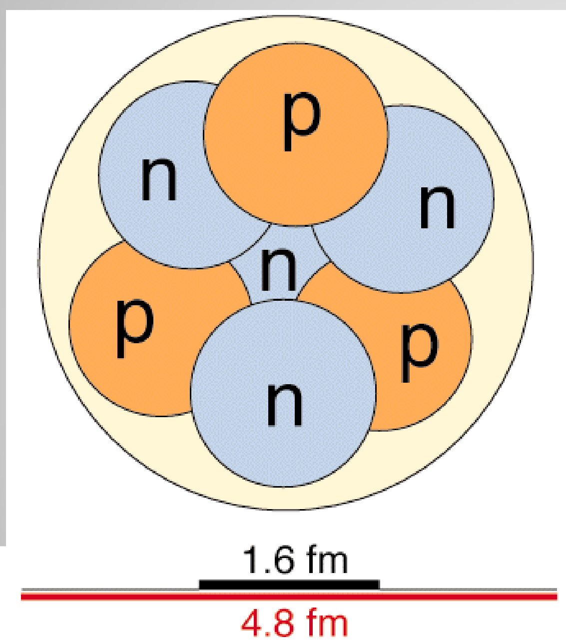
- Nuclear Unruh temperature T~$3\text{x}10^{10}$ K this gives an energy E~3 MeV.

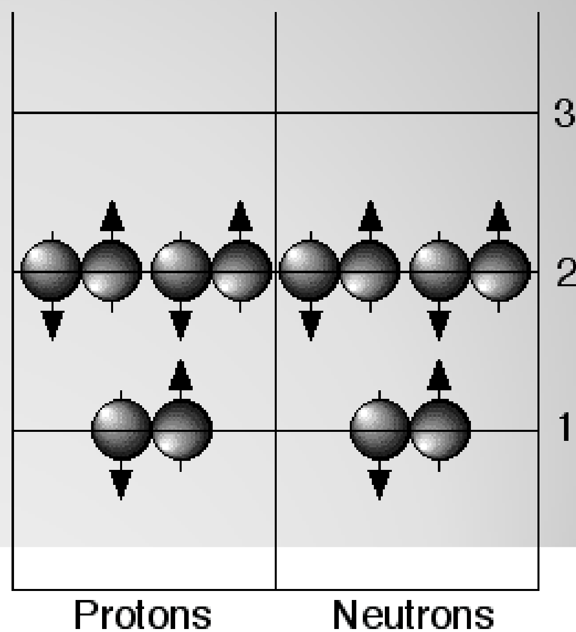
- One needs an element with a low lying energy level and low A (shell model works better for low mass number A)

Circular Unruh effect for ^{7}Li

- Lithium 7 (3 protons + 4neutrons) has a low lying energy level (J=1/2) at ΔE~0.5 MeV above the ground state (J=3/2)

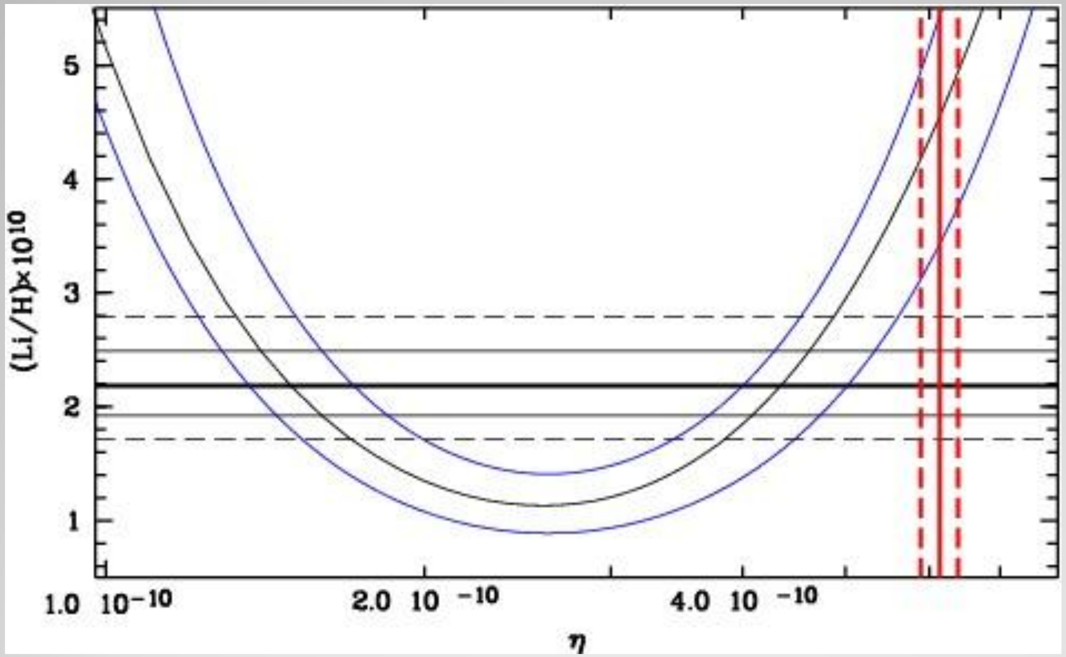
- Using $f(E,T) = \frac{1}{(e^{\Delta E/k_b T})+1} \approx 0.46$





The ^{7}Li problem

- This effect might be related to the lithium problem in cosmology – the is 2 to 4 times less Li then there should be according to BBN.



Curved line → BBN prediction for Li^7 as a function of proton/photon density η. Horizontal line → current measured value. Red vertical line → current predictions

Conclusions

- Electrons in certain atoms experience accelerations comparable to those of electrons in storage rings ~10^{23} m/s^2
- *If* there is an Unruh temperature (~1500K) associated with this *quantum acceleration* this can shift the population of the nearby energy level.
- Fluorine and Oxygen meet these conditions.
- The same effect should work in some nuclei assuming the nuclear shell model works.
- Lithium 7 meets the conditions.