Nuclear spin mixing in hyperfine fields

^{229} Th^{89+} case

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The magic of ^{229}Th

Isomer state at several eV of excitation.

R.G. Helmer, C.W. Reich	(1990,1994)	3.5 (1) eV
B.R. Beck et al.	(2007)	7.6 (5) eV

Strong interplay with atomic structure

Topics

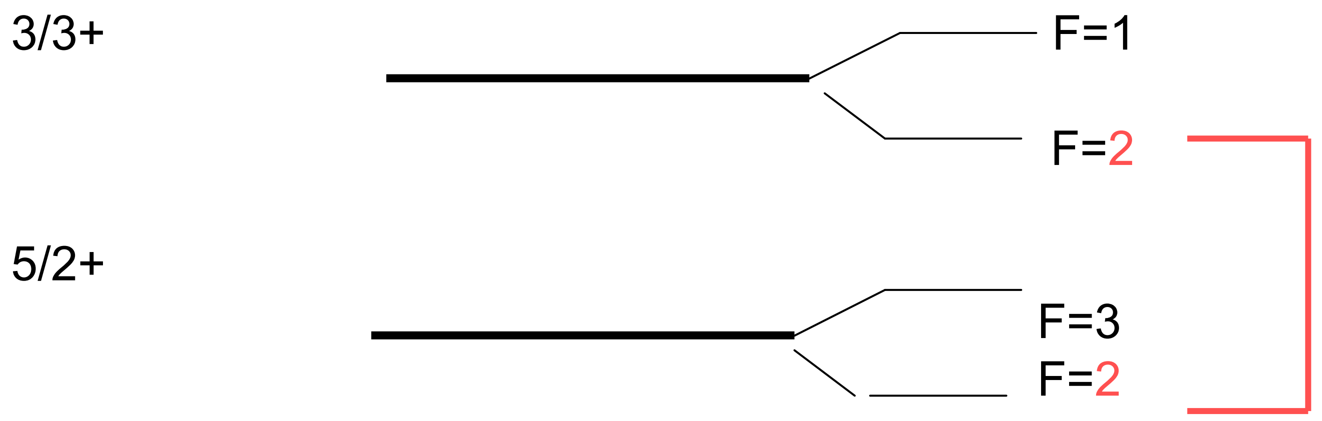
^{229}Th with one electron only

\# Fine structure splitting

\# Nuclear level mixing

\# Oscillations, quantum beating

Fine structure splitting under 1S electron



Born, no mixing yet

$H = e\int \Psi^{*} \boldsymbol{\alpha A} \; \Psi = -\boldsymbol{\mu}_I \, \mathbf{B}_{eff}$ Born, no mixing yet

A - nuclear magnetic field

Ψ - electron , Dirac w.f

F=2 levels mix nuclear states

Technicalities

$\mathbf{A}(r) = \int d\mathbf{r} /(4\pi|r-r'|)\ \mathbf{J}(r')$
$\mathbf{J}(r) = -e/(2M)\ \mathbf{M}(r) \times \mathbf{grad}_r$

Magnetisation M from valence neutron (model)

- precision μ_I (10%)

$B_{eff} = \sim\int dx \exp(-x)\ x^{2\gamma-2}\ n(x)$ fg

$\gamma = sqr(1-Z^2\alpha^2)$, $n(x)$ – magnetism within radius $x\ a_0$
Point nucleus – diverges $Z>118$
$a_0 = 588$ fm, $x = r/a_0$ $B_{eff} = 27.7$ MT

S.W.J.Z. Acta.Phys. Pol.24(1993)637

Nuclear level mixing

Mixing matrix : $< I \,|\, \boldsymbol{\sigma}_N \boldsymbol{\sigma}_e \,|\, I' >$ I – nuclear spin

Calculations : data + shell model

μ(5/2+) , μ(3/2+) well reproduced

$<5/2 \,|\, \boldsymbol{\sigma}_N \boldsymbol{\sigma}_e \,|\, 3/2>$ model + B(M1)

Admixture of upper level to g.s. [$\sin^2(\theta)$]

ΔE [eV] =7.6 4.5 , 3.5 , 2.5 ; μ-atom

$\sin^2(\theta)$[%] = 0.53 1.25 , 2.06 3.51 ; 27

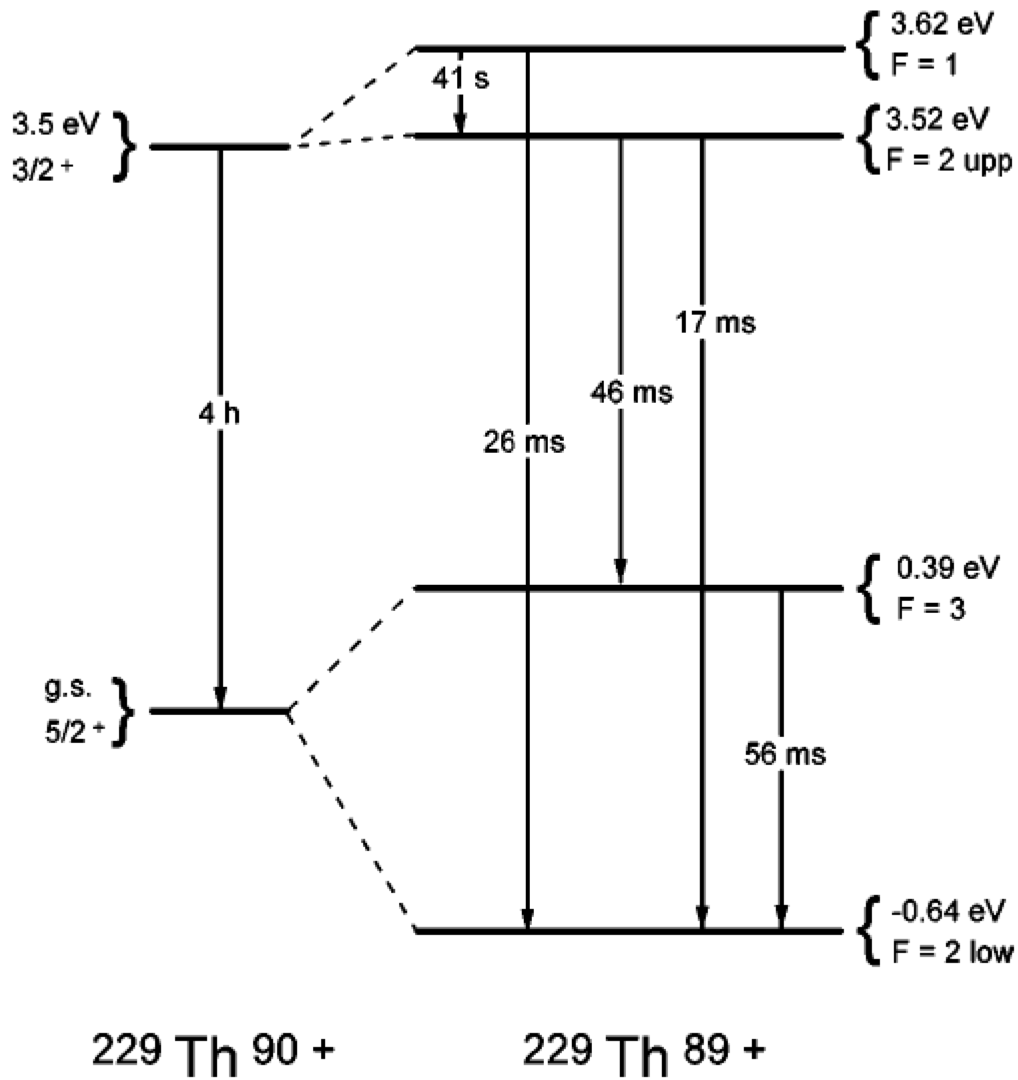
Radiation rate enhancement

M1 transitions from the isomer state are enhanced by 2-3 orders as electron radiates by spin flip.

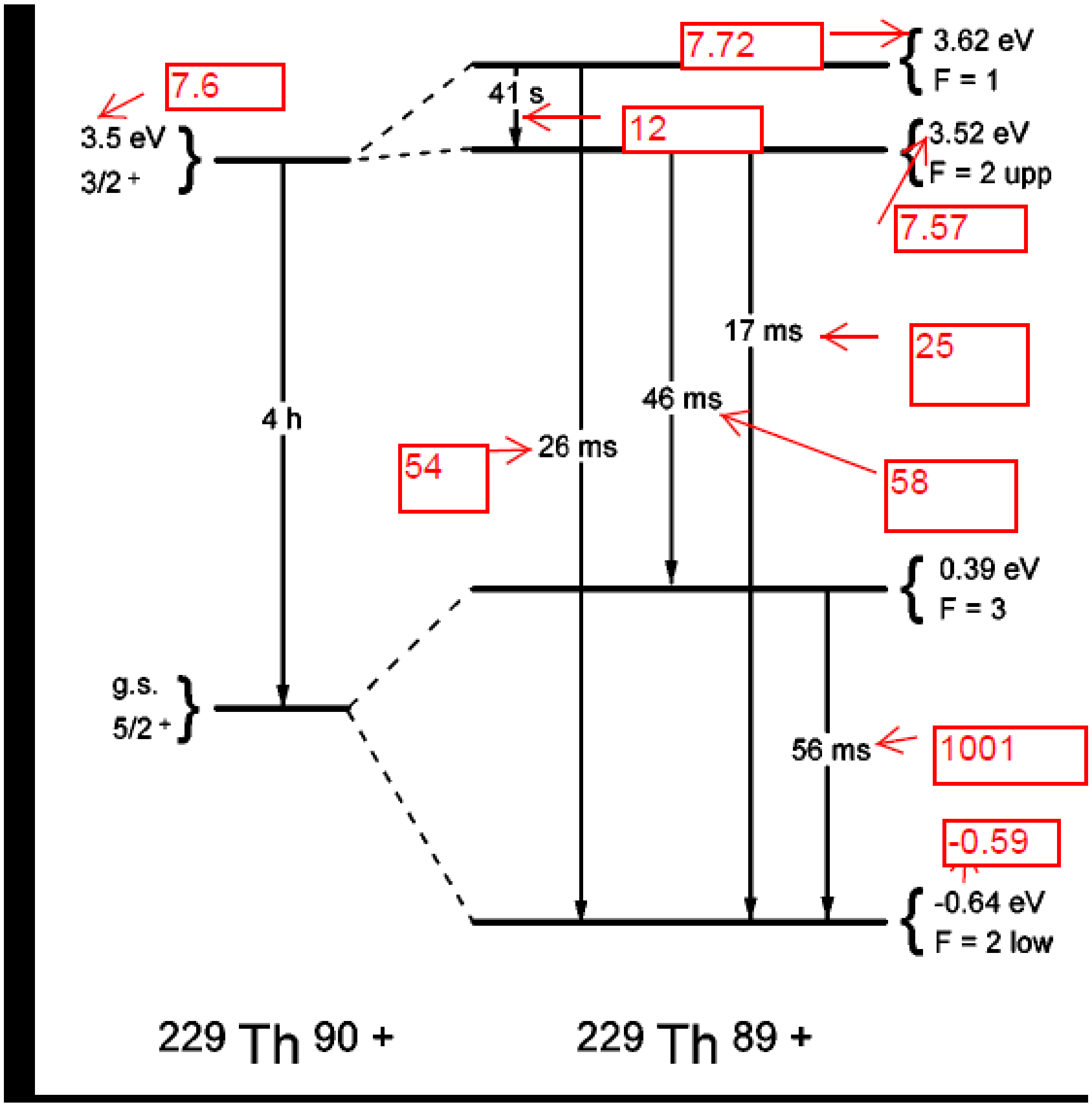
F.Karpeshin…Phys Rev C 57

This meeting

low levels : ΔE = 3.5 [eV]



low levels : ΔE = 7.6 [eV]



Special subsystem F= 2

Two states : upper
lower

Mix nuclear states by magnetic interactions

$$\psi_3 = \cos(\theta)\,\psi[3/2] + \sin(\theta)\,\psi[5/2],$$

$$\psi_1 = -\sin(\theta)\,\psi[3/2] + \cos(\theta)\,\psi[5/2].$$

Quantum beating possible

Nuclear level mixing observation by radiation measurements

very difficult

- $^{229}Th^{90+} \rightarrow$ $^{229}Th^{89+}$ in tube
- observation on 10-100 ms transitions

  $F=2^{up} \rightarrow F=2^{low}$

- time dependence of a given line intensity

Oscillations in $^{229}Th^{89+}$

isomer energy 3.5(1.0) eV (< 2007)

$\sin^2(\theta) = 0.02$

basic F=2 oscillation frequency $6 \cdot 10^{15}$ / sec

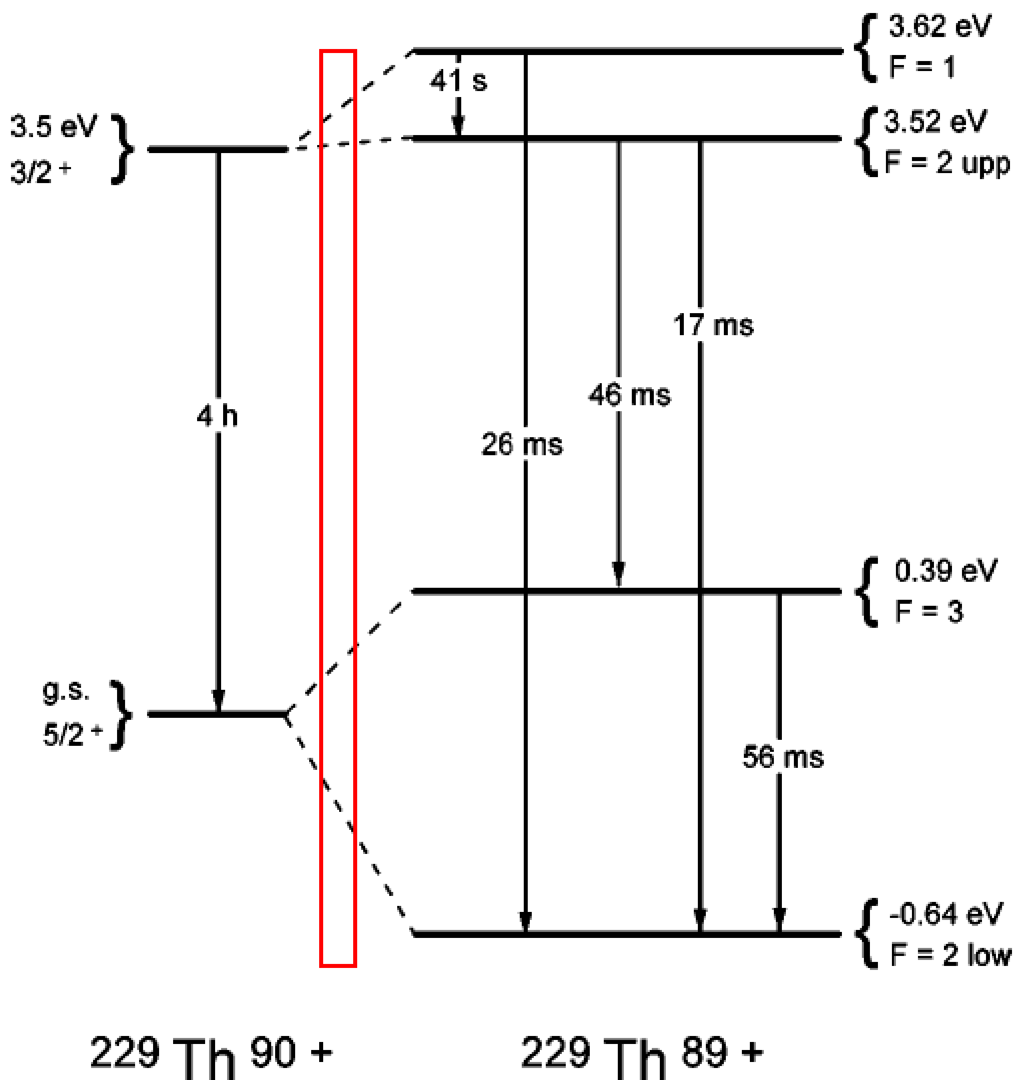
too large to observe directly, time average needed

isomer energy 7.6 eV

$\sin^2(\theta) = 0.005$ oscillation frequency $12 \cdot 10^{15}$ / sec

Shock formation of magnetic field

fast removal of electron



Example – let initial state be the isomer $^{229}Th^{89+}$

Forget decays – only F=2 levels

$\Psi_{t=0}$ = |3/2> = -sin(θ) |low> + cos(θ) |upp>

In time exp($-iE_{low}$ t) exp($-iE_{upp}$ t)

Beating

$P(3/2,t) = 1 - \sin^2(2\theta) \sin^2(t (E_{low} - E_{upp})/2))$

$P(5/2,t) = \sin^2(2\theta) \sin^2(t (E_{low} - E_{upp})/2))$

Time average $< P(5/2,t)> = 2 \sin^2(\theta)$

Larger than the mixing probability

Full system

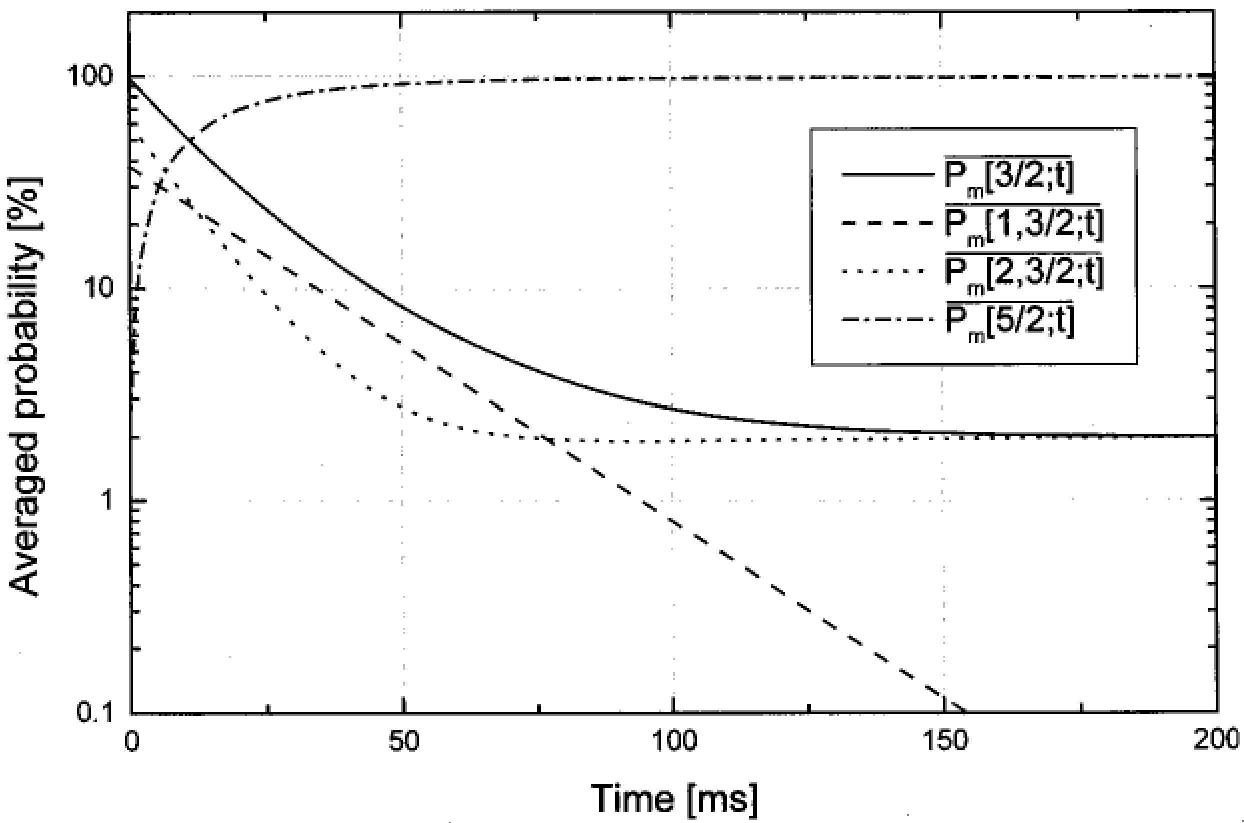
- Four levels
- Five γ magnetic transitions dominated by electron spin flip

Master equation used

K.Pachucki….Phys.Rev. C 64

Ocuppation of nuclear states , averaged over oscillations

isomer at t=0



Occupation probabilities averaged over oscillations

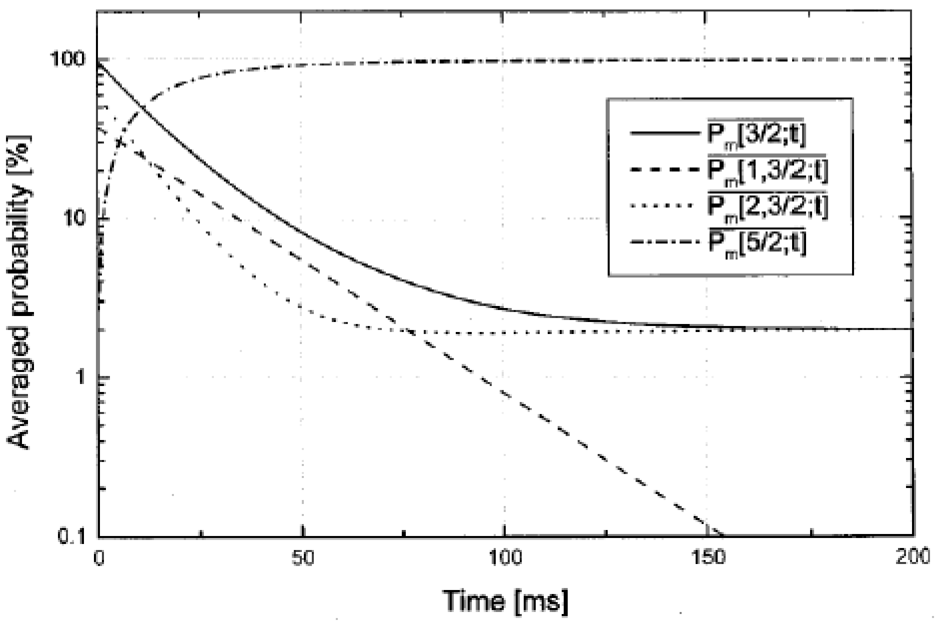


FIG. 2. Time dependence of probabilities $\overline{P_m[3/2;t]}$, $\overline{P_m[1,3/2;t]}$, $\overline{P_m[2,3/2;t]}$, and $\overline{P_m[5/2;t]}$, averaged over t_{osc}, to find the $^{229}Th^{89+}$ ion in the state: $I=3/2$ ($F=2$ or $F=1$), $I=3/2$ ($F=1$), $I=3/2$ ($F=2$), and $I=5/2$ ($F=2$ or $F=3$), respectively. It has been assumed that (i) the nucleus at $t\leqslant 0$ is in the pure $I=3/2$ isomeric state, (ii) the $^{229}Th^{89+}$ ion is created at $t=0$, (iii) the mixing amplitude is $\sin(\theta)=\sqrt{0.02}$. At $t=0$, these probabilities are 97.5, 37.5, 60, and 2.5 %, respectively. At $t\rightarrow\infty$, these are 2, 0, 2, and 98 %.

Experimental problems /chances

formation of ion , mixing of levels

transition $^{229}Th \rightarrow {}^{225}Ra + \alpha$

γ transition in F=2 subsystem

How to perform rapid change,

How to generate isomer in a rapid change

Precise isomer energy - still required