Eduard E. Saperstein (1939 – 2018)

Macroscopic and microscopic aspects of electron capture by polarized nuclei

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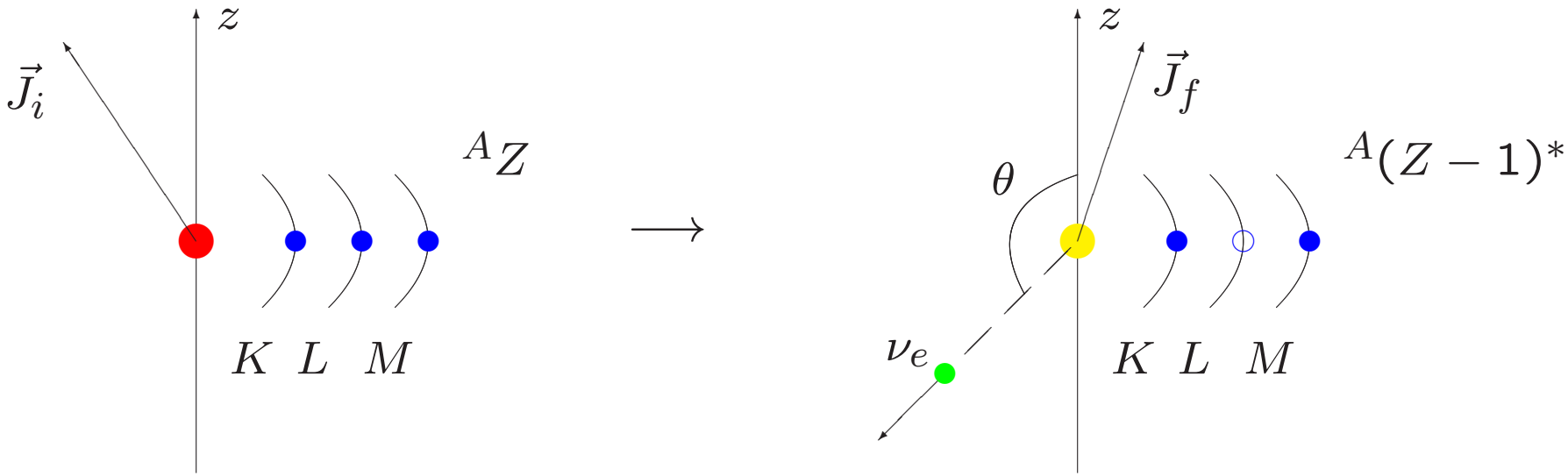
Microscopic aspects of electron capture

Electron capture:

$^{A}Z(J_i) + e^- \rightarrow {}^{A}(Z-1)^*(J_f) + \nu_e$

Allowed transitions:

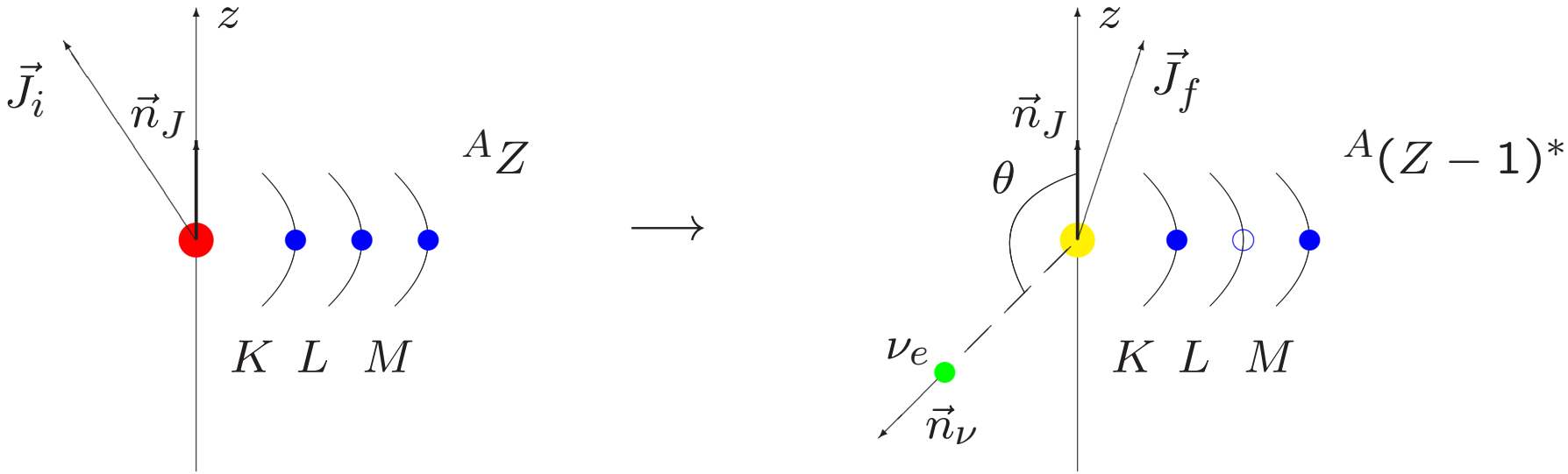
$J_i \rightarrow J_f = J_i$ or $J_i \pm 1$, $\pi_f = \pi_i$



$$M_i c^2 \qquad = \qquad M_f c^2 + E_x^* + E_{\nu x} + E_R$$

$$E_R \simeq \frac{p_{\nu x}^2}{2M_f} \ll E_{\nu x}, \qquad \langle E_\nu \rangle = \sum_x P_x E_{\nu x}, \qquad x = K, L, M, \ldots$$

S.B.Treiman. Recoil effects in K capture and beta decay. - Phys. Rev., 1958, v. 110, p. 448.



$$\frac{dw_{EC}}{d\Omega} = \frac{w_{EC}}{4\pi}\left(1 + B\,P\,\vec{n}_\nu\vec{n}_J\right), \qquad \vec{n}_\nu\vec{n}_J = \cos\theta$$

Nuclei are polarized along $\vec{n}_J$, P — nuclear polarization, B — known asymmetry coefficients (functions of J_i and J_f).

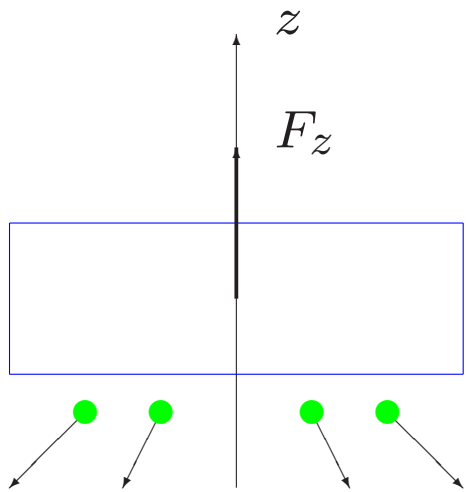
Macroscopic aspects of electron capture

C.DeAngelis, L.M.Folan, V.I.Tsifrinovich. Generation and monitoring neutrino beams using electron-capture beta-decay sources. - Phys. Rev. C, 2012, v. 86, 034615:

(1) only $J_i \to J_f = J_i - 1$,

(2) simplified form of neutrino angular distribution,

(3) only application to neutrino mass measurement



Correct expression for recoil force:

$$\Delta P_z = -N\Delta t \oint \frac{\langle E_\nu \rangle \cos\theta}{c} dw_{EC}(\theta) \quad \Rightarrow \quad F_z = \frac{\Delta P_z}{\Delta t} = -\frac{N I_{EC} \ln 2 \langle E_\nu \rangle B P}{3\, c\, T_{1/2}}$$

The force $F = 10^{-12}$ N can be measured by atomic force microscope. The best case: ^{119}Sb, $P = 1$, the sample mass $m = 4.1 \times 10^{-7}$ g, the sample activity $\alpha = 10.4$ GBq.

Our contribution:

1. All allowed transitions $J_i \to J_f = J_i \pm 1$ or J_i are considered.

2. Correct form of neutrino angular distribution (with account for neutrino mass) is used (however, the mass is so small that this method is not relevant).

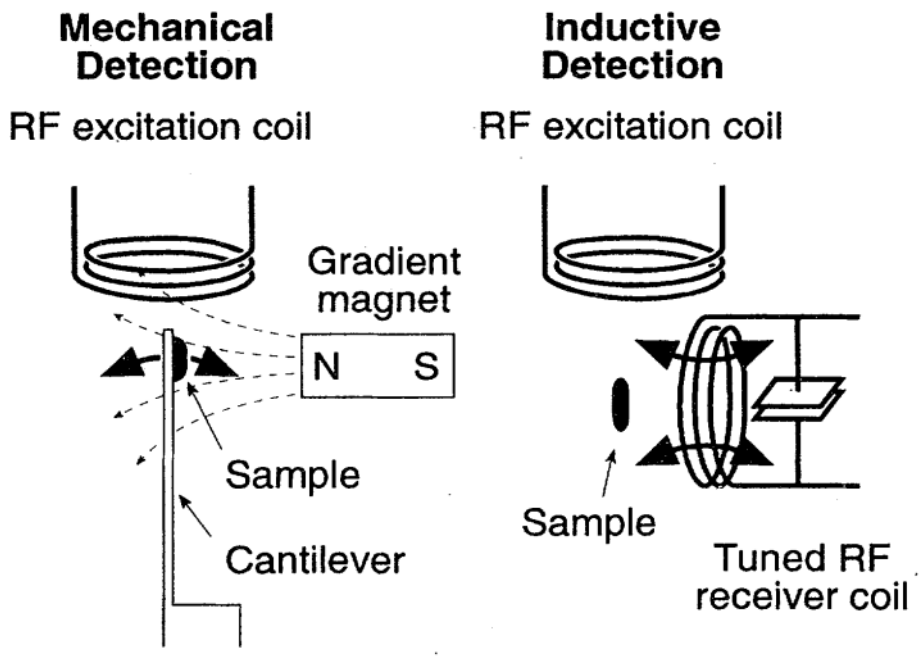
3. Additional applications for the method are found.

4. It is shown that the use of resonance methods would allow to measure recoil forces up to 10^{-19} N with the use of smaller radioactive samples.

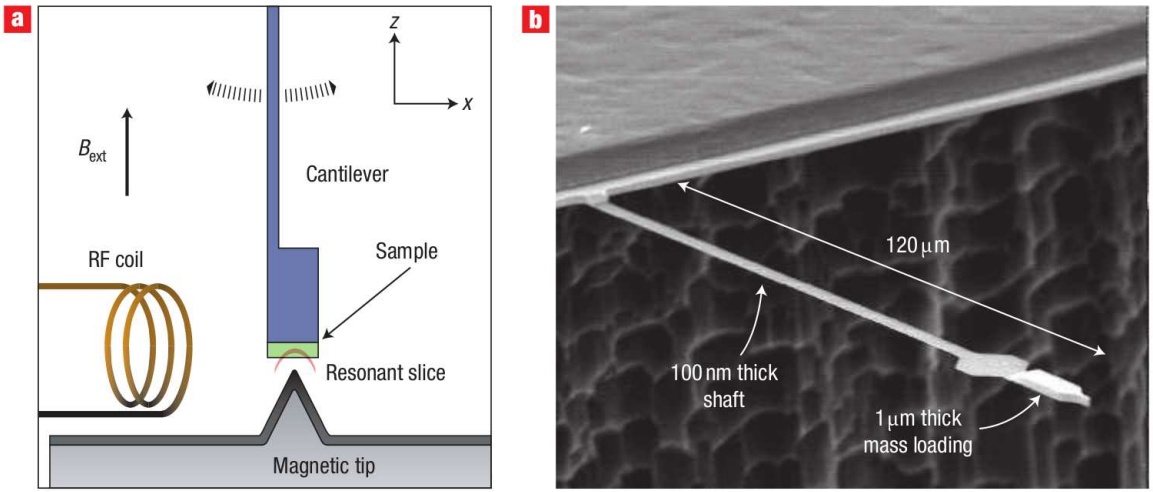
Magnetic resonance force microscopy: $x = \frac{F}{k} \to x_0 = \frac{QF_0}{k}$, Q up to 10^5

J.A.Sidles, J.L.Garbini, K.J.Bruland, D.Rugar, O.Zuger, S.Hoen, C.S.Yannoni. Magnetic resonance force microscopy. - Rev. Mod. Phys., 1995, v. 67, p. 249.

$$F_z = M_z \nabla B(z), \qquad M_z = N\mu P$$



H.J.Mamin, M.Poggio, C.L.Degen, D.Rugar. Nuclear magnetic resonance imaging with 90-nm resolution. - Nature Nanotechnology, 2007, v. 2, p. 301.



Possible applications

1) For $J_i \to J_f = J_i \pm 1$ recoil force is sensitive to P_x via $\langle E_\nu \rangle = \sum_x P_x E_{\nu x}$.

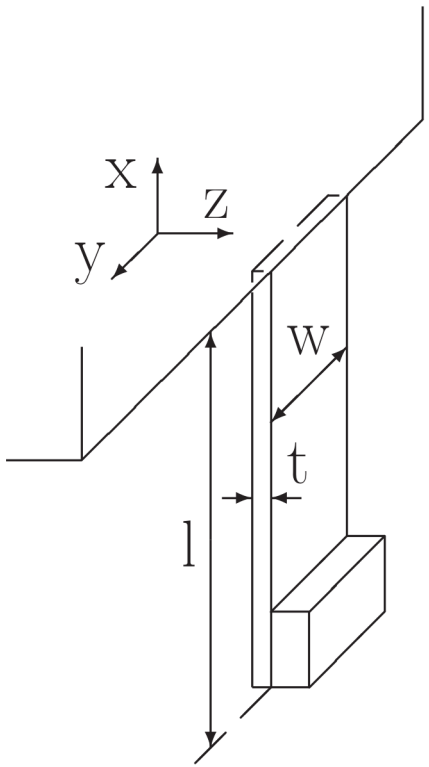
2) For $J_i \to J_f = J_i$ recoil force is sensitive to the ratio M_F/M_{GT}:

$$B = -\frac{1 + 2\sqrt{J_i(J_i+1)}\,\xi}{(J_i+1)(1+\xi^2)}, \quad \xi = \frac{g_V M_F(nJ_iJ_i)}{g_A M_{GT}(nJ_iJ_i)}.$$

3) Testing hypothetical violation of Lorentz invariance.

K.K.Vos, H.W.Wilschut, R.G.E.Timmermans. Testing Lorentz invariance in orbital electron capture. - Phys. Rev. C, 2015, v. 91, 038501.

K.K.Vos, H.W.Wilschut, R.G.E.Timmermans. Symmetry violations in nuclear and neutron beta decay. - Rev. Mod. Phys., 2015, v. 87, p. 1483.



$$\frac{dw_{EC}}{d\Omega} = \frac{w_{EC}}{4\pi}\left(1 + BP\left(\mathbf{n}_\nu \mathbf{n}_J + \chi_r^{jk} n_{\nu j} n_{Jk} + \chi_i^{l0}\left[\mathbf{n}_\nu \times \mathbf{n}_J\right]_l\right)\right),$$

List of Gamow–Teller transitions from the initial nucleus ${}^{A}X_i$ to the ground ($n = 0$) or excited nth state of the final nucleus ${}^{A}X_f$ due to electron capture. Here $T_{1/2}$ and μ are the half-life and the magnetic moment of the initial nucleus, E_n^* is the excitation energy of the final nucleus, $E_{\nu n}$ is the neutrino energy, f_n is the force parameter for the transition, m_{min} is the minimal value for the sample mass. Magnetic moment for ^{179}W is unknown; it was taken to be μ_N as an estimate.

${}^{A}X_i \to {}^{A}X_f$	$J_i^\pi \to J_f^\pi$	$T_{1/2}$	μ/μ_N	E_n^* (keV)	$E_{\nu n}$ (keV)	f_n (N/g)	m_{min} (g)
^{179}W $\to$ ^{179}Ta*	$7/2^- \to 9/2^-$	37.05 m	(1)	30.7	975	$2.2 \cdot 10^{-8}$	$4.5 \cdot 10^{-13}$
^{163}Er $\to$ ^{163}Ho	$5/2^- \to 7/2^-$	75.0 m	$+0.557$	0	1164	$8.0 \cdot 10^{-9}$	$1.3 \cdot 10^{-12}$
^{135}La $\to$ ^{135}Ba	$5/2^+ \to 3/2^+$	19.5 h	$+3.70$	0	1175	$4.1 \cdot 10^{-9}$	$3.6 \cdot 10^{-12}$
^{107}Cd $\to$ ^{107}Ag*	$5/2^+ \to 7/2^+$	6.50 h	-0.615	93.1	1301	$2.9 \cdot 10^{-9}$	$3.5 \cdot 10^{-12}$
^{119}Sb $\to$ ^{119}Sn*	$5/2^+ \to 3/2^+$	38.2 h	$+3.450$	23.9	542	$1.0 \cdot 10^{-9}$	$6.9 \cdot 10^{-12}$
^{111}In $\to$ ^{111}Cd*	$9/2^+ \to 7/2^+$	2.805 d	$+5.503$	416.6	420	$7.8 \cdot 10^{-10}$	$1.1 \cdot 10^{-11}$
^{165}Er $\to$ ^{165}Ho	$5/2^- \to 7/2^-$	10.36 h	$+0.643$	0	332	$3.1 \cdot 10^{-10}$	$3.2 \cdot 10^{-11}$
^{131}Cs $\to$ ^{131}Xe	$5/2^+ \to 3/2^+$	9.69 d	$+3.543$	0	325	$9.5 \cdot 10^{-11}$	$7.5 \cdot 10^{-11}$

Conclusion

Macroscopic aspects of electron capture could help to study the microscopic ones

C.Englert, S.Hild, M.Spannowsky. Particle physics with gravitational wave detector technology. - EPL (Europhysics Letters), 2018, v. 123, 41001.