Diatomic Molecules as Probes for Nuclear Anapole Moment Effect

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Nuclear spin dependent parity violating effects

The NSD-PV effects can be described by the following Hamiltonian,

$$H_{NSD} = \frac{G_F}{\sqrt{2}I} \sum_i (\kappa_{ax} + \kappa_{hfs} + \kappa_A) (\boldsymbol{\alpha}_i \cdot \mathbf{I}) \rho(r_i), \tag{1}$$

where G_F is the Fermi coupling constant; α_i are Dirac matrices; I is nuclear spin; $\rho(r_i)$ is the nuclear density distribution.

- κ_{ax} is independent on A: the electroweak neutral coupling between electron vector and nucleon axial vector currents
- κ_{hfs} is much smaller than κ_A: the nuclear-spin-independent weak interaction combined with the hyperfine interaction (depend on nuclear spin)
- $\kappa_A \sim A^{2/3}$: the nuclear anapole moment contribution

Here A is the mass number of the nucleus.

The last one is the contribution from the nuclear anapole moment effect. Since $\kappa_A \sim A^{2/3}$. It is the dominant contribution for molecules containing heavy element. In a valence nucleon model, κ_A has the following form [V. V. Flambaum, I. B. Khriplovich, and O. P. Sushkov, Phys. Lett. B **146**, 367 (1984)],

$$\kappa_A = 1.15 \times 10^{-3} \left(\frac{K}{I+1} \right) A^{\frac{2}{3}} \mu_i g_i. \tag{2}$$

Nuclear anapole moment

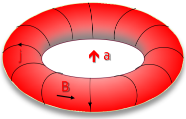
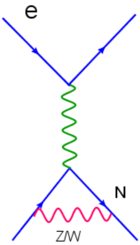


Image courtesy of V. V. Flambaum



A non-zero anapole moment was reported by Wood *et al.* with the size of $\kappa_A \sim 0.127 \pm 0.019$ for Cs, a result differing from zero by 7σ. [Science **275**, 1759 (1997)]

The nuclear anapole moment interaction violates parity. It is the interaction between the nuclear anapole moment and the molecular electronic function that can be described by

$$H_A = \kappa_A \frac{G_F(\boldsymbol{\alpha} \cdot \mathbf{I})}{\sqrt{2} I} \rho(\mathbf{r})$$

For $^2\Sigma_{1/2}$ and $^2\Pi_{1/2}$ electronic states, the nuclear anapole moment interaction can be replaced by

$$H_A = \kappa_A W_A \frac{(\mathbf{n} \times \mathbf{S}') \cdot \mathbf{I}}{I}$$

Here, the W_A depends on electronic structure and can be used to extract information from experiments. It can be defined as follows:

$$W_A = \frac{G_F}{\sqrt{2}} \left\langle \Psi_{^2\Sigma_{1/2}} \left| \rho(\mathbf{r})(\alpha_x + i\alpha_y) \right| \Psi_{^2\Sigma_{-1/2}} \right\rangle$$

Magnitude of the effect

The nuclear anapole moment mixes molecular states with opposite parity.

$$\Psi'_{+} = \Psi_{+} + i\eta_A \Psi_{-} \tag{3}$$

$$i\eta_A = \frac{\langle \Psi_{+} | H_A | \Psi_{-} \rangle}{E_{+} - E_{-} + i\Gamma/2} \sim 10^{-11} \tag{4}$$

$$|\eta_A|^2 \sim 10^{-22} \tag{5}$$

Here, Ψ_{+} has even parity and Ψ_{-} has odd parity. The magnitude of the effect is extremely small. If 10^{22} molecules experience an allowed electromagnetic transition, there would be only one that experiences transition induced by the nuclear anapole moment interaction. This tiny effect needs to be amplified:

- Zeeman effect (increasing the mixing coefficient)
- Stark effect (Stark-PV technique: measuring $\eta_S \eta_A$ instead of η_A^2, since $\frac{\eta_S}{\eta_A} \sim 10^5$ (Wood1997))

Zeeman effect

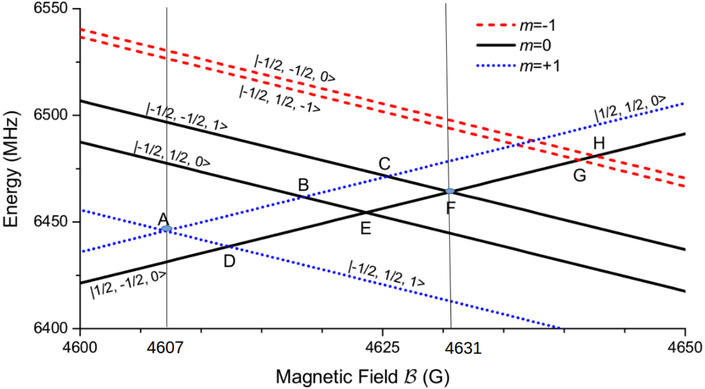


Image from Altunas, *et al*, Phys. Rev. A **97**, 042101 (2018)

$$i\eta_A = \frac{\langle \Psi_+ | H_A | \Psi_- \rangle}{E_+ - E_- + i\Gamma/2} \tag{6}$$

Stark effect and Stark-PV technique

The Stark effect can also mix molecular states with opposite parity.

$$H_S(\boldsymbol{\epsilon}) = -\boldsymbol{\epsilon} \cdot \mathbf{D} \tag{7}$$

$$i\eta_S = \frac{\langle \Psi_+ | H_S | \Psi_- \rangle}{E_+ - E_- + i\Gamma/2} \tag{8}$$

$$\frac{\eta_S}{\eta_A} \approx 10^5 \tag{9}$$

$$\eta_S(-\boldsymbol{\epsilon}) = -\eta_S(\boldsymbol{\epsilon}) \tag{10}$$

Since η_S is odd with respect to the electric field, we could measure $\eta_S \eta_A$ instead of η_A^2. If we switch on the electric field, the total signal should be

$$\begin{aligned} S(\boldsymbol{\epsilon}) &= |\eta_S(\boldsymbol{\epsilon}) \pm \eta_A|^2 \\ &= \eta_S(\boldsymbol{\epsilon})^2 \pm 2\eta_S(\boldsymbol{\epsilon})\eta_A + \eta_A^2 \end{aligned} \tag{11}$$

If we flip the electric field, the mixing term will change sign:

$$\begin{aligned} S(-\boldsymbol{\epsilon}) &= |\eta_S(-\boldsymbol{\epsilon}) \pm \eta_A|^2 \\ &= \eta_S(\boldsymbol{\epsilon})^2 \mp 2\eta_S(\boldsymbol{\epsilon})\eta_A + \eta_A^2 \end{aligned} \tag{12}$$

$$2\eta_S(\boldsymbol{\epsilon})\eta_A \gg \eta_A^2 \tag{13}$$

Then the asymmetry due to nuclear anapole interaction could be obtained by

$$\begin{aligned} P_a &= \frac{S(\boldsymbol{\epsilon}) - S(-\boldsymbol{\epsilon})}{S(\boldsymbol{\epsilon}) + S(-\boldsymbol{\epsilon})} \\ &\approx 2\frac{\langle \Psi_+ | H_A | \Psi_- \rangle}{\Delta} \frac{\omega}{d\epsilon} \end{aligned} \tag{14}$$

where Δ, ω and $d\epsilon$ are experimental parameters and should be known [Altunas, *et al*, Phys. Rev. Lett. **120**, 142501 (2018)]. Once $\langle \Psi_+ | H_A | \Psi_- \rangle$ is known, one could derive κ_A using the value of W_A.

Thank you for your attention