Parity violation and new physics in superconductors

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June 18, 2021

PASCOS 2021, Daejeon, Korea

Phys. Lett. B 811 (2020), arXiv:2009.01494

Parity violation in particle physics

- The parity is intrinsically broken in nature: For instance

$$n \to p^+ + e^- + \bar{\nu}_R$$

Only left-handed neutrinos (right-haned anti-neutrinos) are observed in the beta decay.

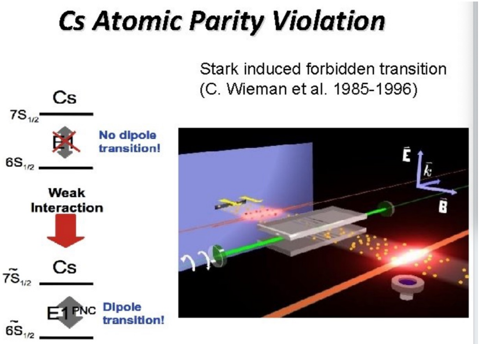
- According to the standard model of particle physics the weak-interaction depends on the handedness (chirality) of particles, breaking intrinsically the parity.
- The weak interaction is of very short-range and thus very weak at a large distance $d \gg M_W^{-1} \simeq 10^{-17}$ m

$$V(r) = \frac{\alpha_{\mathrm{w}}}{r} e^{-M_W r} .$$

Atomic parity violation

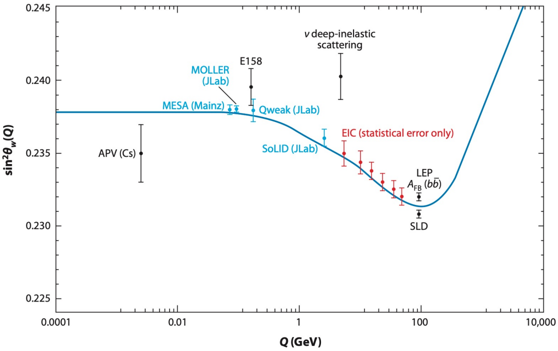
- The APV has been measured (Wood et al, Science 1997), agreeing with SM by 1.5σ: For $6s_{1/2}(F) \to 7s_{1/2}(F')$

$$\mathrm{Im}\left(E_{\mathrm{PNC}}\right) = Q_w \frac{k_{\mathrm{PNC}}}{N} \sim |e| a_0 \times 10^{-11}; \quad Q_w^{\mathrm{exp}} = -73.16(28)(20)$$



Atomic parity violation

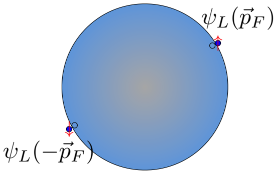
- The measurement of APV places strong constraints on new physics, complementing the collider searches, to give $\Lambda_{\rm NP} \gtrsim 10\ {\rm TeV}$. (Kumar et al 1302.6263)

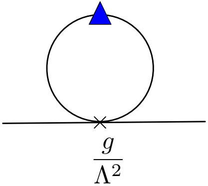


Parity violation in superconductors

- The low energy EFT of electrons in metal is described by

$$\mathcal{L}_{\text{eff}} = \Psi^\dagger \left[iD_t + \frac{1}{2m_*}\left(\vec{\sigma}\cdot\vec{D}\right)^2 + \mu \right]\Psi + \frac{g}{\Lambda^2}\left(\Psi^\dagger\sigma^2\Psi\right)^2 + \cdots$$



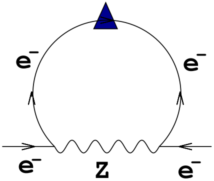


- The phonon int. opens a gap at the Fermi surface (BCS):

$$\langle\psi_L(\vec{p}_F)\psi_L(-\vec{p}_F)\rangle = \langle\psi_R(\vec{p}_F)\psi_R(-\vec{p}_F)\rangle \sim \Delta$$

Parity violation in superconductors

- In addition to the phonon exchange the electrons interact with each other via the weak Z gauge-boson exchange:



- At low energy the Z-boson exchange is approximately

$$\mathcal{L}_{\rm eff}^{NC} = -\frac{G_F}{\sqrt{2}} J_\mu^Z J^{Z\mu}$$

where $J_\mu^Z = -\bar{\psi}_L \gamma^\mu \psi_L + 2\sin^2\theta_{\rm W}\,\bar{\psi}\gamma^\mu\psi$.

Parity violation in superconductors

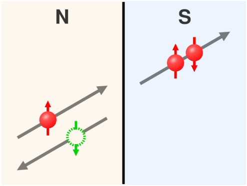
- The parity-violating Cooper-pair gap is found to be

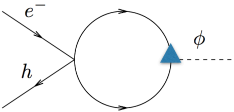
$$\delta\Delta = \Delta_R - \Delta_L = \left(1 - 4\sin^2\theta_W\right) \cdot \frac{G_F}{\sqrt{2}} \cdot \frac{2p_F^2}{\pi^2} \frac{\Delta}{v_F} \cdot \ln\left(\frac{E_F}{\Delta}\right) \approx 1.2 \times 10^{-15}\,\Delta\,,$$

  where we have taken the weak mixing angle $\sin^2\theta_W = 0.23$, $E_F = \frac{p_F^2}{2m_*} = 10\,\mathrm{eV}$ and $\Delta = 10^{-2}\,\mathrm{eV}$.
- The weak interaction induces the helicity-dependence on the Cooper-pair gap $\sim 10^{-15}\Delta$, which might be measurable for the processes that depend directly on the gap such as the Andreev reflection.

Andreev reflection

- The Andreev-reflection vertex is found to be





$$\mathcal{L}_{ar} = i\kappa\, \partial^\mu \theta(x)\, \partial_\mu \phi\, \bar{\psi}^C \sigma^2 \psi\,,$$

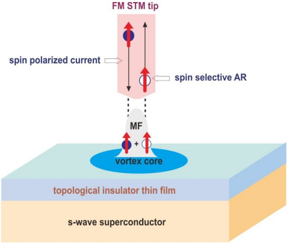
with the coupling $\kappa = \frac{g}{2\pi^2} \cdot \frac{\Delta}{F} \cdot \frac{p_F^2}{\Lambda^2} \ln\left(\frac{E_F}{\Delta}\right)$.

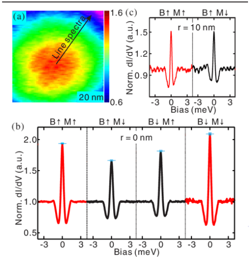
Andreev reflection

- Upon the Andreev reflection electrons gets polarized: the bigger the gap, the more reflected. At each scattering the electrons will be polarized by

$$\frac{\delta\Delta}{\Delta} \sim 10^{-15}$$

- This polarization might be measured by the Spin-selective Andreev reflection (SSAR) used to detect Majorana fermions -Sun et al PRL (2016)





Majorana neutrino in superconductors

- If the neutrinos are Majorana fermions, its mass violates the electron number by two and contributes to the gap of left-handed electron:

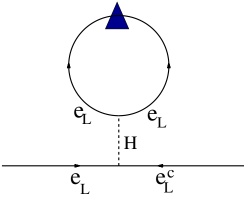
$$\delta\Delta = \Delta_L - \Delta_R = 10^{-36}\,\Delta \left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right)^2 \left(\frac{E_F}{10\ \mathrm{eV}}\right)^2,$$

Doubly charged Higgs

- Certain BSM model such as type II seesaw predicts a heavy, doubly charged Higgs, which will induce at low energy

$$\mathcal{L}_{4F} = \frac{y^2}{M_H^2} \left(\bar{\psi}_L^c \psi_L\right)^2 + \text{h.c.}$$

- The doubly charge Higgs will contribute to the gap of left-handed electrons:



$$\frac{\delta\Delta_L}{\Delta_L} \sim 10^{-16} \left(\frac{p_F}{3\,\text{keV}}\right)^2 \cdot \left(\frac{500\,\text{GeV}}{M_H}\right)^2$$

Conclusion

- We estimate the effect of parity-violating weak interactions on the superconducting gap.
- The effect is tiny but comparable to APV that has been measured.

$$\delta\Delta = \Delta_R - \Delta_L \approx 1.2 \times 10^{-15}\,\Delta\,,$$

- We propose to measure the parity-violating gap by using SSAR
- This new effect could test SM at low energy and put constraints on possible new BSM physics.

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