Probing Beta Decay Matrix Elements through Heavy Ion Charge Exchange Reactions

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Introduction

Nowadays neutrinoless double beta decay ($0\nu\beta\beta$) represents one of the key cases to probe Physics beyond the Standard Model. From the half – life of nuclei which may undergo double beta decay it would be possible to extract the neutrino effective mass, once determined Phase Space (PS) factor and Nuclear Matrix element (NME)

$$[T^{0\nu}_{1/2}(\mathcal{N})]^{-1} = G^{\mathcal{N}}_{0\nu} \left|\mathcal{M}^{\mathcal{N}}_{0\nu}\right|^2 \frac{|m_{2\beta}|^2}{m_e^2}$$

elementary particle physics factor

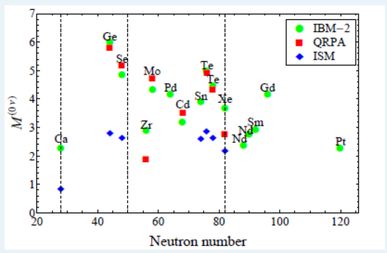
Beyond Standard Model Physics?

$$m_{2\beta} = c_{12}^2 c_{13}^2 m_1 + e^{2i\lambda_2} s_{12}^2 c_{13}^2 m_2 + e^{2i(\lambda_3-\delta_{13})} s_{13}^2 m_3$$

PS factor

$0\nu\beta\beta$ NME (strength)

calculated through different nuclear structure models
→ values differ of about a factor of 3 [1]



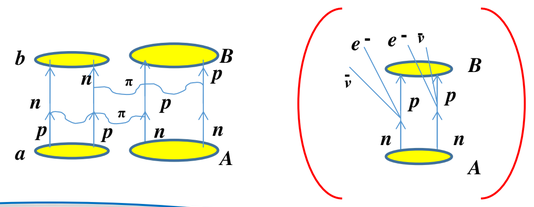
lot of analogies between Haevy Ion Double Charge Exchange (DCE) reactions and $0\nu\beta\beta$ [2]

- ***0νββ strength*** from DCE Cross Section measurements → DCE Cross Section factorization into the product of a reaction term and a nuclear structure one, the latter giving information about ***0νββ strength***
- once calculated the reaction term, from Heavy Ion DCE Cross Section measurements it would be possible to probe the ***ββ strength*** , gaining a model-independent insigth into NMEs.

CEX Cross Section Factorization

DCE

analogy with ***2νββ***
→ DCE = sequence of two ***uncorrelated*** SCE processes



analogy with ***0νββ***
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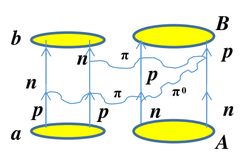
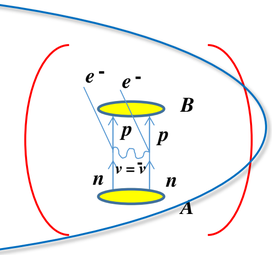




work in progress!

- **Charge Exchange (CEx) Cross Section**

$$\frac{d^2\sigma^{(CEx)}}{dEd\Omega} = \frac{E_\alpha E_\beta}{(2\pi\hbar c)^4}\frac{k_\beta}{k_\alpha}\frac{1}{(2J_A+1)}\frac{1}{(2J_a+1)}\sum_{\substack{m_a,m_A\\ m_b,m_B}}\Big|\sum_{\substack{\tau=C,T\\ SO}}\mathcal{M}^{(\tau)}_{\alpha\beta}(\mathbf{k}_\alpha,\mathbf{k}_\beta)\Big|^2$$

Transition Matrix Element

DWBA + Zero range approximation

$$\mathcal{M}^{(\tau)}_{\alpha\beta} = \sum_{S,T}\int d^3p\, K^{(\tau,ST)}_{\alpha\beta}(\mathbf{p})\, N^D(\mathbf{k}_\alpha,\mathbf{k}_\beta,\mathbf{p})$$

Reaction Kernels

Distortion Factor

$$N^D = \frac{1}{(2\pi)^3}\int d^3r\, \chi^*_f(\mathbf{r})\chi_i(\mathbf{r})e^{-i\mathbf{p}\cdot\mathbf{r}}$$

$$K^{(ST)}_{\alpha\beta}(q_{\alpha\beta}) = V^{(C)}_{ST}(q_{\alpha\beta})F^{(ST)\dagger}_{ab}F^{(ST)}_{AB} + \delta_{S1}\sqrt{\frac{24\pi}{5}}V^{(T)}_{ST}(q_{\alpha\beta})Y^*_2(\hat{q}_{\alpha\beta})\left[F^{(ST)\dagger}_{ab}\otimes F^{(ST)}_{AB}\right]_2$$

M3Y Effective Nuclear Interaction Potential is used

$$Y^*_2(\hat{q}_{\alpha\beta})\left[F^{(ST)\dagger}_{ab}\otimes F^{(ST)}_{AB}\right]_2 = \sum_M Y^*_{2M}(\hat{q}_{\alpha\beta})\left[F^{(ST)\dagger}_{ab}\otimes F^{(ST)}_{AB}\right]_{2M}$$

radial transition density

$$\rho_{ab}(q^{(L,S,J_1)}_{\alpha\beta}) = 4\pi\int_0^\infty dr\, r^2\rho_{ab}(r)j_L(q_{\alpha\beta}r)$$

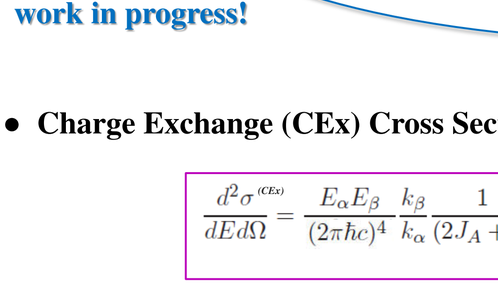
~ ***β / ββ decay strength***

Transition Form Factor

$$F^{(ST)}_{ab}(\mathbf{q}_{\alpha\beta}) = \langle J_b m_b|\frac{1}{4\pi}e^{i\mathbf{q}_{\alpha\beta}\cdot\mathbf{r}_a}\mathcal{O}^{(ST)}|J_a m_a\rangle = \sum_{\substack{L,M_L,M_S\\ J_1,M_1}}(J_a,m_a,J_b,m_b|J_1,M_1)\,(L,M_L,S,M_S|J_1,M_1)\,\rho^{(L,S,J_1)}_{ab}(q_{\alpha\beta})\,i^L Y_{L,M_L}(\hat{q}_{\alpha\beta})$$

Transition Matrix Element factorization

→ ***Direct Reactions*** ➡ *separation ansatz* : Reaction Kernel ***Gaussian*** shaped [3]



$$K^{(ST)}_{\alpha\beta}(\mathbf{r}) = \frac{1}{4\pi}U_0 e^{-\frac{(\mathbf{r}-\mathbf{R})^2}{2\sigma^2}}$$

- $\sigma^2 = \sigma_a^2 + \sigma_A^2$
- $R^2 = R_a^2 + R_A^2$

$$K^{(ST)}_{\alpha\beta}(\mathbf{p}) = \sqrt{\frac{\pi}{2}}\sigma^3 e^{i\mathbf{p}\cdot\mathbf{R}}e^{-\frac{1}{2}\sigma^2p^2}$$

$\mathbf{p} = \mathbf{q}_{\alpha\beta} - \mathbf{q}$

$$K^{(ST)}_{\alpha\beta}(\mathbf{q},\mathbf{q}_{\alpha\beta}) = K^{(ST)}_{\alpha\beta}(\mathbf{q}_{\alpha\beta})h_{\alpha\beta}(\mathbf{q},\rho)$$

$$h_{\alpha\beta}(\mathbf{q},\rho) = e^{-\frac{1}{2}\sigma^2q^2}e^{-i\mathbf{q}\cdot\rho}$$

$$\mathcal{M}^{(\tau)}_{\alpha\beta} = \sum_{S,T}K^{(ST)}_{\alpha\beta}(\mathbf{q}_{\alpha\beta})\int d^3q\, h_{\alpha\beta}(\mathbf{q},\rho)N^D(\mathbf{k}_\alpha,\mathbf{k}_\beta,\mathbf{q})$$

$\rho = \mathbf{R} + i\sigma^2\mathbf{q}_{\alpha\beta}$

not **exact factorization**

Black Disk Approximation (*BDA*)

$|V| << |W|$ → $\chi(r) \sim 0$ dove $|W| \neq 0$ e $\chi(r)$ = Plane Wave dove $|W| = 0$
→ analytical determination of Distortion Factor [3]

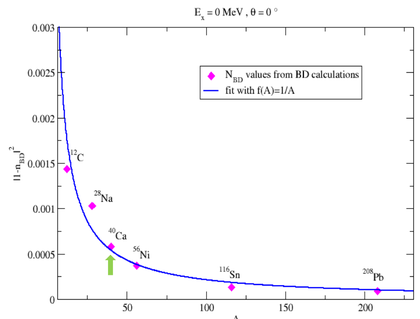
Optical Potential calculated in Impulse approximation, through doubly folding NN interaction potential from [5] with one-body local nuclear densities

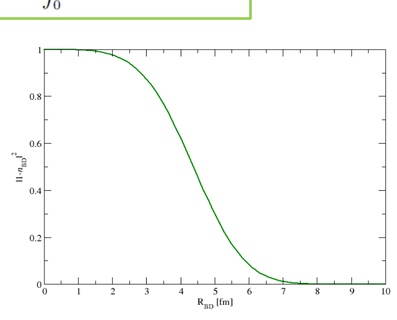
Distortion Factor $N^D = \delta(\mathbf{q}) - N^{(BD)}_{PW}$

$$N^{(BD)}_{PW} = \frac{1}{2\pi^2}\frac{R_{abs}}{q}\left(-\frac{\partial}{\partial q}\right)j_0(qR_{abs})$$

$$M_{\alpha\beta} = \sum_{ST}K_{\alpha\beta}(\mathbf{q}_{\alpha\beta})\,(1 - n_{BD})$$

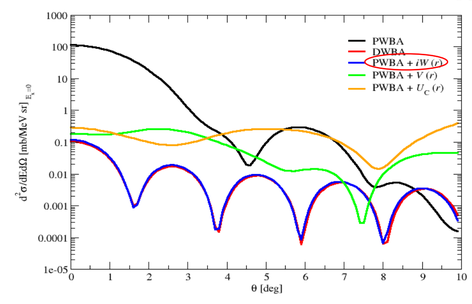
$$n_{BD} = 4\pi\int_0^\infty dq q^2 N^{(BD)}_{PW}\, h^{(ST)}(q)$$

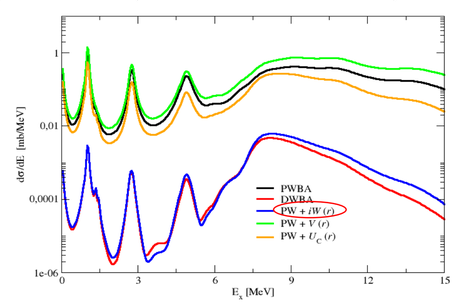




- BDA works very well for Heavy Ion reactions at low energies → simulations with **HIDEX** code (H. Lenske) [4] on **SCEX** Cross Section for Heavy Ions [3] .

^{40}Ca (^{18}O,^{18}F)^{40}K @ 270 MeV (1$^+$ state for both ^{40}K and ^{18}F)





DCE - 2νββ

DCE Reaction Kernel can be expressed as

$$\langle\psi_B\varphi_b|\mathbb{V}^{(DCE)}|\psi_A\varphi_a\rangle \simeq \langle\psi_B\varphi_b|\,\mathbb{V}^{(SCE)}\,\mathcal{G}_0\,\mathbb{V}^{(SCE)}|\psi_A\varphi_a\rangle$$

free propagator

$$\sum_\Gamma\int\frac{d^3k_\gamma}{(2\pi)^3}|\Gamma,\mathbf{k}_\gamma><\Gamma,\mathbf{k}_\gamma| = 1$$

$$\sum_\Gamma\int\frac{d^3k_\gamma}{(2\pi)^3}\langle\psi_B\varphi_b|\mathbb{V}^{(SCE)}|\Gamma,\mathbf{k}_\gamma\rangle\mathcal{G}_{0\gamma\Gamma}\langle\Gamma,\mathbf{k}_\gamma|\mathbb{V}^{(SCE)}|\psi_A\varphi_a\rangle = \sum_\Gamma\int\frac{d^3k_\gamma}{(2\pi)^3}K^{(SCE)}(\mathbf{q}_{\alpha\gamma},\mathbf{R})\mathcal{G}_{0\gamma\Gamma}K^{(SCE)}(\mathbf{q}_{\gamma\beta},\mathbf{R}')$$

Separation Ansatz for the two SCE

+

Pole Approximaxion ➡ $\mathcal{G}_{0\gamma\Gamma} \simeq \delta(E_{\gamma\Gamma} - E_\omega) = \delta(k_\gamma - k_\omega)\frac{\mu_\omega}{k_\omega}$

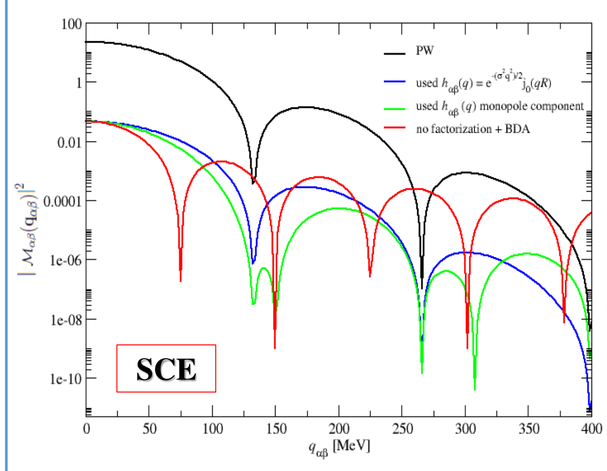
+

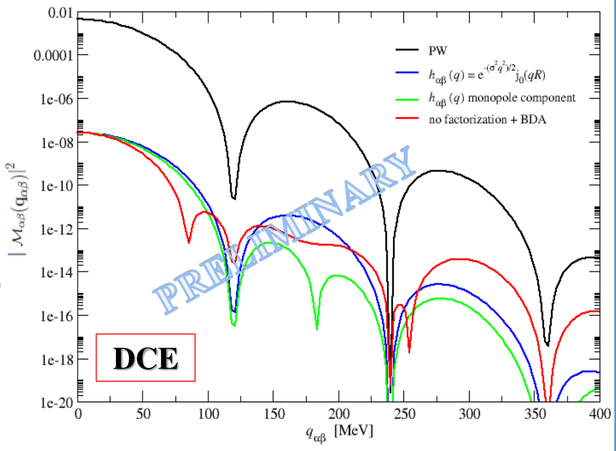
Single state dominance (***SSD***) is assumed

$$\simeq \frac{1}{2\pi^2}\mu_\omega k_\omega e^{-\frac{1}{2}\sigma^2q^2_{\alpha\omega}}e^{-\frac{1}{2}\sigma^2q^2_{\omega\beta}}e^{ik_\alpha R}e^{-ik_\beta R'}j_0(k_\omega|\mathbf{R}-\mathbf{R}'|)$$
$$\simeq \frac{1}{2\pi^2}\mu_\omega k_\omega K^{(SCE)}(\mathbf{q}_{\alpha\omega})K^{(SCE)}(\mathbf{q}_{\omega\beta})j_0(k_\omega|\mathbf{R}-\mathbf{R}'|)$$

$$\frac{d^2\sigma}{dEd\Omega} = \frac{E_\alpha E_\beta}{(2\pi\hbar c)^4}\frac{k_\beta}{k_\alpha}\frac{1}{(2J_A+1)}\frac{1}{(2J_a+1)}\sum_{\substack{m_a,m_A\\ m_b,m_B}}|j_0(k_\omega|\mathbf{R}-\mathbf{R}'|)|^2k_\omega^2\mu_\omega^2|K^{(SCE)}(\mathbf{q}_{\alpha\omega})|^2|K^{(SCE)}(\mathbf{q}_{\omega\beta})|^2|1-n_{\alpha\beta}|^2$$

CEx Cross Section factorization validity range





Conclusions and Outlooks

- We provide Heavy Ion CEx Cross Section factorization by assuming ***Gaussian*** Reaction Kernel, due to the ***Direct*** nature of such reactions. Such ansatz gives exact factorization for momentum transfer $q_{\alpha\beta} = 0$, but works well up to $q_{\alpha\beta} \approx 25 - 30$ MeV.
- Calculations made within BDA framework → analytical expression for distortion factor.
- DCE formalism code implementation in DWBA, without separation ansatz.
- Study of the link between DCE reactions and 0νββ decay.

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