Nuclear structure studies relevant to $\beta\beta$ decay of ^{136}Xe

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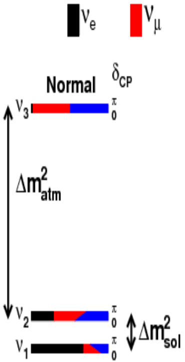
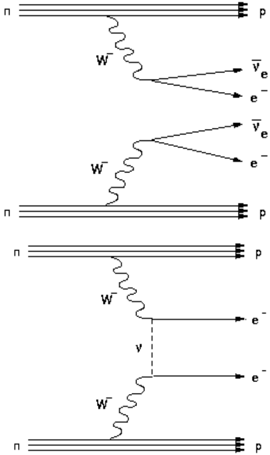
Open Questions in Neutrino Physics

- **Neutrino mass**



- **Neutrino nature**

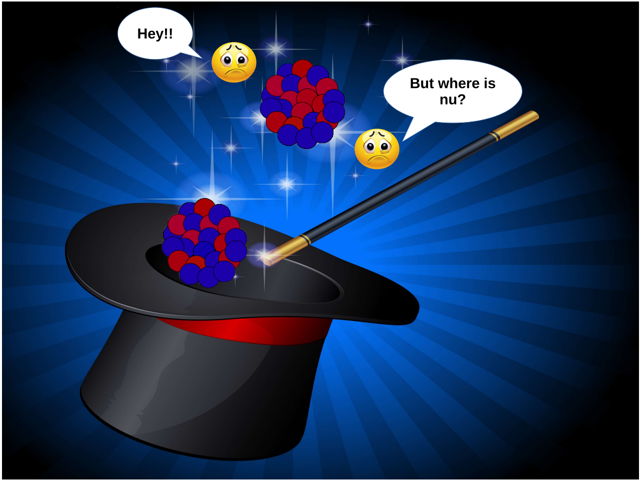


Observation of $0\nu\beta\beta$ decay could answer some of these questions.

If $0\nu\beta\beta$ decay is observed...

what is driving the decay?

$$[T^{0\nu}_{1/2}]^{-1} = \sum_i G_i^{0\nu}(Q,Z)|M^{0\nu}|^2\eta_i^2$$



If $0\nu\beta\beta$ decay is observed...

$$[T^{0\nu}_{1/2}]^{-1} = \sum_i G^{0\nu}_i(Q,Z)|M^{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

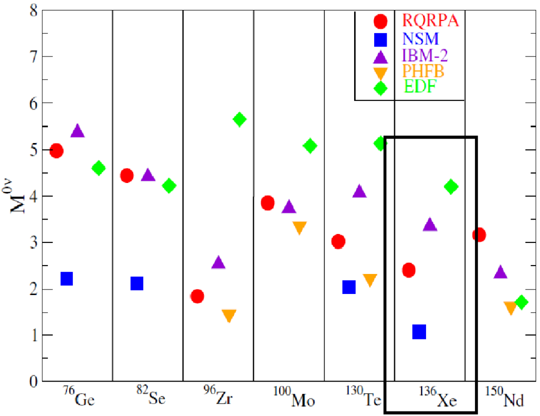
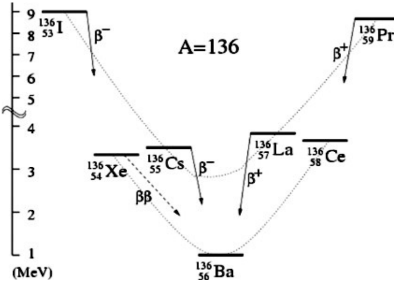
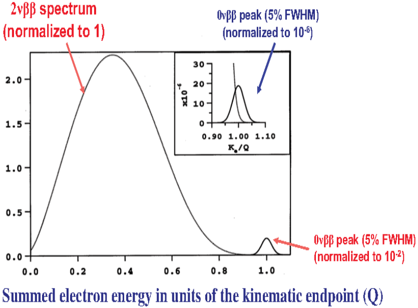


Figure : Petr Vogel, J. Phys. G: Nucl. Part. Phys. **39** 124002 (2012)

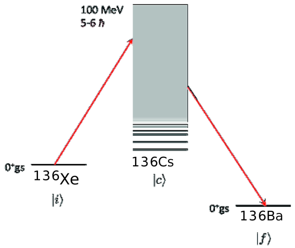
The Case of ^{136}Xe Double Beta Decay





- ^{136}Xe $(N = 82, Z = 54)$ singly closed shell and nearly spherical $\Rightarrow$ matrix element calculations relatively simpler.
- From measured half life, $|\mathrm{M}^{2\nu}| = 0.019$ MeV^{-1} $\Rightarrow$ $2\nu\beta\beta$ decay background suppressed.
- Possibility of the Ba ion tagging allows for maximal background reduction.

Closure approximation and Beyond



- Usually NME calculations done using the closure approximation[1]
- This introduces $\sim 10\%$ uncertainity in $\mathrm{M}^{0\nu}$
- Recently, theoretical approaches have tried to move beyond the closure approximation.[2].

- Mixed approach: non-closure for low excitation energies closure for high excitation energy.

- Experimental information about low lying states in the intermediate nucleus would be beneficial.

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[1] Horoi M and Stoica S 2010 *Phys. Rev.* C **81**, 024321

[2] A. Brown, M.Horoi and R.Sen'kov. Phys. Rev. Lett.**113**,262501 (2014).

Knowledge of low-lying excited states in ^{136}Cs

2009 ^{136}Cs Levels

E(level)	Jπ†	$T_{1/2}$	Comments
0.0	5		μ=+3.71 *2* (1981Th06).
x	8	19 s *2*	$T_{1/2}$: from 1975Ra03. μ=+1.319 *7* (1989Ra17,1981Th06); Q=+0.74 *10* (1989Ra17,1981Th06). %IT>0. Q: includes polarization correction. %IT: Suggested by evaluator from the observation of Cs x-rays by 1975Ra03.

K. WIMMER *et al.* PHYSICAL REVIEW C **84**, 014329 (2011)

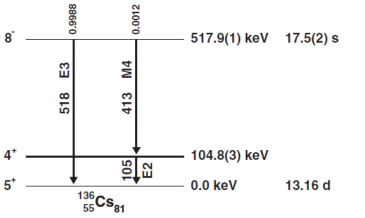
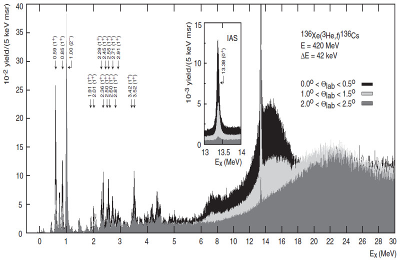


FIG. 3. Proposed level scheme of ^{136}Cs. Previously known were only the spins of the ground state and the isomeric state as well as the half-life of ^{136}Cs.

PHYSICAL REVIEW C **84**, 051305(R) (2011)

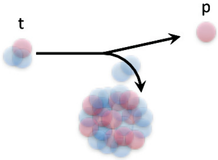


PHYSICAL REVIEW C **95**, 034619 (2017)

- ^{136}Cs is an odd-odd nucleus ⇒ higher density of states.

Pairing and Double Beta Decays

- QRPA calculations assume the GS of even-even nuclei to be a BCS sea of neutron and proton pairs.
- BCS is not valid in nuclei that fall within regions of changing shapes, or when there is a large gap in single particle states-near a shell closure.



- Experimental probe for pair correlations - a pair-transfer reaction:
  n-pair transfer - (p, t), (t, p)
  p-pair transfer - $(^3\mathrm{He}, \mathrm{n})$, $(\mathrm{n}, ^3\mathrm{He})$.
- Strong population of the excited 0^+ states in these reactions would imply breakdown of the BCS approximation.

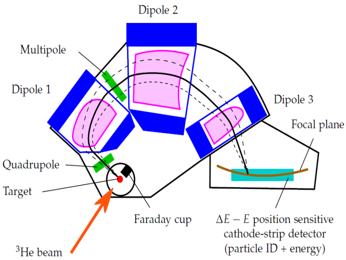
In summary, this talk focusses on work done to

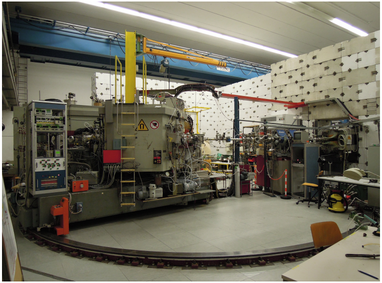
- Further improve our knowledge about low-lying states in the intermediate $^{136}\mathrm{Cs}$ nucleus.
- Study neutron pairing correlations in the $^{136}\mathrm{Ba}$ nucleus.

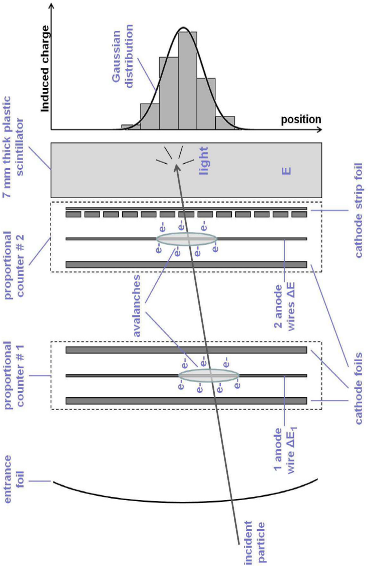
Experimental Details

- $^{138}\mathrm{Ba}(d,\alpha)^{136}\mathrm{Cs}$ - obtain experimental information in the intermediate nucleus.
  $^{138,136}\mathrm{Ba}(p,t)^{136,134}\mathrm{Ba}$ - to study neutron pairing correlations.
- Beam Details : 22 MeV unpolarized deutrons, 23 MeV unpolarized protons.
- Target : 40μg/cm^2 ^{138,136}Ba on 30μg/cm^2 on a carbon backing.
- Facility : High Resolution Q3D Magnetic Spectrometer at Maier-Leibnitz-Laboratorium (MLL), Garching (Germany)

Experimental Details : Q3D Magnetic Spectrometer

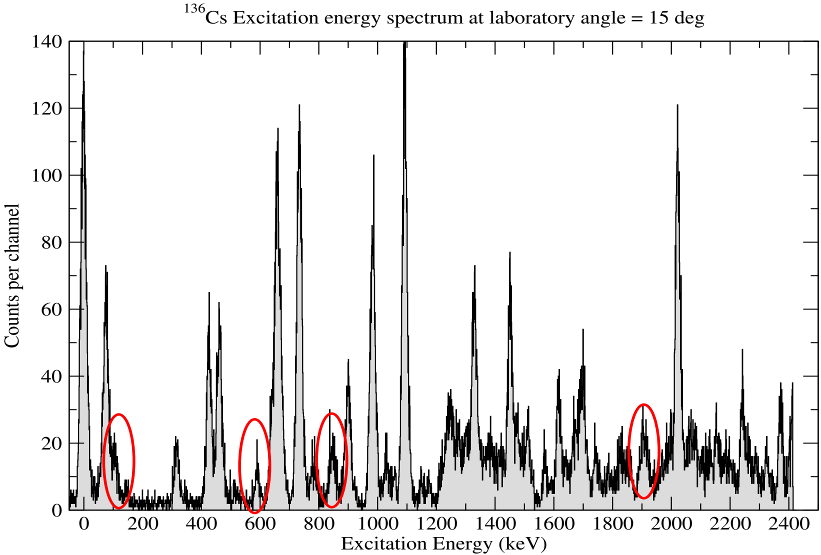






Discussion of results - I

$$^{138}\mathrm{Ba}(\mathrm{d},\alpha)^{136}\mathrm{Cs}$$

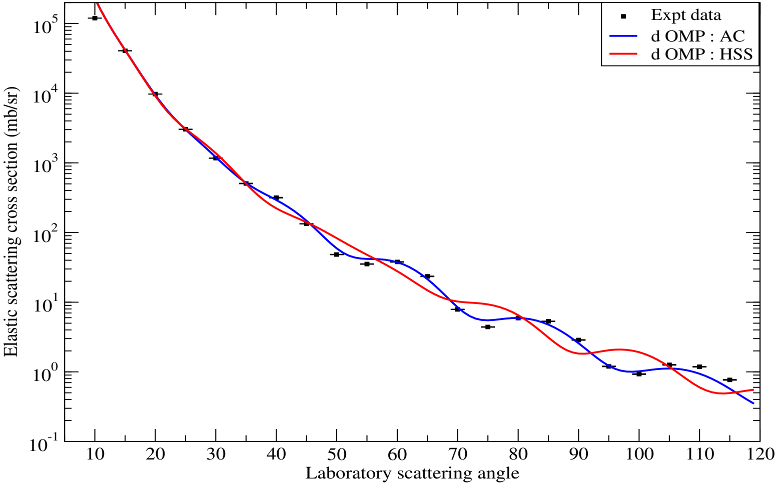


- We identify approx 25 new states in ^{136}Cs upto an excitation energy of 2.4 MeV.
- Resolution $\sim 10 - 12$ keV

$^{138}\mathrm{Ba}(\mathrm{d},\alpha)^{136}\mathrm{Cs}$

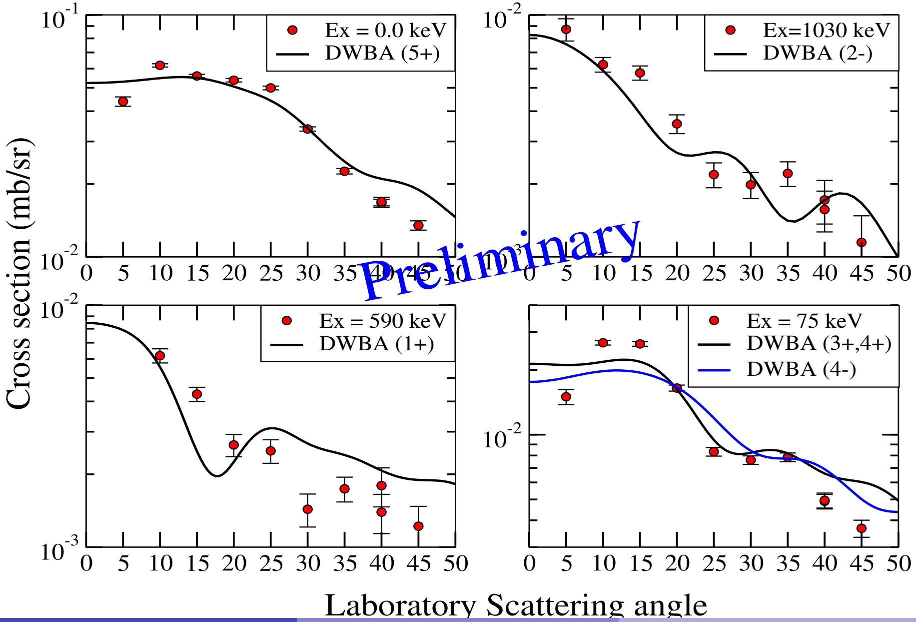
- Depending on the energy of the incident deutron, various multipolarity states can be populated.
- Selectivity: $J = L \oplus 1$
  $J_f = L+1, L-1$ for unnatural parity states - $1^+, 2^-, ...$
  $J_f = L$ for natural parity states - $1^-, 2^+, ...$
- J^π assignments can be made easily by comparing experimental cross-sections with theoretical predictions using DWBA codes, e.g. DWUCK4.
- DWBA calculation done assuming an optical model potential, with OMP parameters obtained from global OMP sets.
- OMP for deutron : H. An and C. Cai. Phys. Rev. C **73**, 054605 (2006).
- OMP for alpha : L. McFadden and G.R.Satchler. Nucl. Phys. A **84**, 177-200 (1966).

^{138}Ba - deutron optical model potential selection



- AC - An and Cai. Phys. Rev. C **73**, 054605 (2006)
- HSS - Han, Shi, and Shen, Phys. Rev. C 74, 044615 (2006).

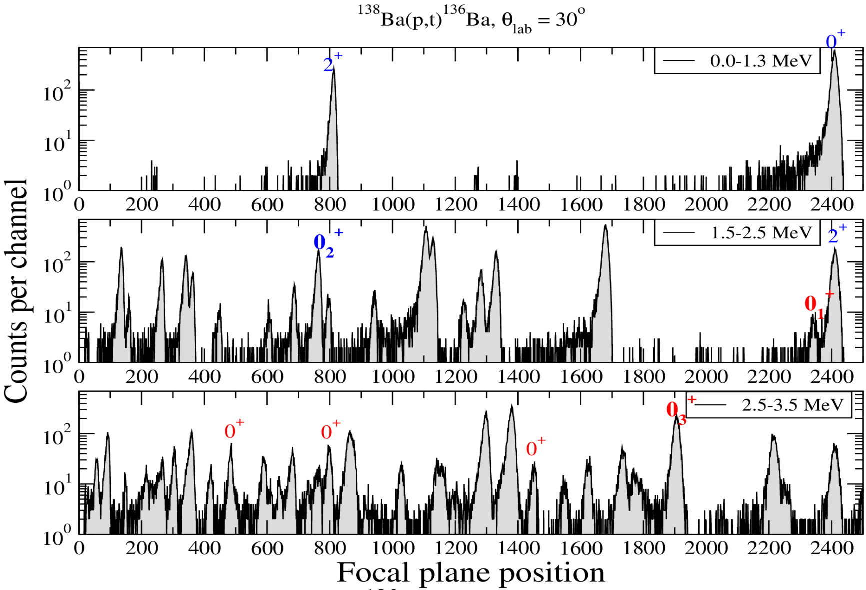
$^{138}Ba(d,\alpha)^{136}Cs$ Spin-Parity Assignments



Discussion of results - I

$$^{138}\mathrm{Ba(p,t)}^{136}\mathrm{Ba}$$
$$^{136}\mathrm{Ba(p,t)}^{134}\mathrm{Ba}$$

Preliminary Results : $^{138}\mathrm{Ba(p,t)}^{136}\mathrm{Ba}$



We identify 5 new 0^+ states in $^{136}\mathrm{Ba}$.

$^{136}\mathrm{Ba}(\mathrm{p,t})^{134}\mathrm{Ba}$

- The (p,t) reaction allows for only natural parity states to be populated.

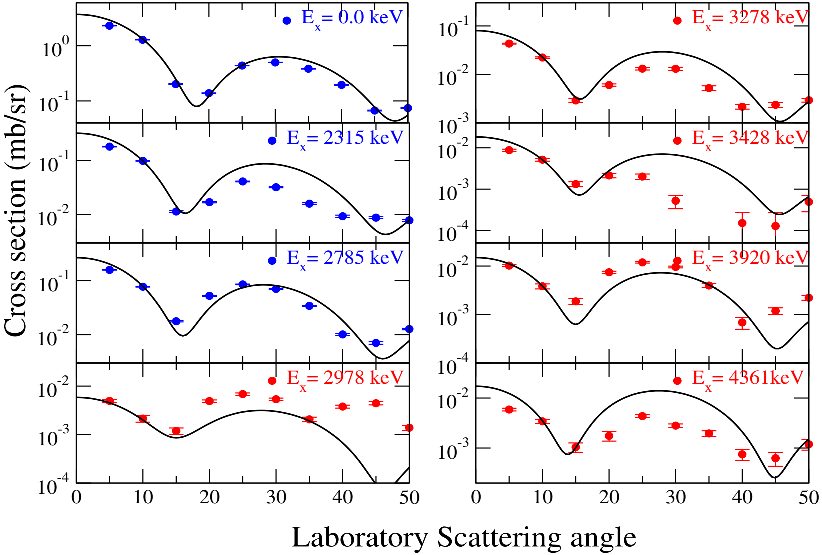
- Selectivity: $J = L$, $\pi = (-1)^L$

- Similar to the case of (d, α), J^π assignments can be made easily by comparing experimental cross-sections with theoretical predictions using DWBA codes using the optical model potential best reproducing the elastic scattering data.

- OMP for protons : A. J. Koning and J. P. Delaroche. Nucl. Phys. A **713**, 231-310 (2003).

- OMP for tritons : X. Li, C. Liang and C.Cai. Nucl. Phys. A **789**, 103-113 (2007).

Identification of 0^+ states in ^{136}Ba

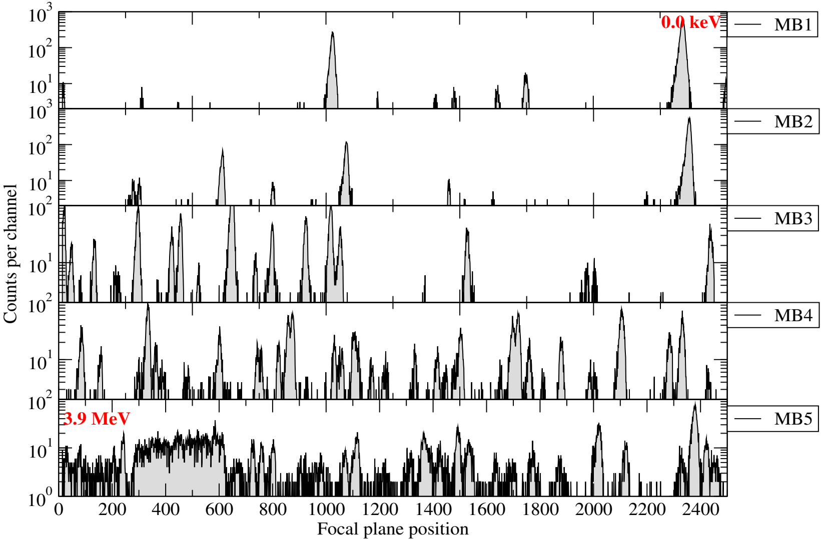


Preliminary Results -Strength of excited 0^+ states in $^{138}\mathrm{Ba(p,t)}^{136}\mathrm{Ba}$

$\mathrm{E_x}$ (keV)	$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{rel}}$ at $\theta = 5^\circ$	$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{rel}}$ at $\theta = 10^\circ$
2315 (0_2^+)	10.1(8)	11.3(9)
2785 (0_3^+)	10.1(1)	10.4(1)
2978	5.1(4)	4.1(6)
3278	3.21(7)	3.6(1)
3428	0.68(4)	0.88(7)
3920	1.07(5)	0.9(1)

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{rel}} = \frac{\left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{lab}}_{0^+_{\mathrm{ex}}}}{\left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{dwba}}_{0^+_{\mathrm{ex}}}} \Bigg/ \frac{\left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{lab}}_{0^+_{\mathrm{gs}}}}{\left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{dwba}}_{0^+_{\mathrm{gs}}}}$$

Preliminary Results: $^{136}\mathrm{Ba}(\mathrm{p,t})^{134}\mathrm{Ba}$, $\theta_{lab} = 25$ deg



Experiment performed in July 2017 .

Data analysis part of M.Sc. thesis of Jespère Ondzé (UWC).

Conclusions

- $^{138}\mathrm{Ba(d,\alpha)}^{136}\mathrm{Cs}$
  1. Identified 25 new states in $^{136}\mathrm{Cs}$.
  2. Angular distribution analysis in progress.
- $^{138}\mathrm{Ba(p,t)}^{136}\mathrm{Ba}$
  1. Identified 5 new 0^+ states in $^{136}\mathrm{Ba}$.
  2. Preliminary analysis show the $\ell = 0$ strength of the 0^+_2 and 0^+_3 states relative to the ground state $\sim 10\%$.
- $^{136}\mathrm{Ba(p,t)}^{134}\mathrm{Ba}$
  1. Experiment performed in July 2017, analysis in progress.

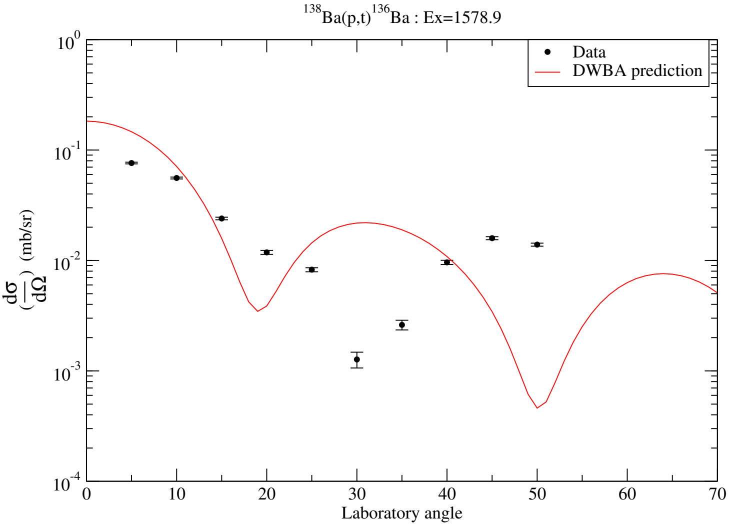
Collaborators

- **University of the Western Cape, Cape Town**: S. Triambak, R. Lindsay, J. Ondzé, M. Kamil, P.Z. Mabika
- **University of Guelph, Canada**: P.E. Garrett, C. Burbadge, V. Bildstein, A. Diaz-Varela, E. Rand, A. Radich,
- **IPN, Orsay**: P. Adsley
- **TRIUMF, Canada**: G.C. Ball
- **LMU, Munich**: R. Hertenberger, H.F. Wirth
- **TUM, Munich**: T. Faestermann
- **Colorado School of Mines**: K. Leach

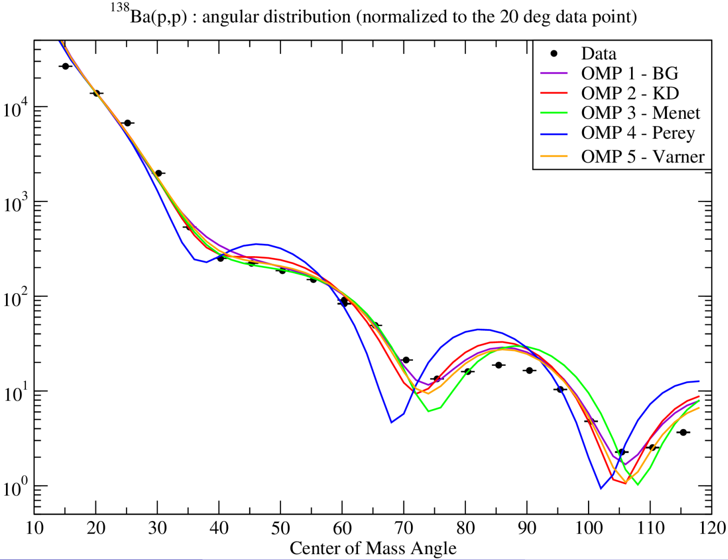
SOMEWHERE, SOMETHING INCREDIBLE IS WAITING TO BE KNOWN

CARL SAGAN

Back Up Slides : Ex=1578.9 keV in ^{136}Ba



Elastic Scattering Angular Distribution for the $^{138}\mathrm{Ba}(\mathrm{p},\mathrm{t})$ experiment



Status of Pairing in $\beta\beta$ decay nuclei

SYSTEM	DATA	COMMENTS
^{76}Ge-Se	New data.	BCS approximation good. Pairing similar across parent and daughter.
^{82}Se-Kr	Sparse data: Se(t,p) only.	Difficult to be definitive, but some evidence of fragmentation in neutron pair removal.
^{100}Mo-Ru	New (p,t) data.	Fragmentation due to deformation, parent-daughter differences. Overall pairing looks similar across parent and daughter.
^{130}Te-Xe	New (p,t) data.	Neutron BCS approximation good. Proton pairing vibration associated with Z=64.
^{136}Xe-Ba	Some relevant data available.	Apparent influence of pairing vibrations associated with Z=64.
^{150}Nd-Sm	Extensive data in literature	Fragmentation due to deformation in neutron transfer.

Some evidence of breaking of BCS in ALL these cases, except for ^{76}Ge-Se.

Adapted from S. Freeman's talk from the TRIUMF Double Beta Decay Workshop, May 2016.