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

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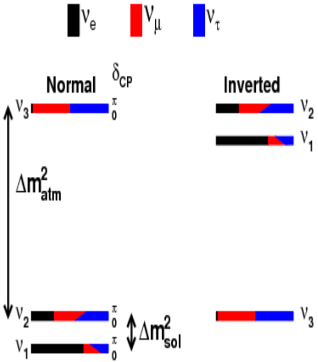
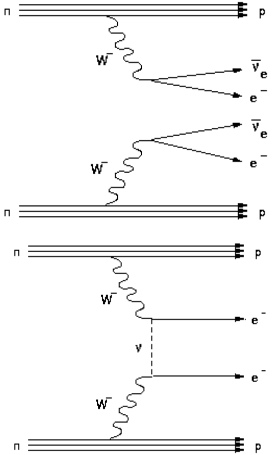
Open Questions in Neutrino Physics

- **Neutrino mass**



- **Neutrino nature**

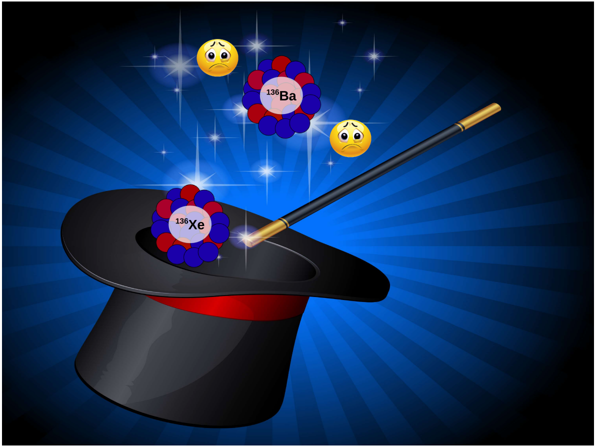


Observation of $0\nu\beta\beta$ decay could answer some of these questions.

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

what is driving the decay?

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



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

If light LH Majorana neutrino

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

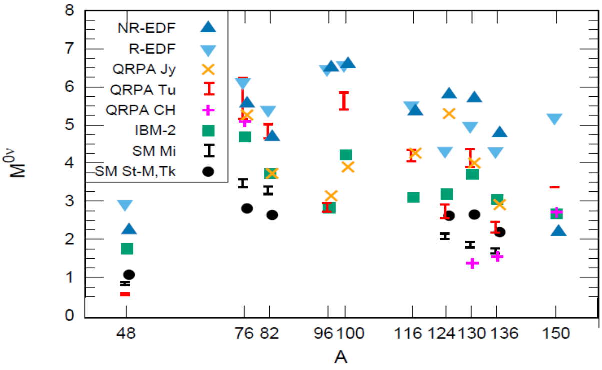
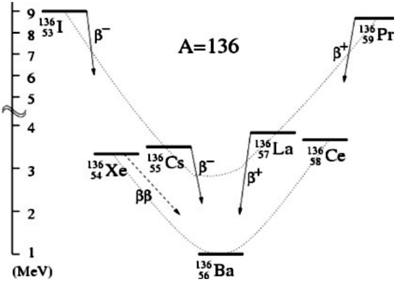
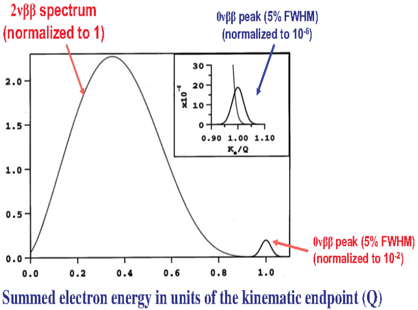


Figure : J. Engel and J. Menéndez, Reports on Progress in Physics, **80**, 4 (2017)

The Interesting Case of $^{136}\mathrm{Xe} \rightarrow^{136} \mathrm{Ba}$



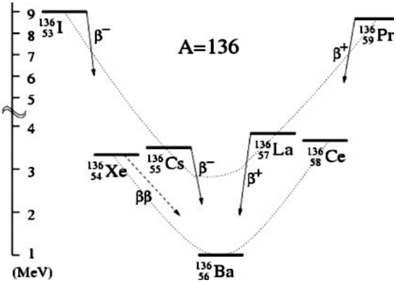

2νββ spectrum (normalized to 1)

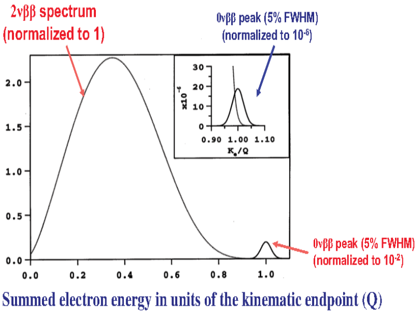
0νββ peak (5% FWHM) (normalized to 10^{-6})

0νββ peak (5% FWHM) (normalized to 10^{-2})

- $^{136}\mathrm{Xe}$ $(N = 82, Z = 54)$ singly closed shell and nearly spherical $\Rightarrow$ matrix element calculations relatively simpler.
- From measured half life, $|\mathrm{M}^{2\nu}| = 0.021$ MeV^{-1} $\Rightarrow$ $2\nu\beta\beta$ decay background suppressed.

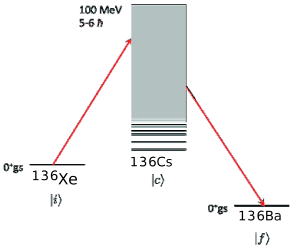
The Interesting Case of $^{136}\mathrm{Xe} \rightarrow ^{136}\mathrm{Ba}$





- $^{136}\mathrm{Xe}$ is relatively abundant, affordable and easy to purify.
- Decay has a large Q value (~ 2.5 MeV) ⇒ beta endpoint not plagued by room backgrounds.
- 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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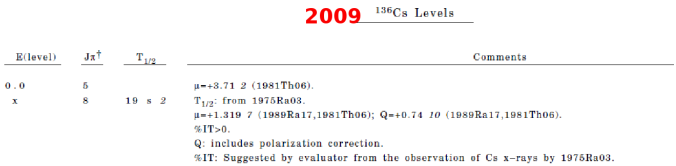
[1] Horoi M and Stoica S 2010 *Phys. Rev.* C **81**, 024321

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

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



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)

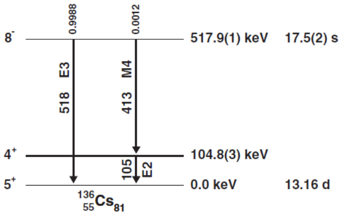
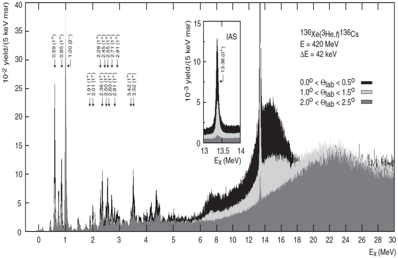


FIG. 3. Proposed level scheme of ^{136}Cs. Previously known were only the spins of the ground state and the isomeric state as well as the half-life of ^{136}Cs.

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

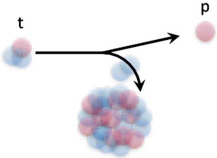


PHYSICAL REVIEW C **95**, 034619 (2017)

- $^{136}\mathrm{Cs}$ 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 - $(\mathrm{p,t})$, $(\mathrm{t,p})$
  p-pair transfer - $(^3\mathrm{He,n})$, $(\mathrm{n,^3He})$.
- Strong population of the excited 0^+ states in these reactions would imply breakdown of the BCS approximation.

Pairing and Double Beta Decays : ^{136}Ba

- 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.

- Any structural difference between the initial and final nucleus tends to reduce the NME.

- Ba isotopes belong to a transitional region.[3]

- (p, t) reaction on lighter $^{(128-134)}$Ba isotopes have shown strong population of excited 0^+ states. [4]

- Pairing studies in ^{136}Ba and ^{136}Xe would be useful to constain NME calculations.

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[3] Pascu *et. al* PRC **81, 014304 (2010).**

[4] Pascu *et. al PRC* **79, 064323 (2009).**

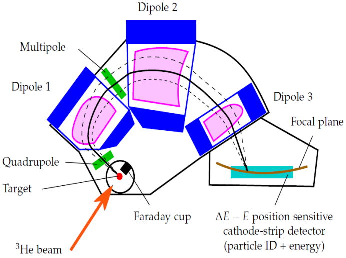
In summary, this talk focusses on work done to

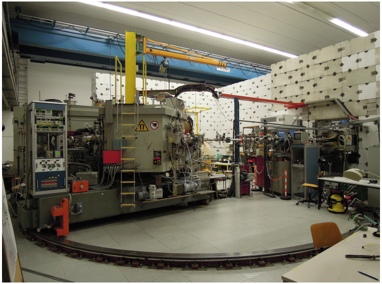
- Further improve our knowledge about low-lying states in the intermediate $^{136}\mathrm{Cs}$ nucleus.
- Study neutron pairing correlations in the $^{136}\mathrm{Ba}$ nucleus.

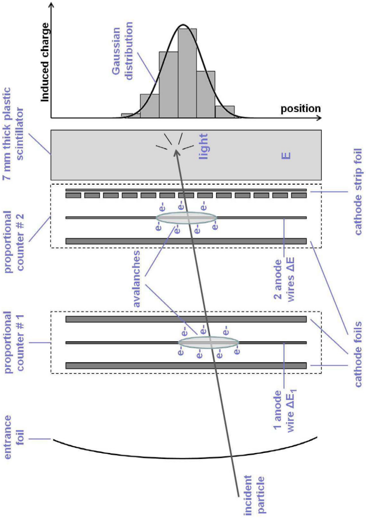
Experimental Details

- $^{138}\mathrm{Ba}(d,\alpha)^{136}\mathrm{Cs}$ - 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 deutrons, 23 MeV 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

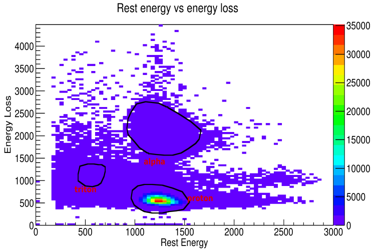


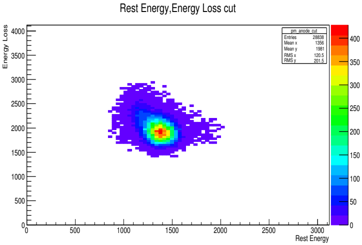


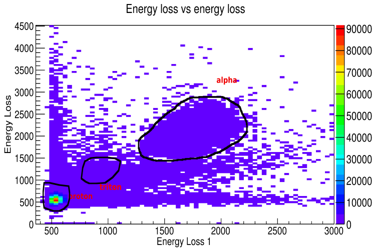


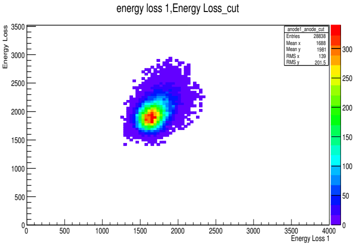
$$\Delta E \sim 10 - 12 \text{ keV}$$

Gating for particle identification


Rest energy vs energy loss


Rest Energy,Energy Loss cut

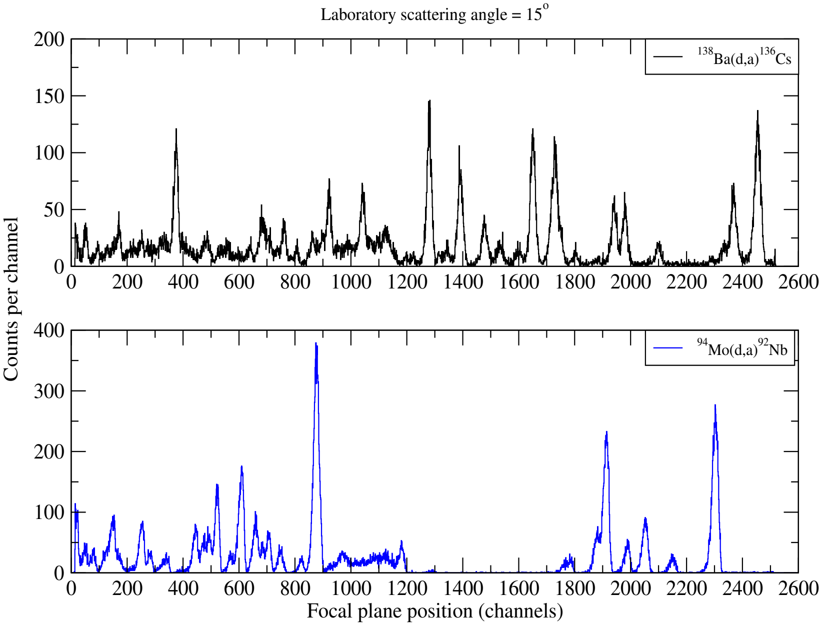

Energy loss vs energy loss


energy loss 1,Energy Loss_cut

Discussion of results - I

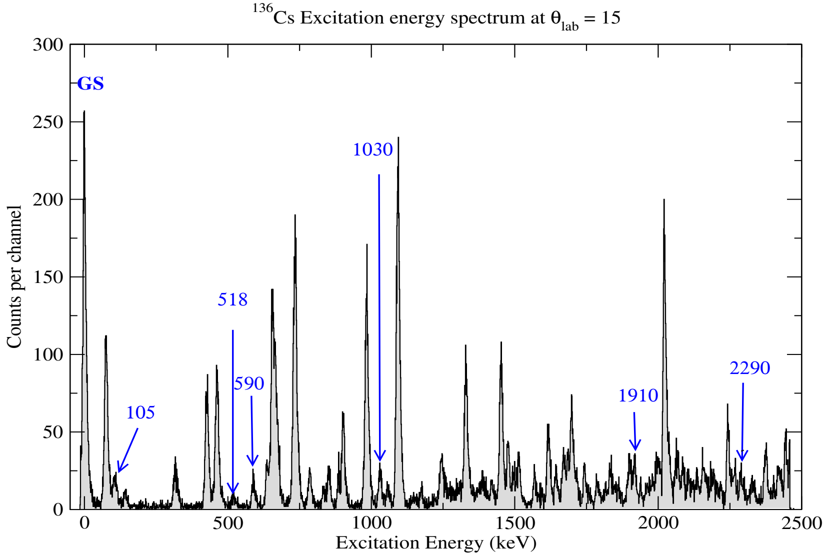
$$^{138}\mathrm{Ba}(\mathrm{d},\alpha)^{136}\mathrm{Cs}$$

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



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

- Target 1. 40μg/cm^2 ^{138}BaCO$_3$ on 30μg/cm^2 of carbon backing.
- Target 2. 100μg/cm^2 ^{94}MoO$_3$ on 40μg/cm^2 of carbon backing.
- Calibration done in α momentum, assuming reaction occurs at center of target.
- Systematic effects,
    1. Reaction location.
    2. d and α energy loss is targets.
    3. Stopping power from SRIM.
    4. Beam energy.
    5. Target thickness.



- We identify approx 50 new states in ^{136}Cs upto an excitation energy of 2.4 MeV.
- Resolution ~ 12 keV.

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

- Selectivity: $J = L \pm 1$
  $J_f = L+1, L-1$ for unnatural parity states $(1^+, 2^-, ...)$
  $J_f = L$ for natural parity states $(1^-, 2^+, ...)$
- DWBA calculation done assuming a single-step stripping of a 'deuteron' so that the transfered proton-neutron pair *only* couple to $S = 1$ and $T = 0$.[5]
- Furthermore, the large (positive) Q-value for the (d, α) reaction allows for larger L values to be transfered, favoring transitions to states with (reasonably) higher angular momentum.[6]

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[5] Glendenning NK. *Phy. Rev.* **137**, 1B (1965).

[6] Rivet E, Pehl RH, Cerny J and Harvey BG. *Phy. Rev.* **141**, No. 3 (1966).

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

- Selectivity: $J = L \pm 1$
  $J_f = L+1, L-1$ for unnatural parity states $(1^+, 2^-, ...)$
  $J_f = L$ for natural parity states $(1^-, 2^+, ...)$
- DWBA code used - DWUCK4.
- 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).

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

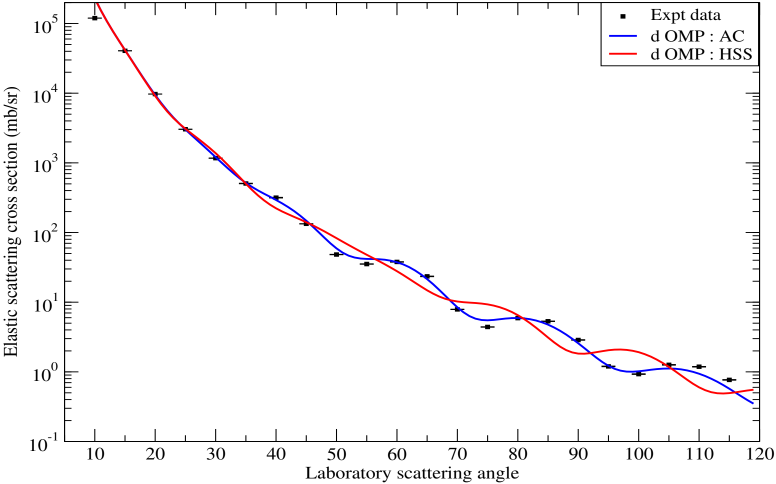
- Selectivity: $J = L \pm 1$
  $J_f = L+1, L-1$ for unnatural parity states $(1^+, 2^-, ...)$
  $J_f = L$ for natural parity states $(1^-, 2^+, ...)$
- To assign J^π, compare experimental cross-sections with DWBA predictions and normalize.
- Natural parity states :

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{expt}} = \alpha \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{DWBA:J=L}}$$

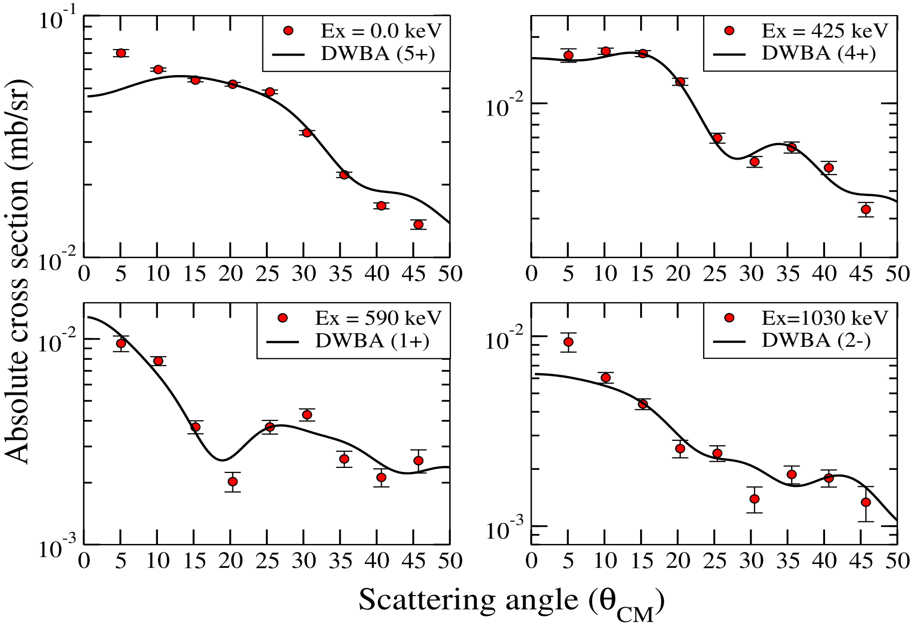
- Unnatural parity states

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{expt}} = \beta \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{DWBA:J=L+1}} + \gamma \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{DWBA:J=L-1}}$$

$d-^{138}$Ba optical model potential selection



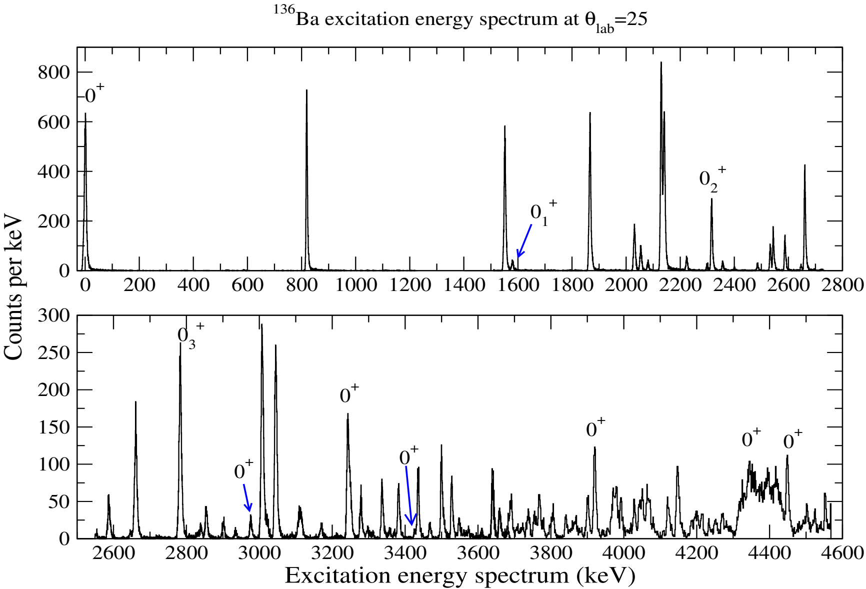
- AC - H. An and C. Cai. Phys. Rev. C **73**, 054605 (2006).
- HSS - Han, Shi, and Shen, Phys. Rev. C **74**, 044615 (2006).


Ex = 0.0 keV
DWBA (5+)
Ex = 425 keV
DWBA (4+)
Ex = 590 keV
DWBA (1+)
Ex=1030 keV
DWBA (2-)
10^{-1}
10^{-2}
10^{-3}
0 5 10 15 20 25 30 35 40 45 50
Absolute cross section (mb/sr)
Scattering angle (θ_{CM})

Discussion of results - II

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

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

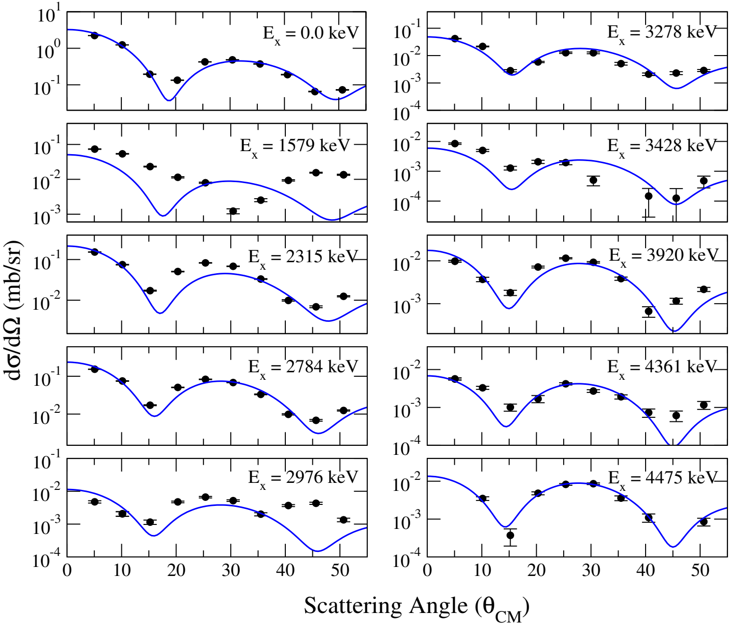


We identify 6 new 0^+ states in $^{136}\mathrm{Ba}$.

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

- The (p,t) reaction preferably selects natural parity states.
- $J = L$, $\pi = (-1)^L$
- J^π assignments made by comparing experimental cross-sections with DWBA predictions.
- OMP for protons : R. L. Varner. Phys. Rpts. **201**, No. 2, 57-119 (1991).
- OMP for tritons : X. Li, C. Liang and C.Cai. Nucl. Phys. A **789**, 103-113 (2007).

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

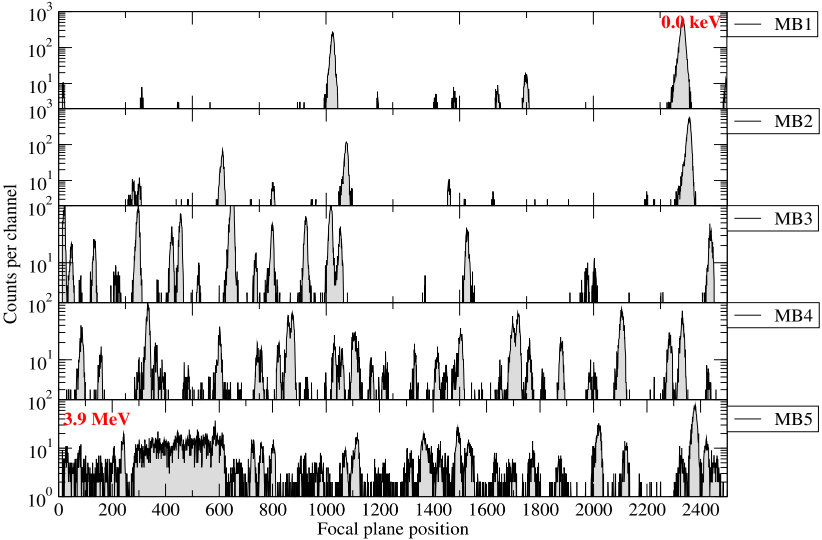


Preliminary Results -Strength of excited 0^+ states in $^{138}\mathrm{Ba(p,t)}^{136}\mathrm{Ba}$

$\mathrm{E_x}$ (keV)	$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{rel}}$ at $\theta = 10^\circ$
2315 (0_2^+)	11.3(9)
2785 (0_3^+)	10.4(1)
2976	4.1(6)
3278	3.6(1)
3428	0.88(7)
3920	0.9(1)
4361	2.2(2)

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Rel}} = \left(\frac{\left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{Lab}}_{0^+_{\mathrm{ex}}}}{\left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{DWBA}}_{0^+_{\mathrm{ex}}}}\right)\left(\frac{\left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{Lab}}_{0^+_{\mathrm{gs}}}}{\left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{DWBA}}_{0^+_{\mathrm{gs}}}}\right)^{-1}$$

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



Experiment performed in July 2017. Analysis in progress.

Conclusions

- $^{138}\mathrm{Ba}(\mathrm{d},\alpha)^{136}\mathrm{Cs}$
  1. Identify 50 new states in $^{136}\mathrm{Cs}$.
  2. Angular distribution analysis complete.
- $^{138}\mathrm{Ba}(\mathrm{p},\mathrm{t})^{136}\mathrm{Ba}$
  1. Identify 6 new 0^+ states in $^{136}\mathrm{Ba}$ in addition to several other states above 2.5 MeV.
  2. Preliminary analysis show the $\ell = 0$ strength of the 0_2^+ and 0_3^+ states relative to the ground state $\sim 10\%$ for each.
- $^{136}\mathrm{Ba}(\mathrm{p},\mathrm{t})^{134}\mathrm{Ba}$
  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, N.J.Orce.
- **University of Guelph, Canada**: P.E. Garrett, C. Burbadge, V. Bildstein, A. Diaz-Varela, E. Rand, A. Radich.
- **IPN, Orsay, iThemba LABS, SA**: P. Adsley.
- **TRIUMF, Canada**: G.C. Ball.
- **LMU, Munich**: R. Hertenberger, H.F. Wirth.
- **TUM, Munich**: T. Faestermann.
- **Colorado School of Mines**: K. Leach.