

Sub-Barrier Coulomb Excitation of $^{106,108,110}\text{Sn}$

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for the IS418 collaboration REX-ISOLDE, CERN

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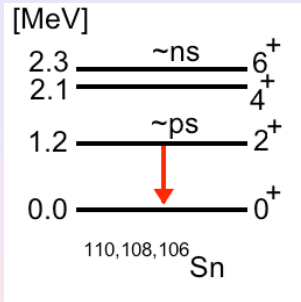
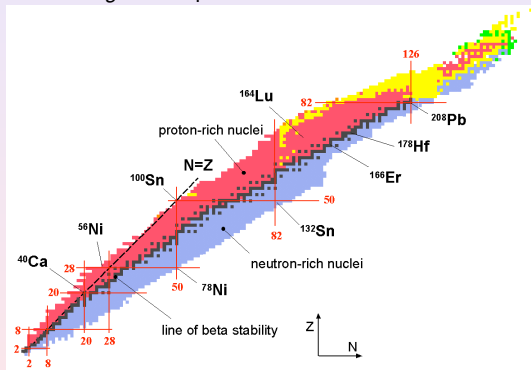
²PH Department
CERN

EGP-Workshop Paris 2008

- 1 Introduction
 - Purpose of Experiment
 - Seniority and Shell-Model Calculations
- 2 Experiment
 - ISOLDE
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- 3 Analysis
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 - Present Situation Towards $N = Z = 50$
 - Outlook

Purpose of Experiment

$B(E2; 0_{gs}^+ \rightarrow 2_1^+)$ in $^{110,108,106}\text{Sn}$



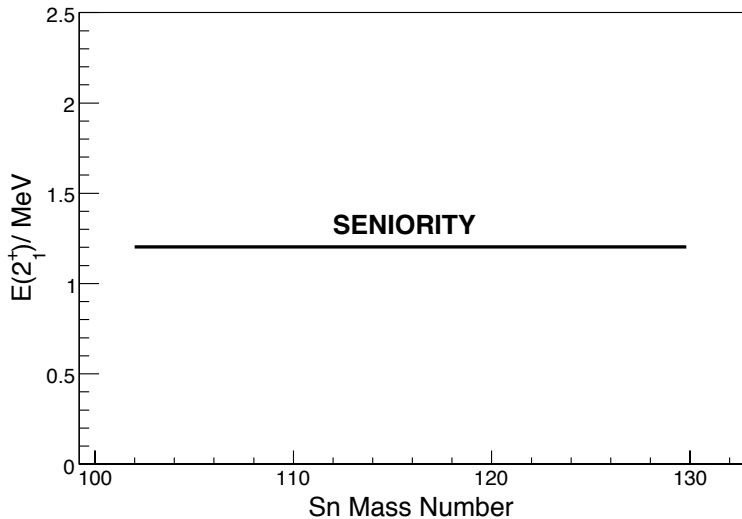
Energy of 2_1^+

$$^{110}\text{Sn}: E(2_1^+) = 1.212 \text{ MeV}$$

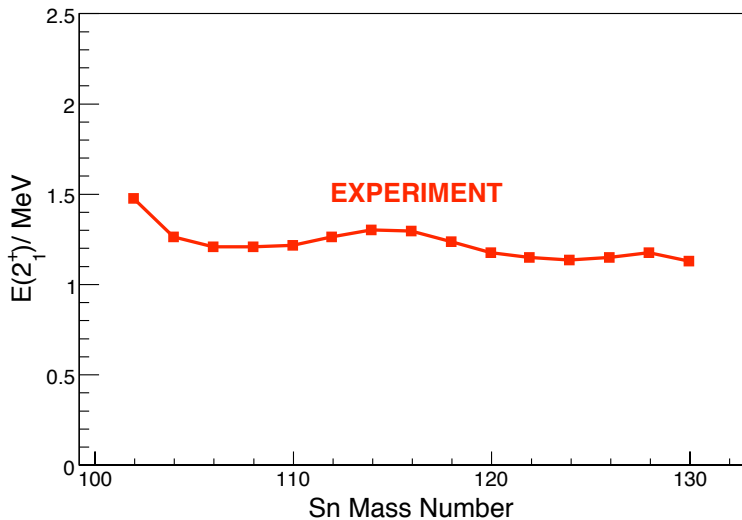
$$^{108}\text{Sn}: E(2_1^+) = 1.206 \text{ MeV}$$

$$^{106}\text{Sn}: E(2_1^+) = 1.206 \text{ MeV}$$

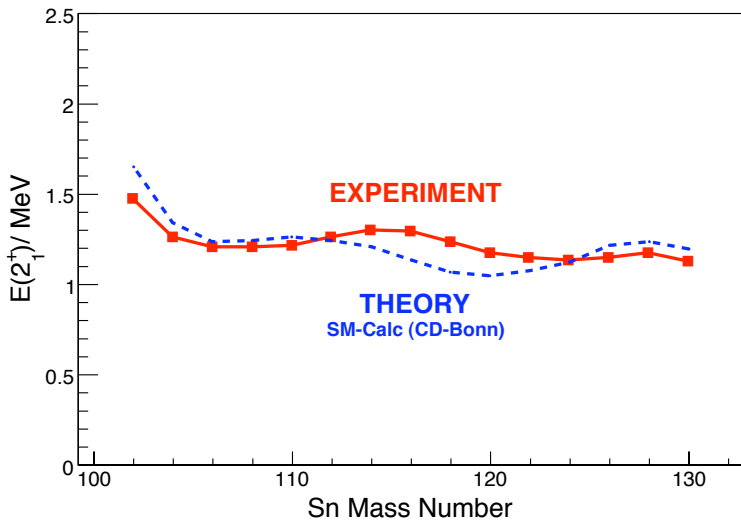
$E(2^+)$ in the Even-Mass Sn Isotopes



$E(2^+)$ in the Even-Mass Sn Isotopes



$E(2^+)$ in the Even-Mass Sn Isotopes



$B(E2)$ in the Even-Mass Sn Isotopes

Experimental Data A=116-130

Exhibit expected parabolic behaviour

SM-Calculation I

Not including any excitations across the $N = Z = 50$ gap

A. Banu *et al.* PRC (2005)

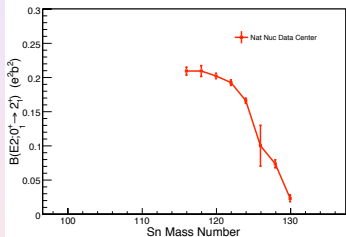
Experimental Data A=112,114

Deviation from parabolic trend

SM-Calculation II

Including proton excitations across the $Z = 50$ gap

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$B(E2)$ in the Even-Mass Sn Isotopes

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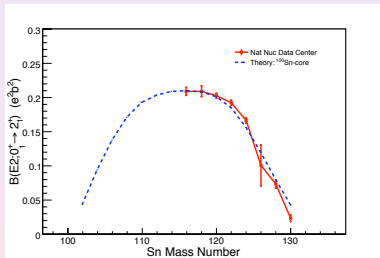
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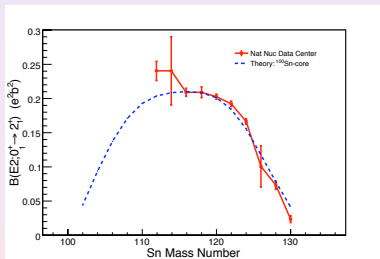
A. Banu *et al.* PRC (2005)

Experimental Data A=112,114

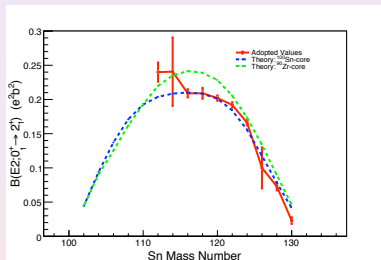
Deviation from parabolic trend

SM-Calculation II

Including proton excitations across the $Z = 50$ gap A. Banu *et al.* PRC (2005)



$B(E2)$ in the Even-Mass Sn Isotopes



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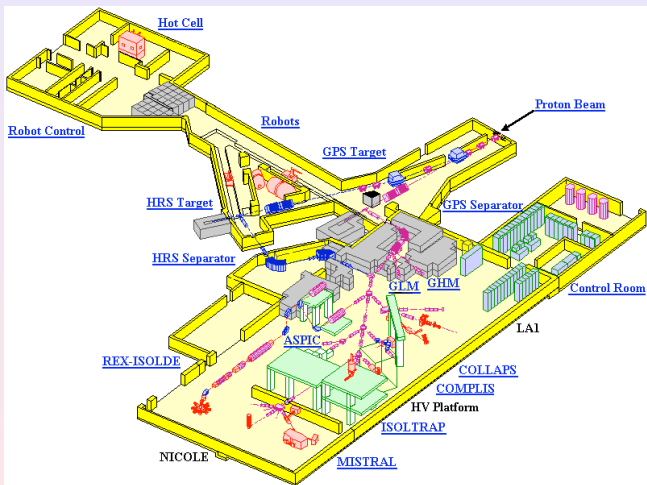
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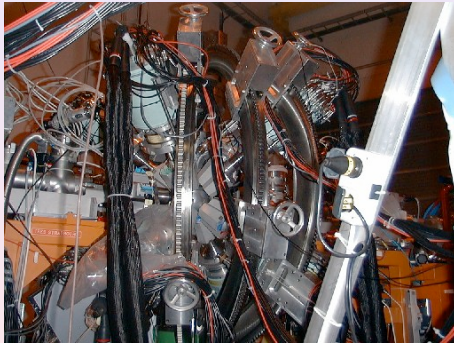
ISOLDE

Isotope Separator On-Line



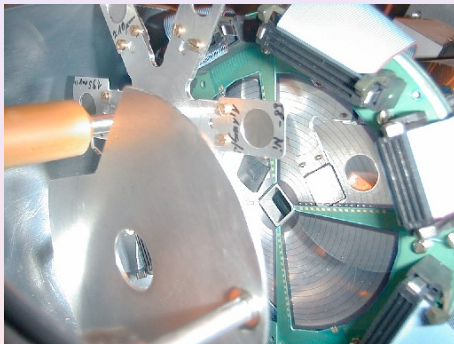
MINIBALL

γ -ray detector



DSSSD

Double Sided Silicon Strip Detector

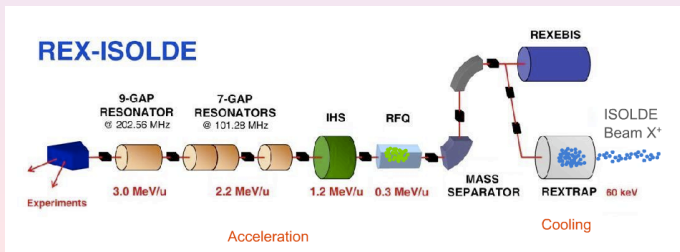


REX-ISOLDE

Radioactive beam EXperiment at ISOLDE

$^{110,108,106}\text{Sn}$ Experiment with REX

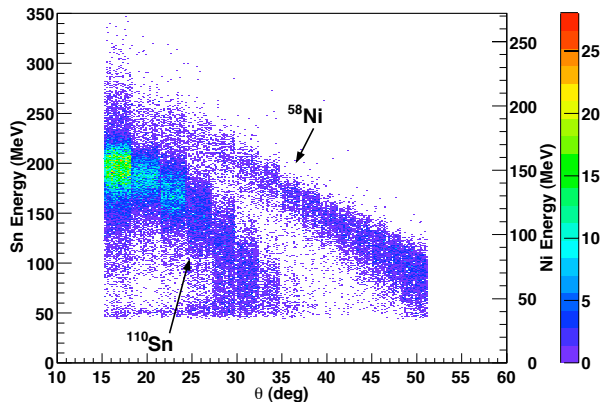
Isotope	Energy [MeV/u]	Sn Fraction [%]	Target
^{110}Sn	2.82	90.0(14)	2.0 mg/cm ² ^{58}Ni
^{108}Sn	2.82	59.0(27)	2.0 mg/cm ² ^{58}Ni
^{106}Sn	2.83	29.2(42)	2.0 mg/cm ² ^{58}Ni



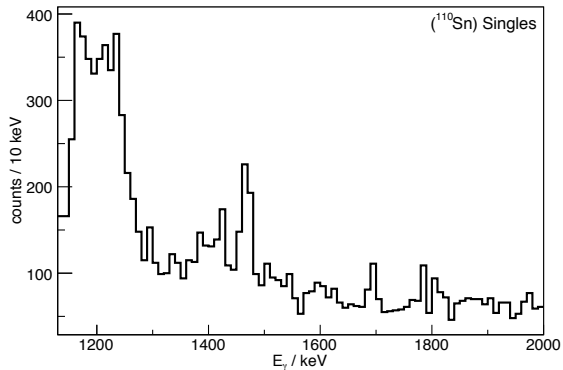
Particles

Data From ^{110}Sn Experiment

Scattered Particles



Singles



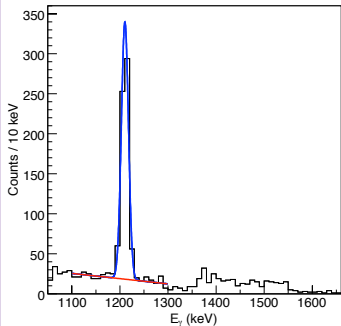
Data Analysis Procedure

- Ejectile (Sn..) Recoil (Ni) selection through kinematical cut
- Prompt particle- γ cuts for each quadrant of the DSSSD
- Selecting only ejectiles and recoils scattered into DSSSD simultaneously (2p events)
- Reconstructing missing particle in 1p events
- γ -ray Addback in order to improve statistics ($\sim 10\%$) ($^{106,108}\text{Sn}$)
- Doppler correction

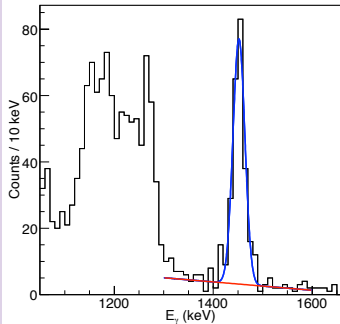
^{110}Sn γ -rays

^{110}Sn J. Cederkall et al. PRL **98**, 172501 (2007)

^{110}Sn



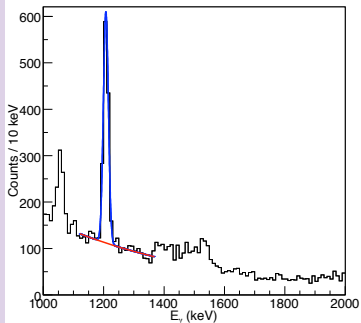
^{58}Ni



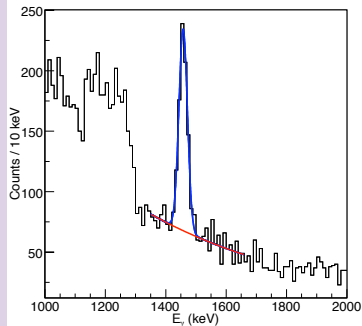
^{108}Sn γ -rays

^{108}Sn Submitted

^{108}Sn



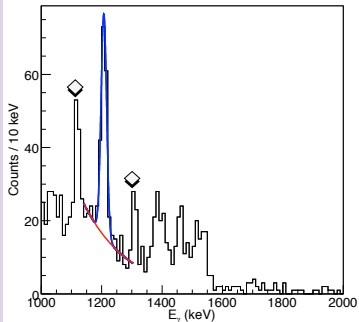
^{58}Ni



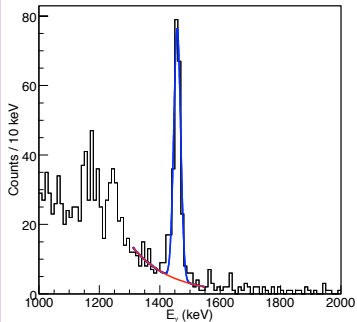
^{106}Sn γ -rays

^{106}Sn Submitted

^{106}Sn



^{58}Ni



Input

- Level scheme and known matrix elements
- Kinematics and detector geometry
- Target thickness and dE/dx
- Angular integration limits
- Internal conversion coefficients, branching ratios...

Output

Minimization routine \Rightarrow

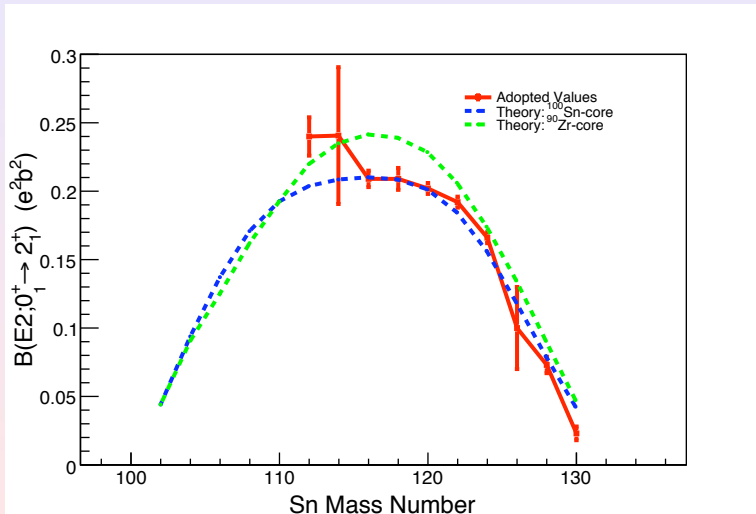
- $B(O\lambda)$ values!
- Angular distribution correction included
- Nuclear deorientation effect included ...

RESULTS, $B(E2; 0_1^+ \rightarrow 2_1^+)$

- $B(E2; ^{110}\text{Sn}) = 0.220(22) e^2b^2$ PRL **98**, 172501 (2007)
- $B(E2; ^{108}\text{Sn}) = 0.222(19) e^2b^2$ (Submitted)
- $B(E2; ^{106}\text{Sn}) = 0.195(39) e^2b^2$ (Submitted)

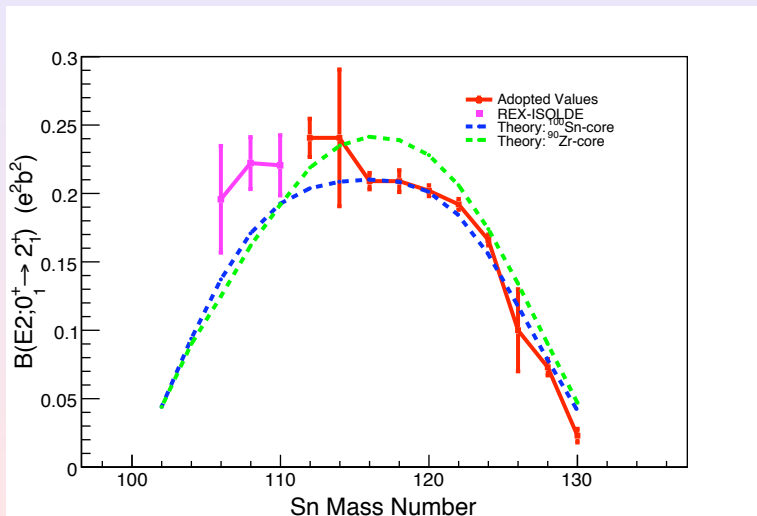
REX-ISOLDE $B(E2)$ -values, $^{110,108,106}\text{Sn}$

Adopted values from A. Banu et al. PRC 72, 061305(R) (2005)



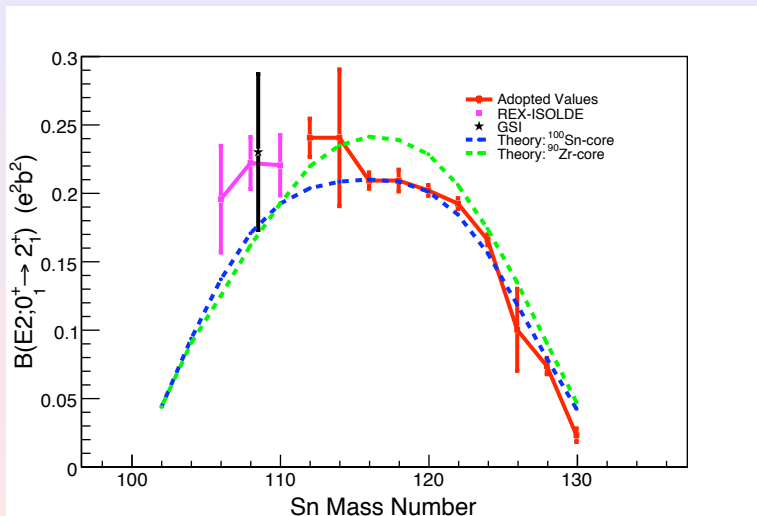
REX-ISOLDE $B(E2)$ -values, $^{110,108,106}\text{Sn}$

REX ^{110}Sn J. Cederkall et al. PRL **98**, 172501 (2007)



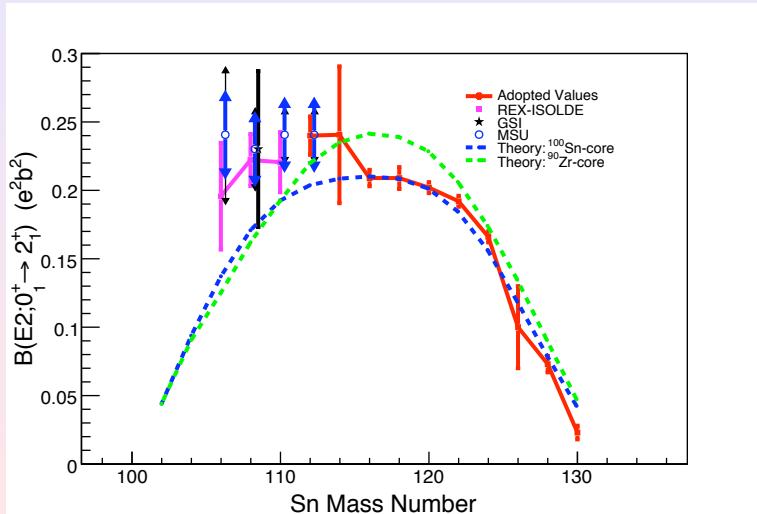
All Data (REX+ Other Published Results)

GSI ^{108}Sn A. Banu et al. PRC 72, 061305(R) (2005)

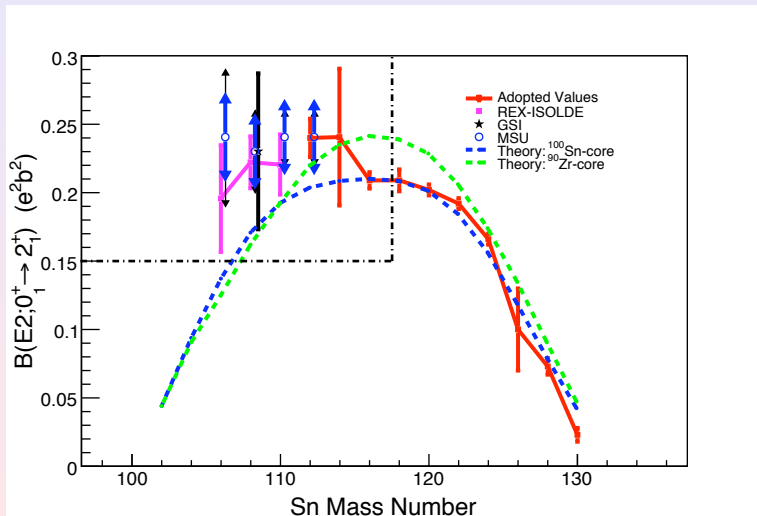


All Data (REX+ Other Published Results)

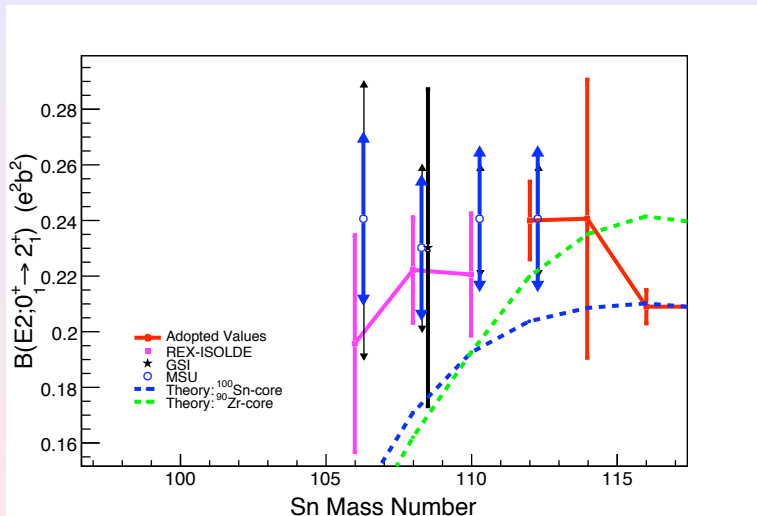
MSU ^{112,110,108,106}Sn C. Vaman et al. PRL **99**, 162501 (2007)



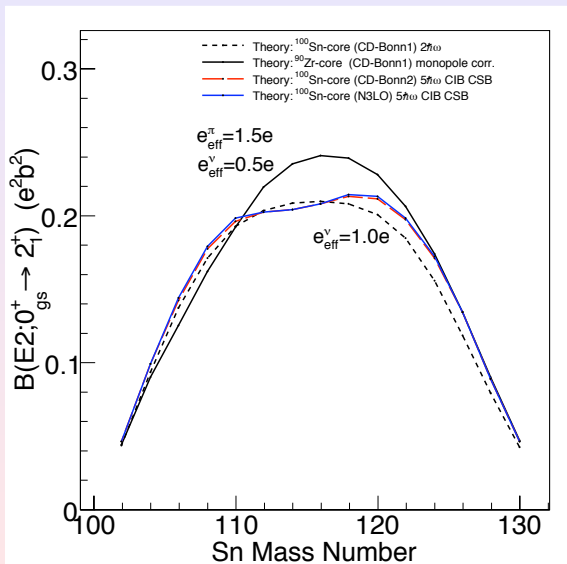
All Data (REX+ Other Published Results) ZOOM



All Data (REX+ Other Published Results) ZOOM



More Calculations (N3LO...)



- Extended shell-model calculations:
 - Increase model space to include **proton**-neutron excitations across the $N = Z = 50$ gap and investigate the impact of the proton/neutron effective charges
 - Spin-orbit partners
 - Strength of the shell closure...
- More experiments in this region needed:
 - Even-mass (100,102,104) neutron-deficient Cd-isotopes this summer
 - Measure ^{104}Sn !

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The End
Thank You For Your Attention!

Appendix

Appendix I: Coulomb Excitation

Semi-Classical Coulomb (Projectile) Excitation Cross Section

$$d\sigma_{E\lambda} = \left(\frac{Z_t e}{\hbar v} \right)^2 a^{-2\lambda+2} B(E\lambda) df_{E\lambda}(\nu, \xi) \quad (1)$$

a - half distance of closest approach

$$a = \frac{Z_p Z_t e^2}{m_0 v} \quad (2)$$

$B(\mathcal{O}\lambda; I_i \rightarrow I_f)$ Definition

$$B(\mathcal{O}\lambda; I_i \rightarrow I_f) = \frac{1}{2I_i + 1} |\langle I_i || \mathcal{O}\lambda || I_f \rangle|^2 \quad (3)$$

Appendix II: Weisskopf Units (W.u.) For E2 Transitions

W.u. **Defined** for $2^+ \rightarrow 0^+$ as

$$1 \text{ W.u.} = 5.94 \times 10^{-6} A^{4/3} e^2 b^2 \quad (4)$$

REMEMBER spin factor in $B(\mathcal{O}\lambda)$ definition

$$B(\mathcal{O}\lambda; I_i \rightarrow I_f) = \frac{2I_f + 1}{2I_i + 1} B(\mathcal{O}\lambda; I_f \rightarrow I_i) \quad (5)$$

The single particle unit (spu) is defined for $0^+ \rightarrow 2^+$ transition. So,

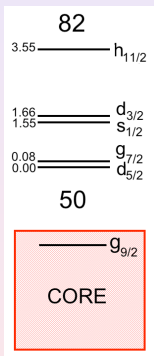
$$\text{spu} = 5 \cdot \text{W.u.} \quad (6)$$

Hence, transitions expressed in spu are 5 times smaller than when expressed in W.u.
It's all about the direction....

Confused?! \Rightarrow USE $e^2 b^2$

Appendix III: SM Calculation Details

ν model space



SM-Calculation I

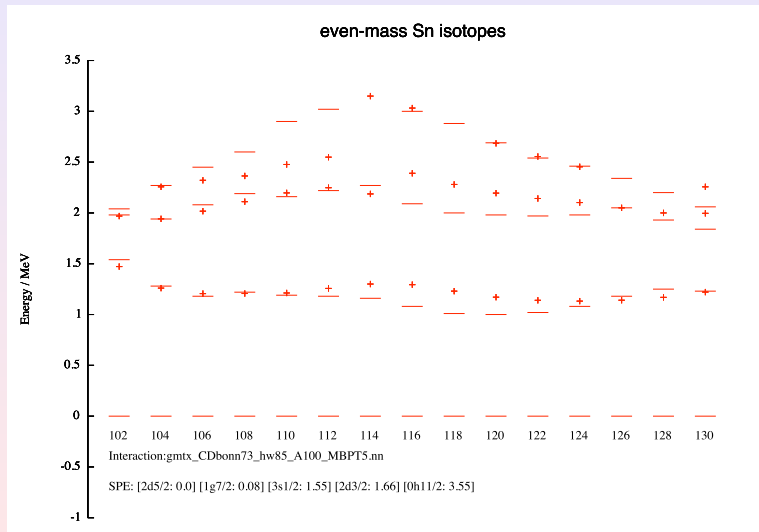
CD-Bonn, G-matrix renormalization, $e_{\nu}^{eff} = 1.0 e$.
model space: $\nu(0g_{7/2}, 1d, 2s, 0h_{11/2})$
PRC 72, 061305(R) (2005)

SM-Calculation II

CD-Bonn, G-matrix renormalization, $e_{\nu}^{eff} = 0.5 e$,
 $e_{\pi}^{eff} = 1.5 e$
model space: $\nu(0g_{7/2}, 1d_{5/2}, 1d, 2s, 0h_{11/2})$ and
 $\pi(g, d, s)$
up to $4p - 4h$ excitation. (seniority truncation $\nu = 8$)
PRC 72, 061305(R) (2005)

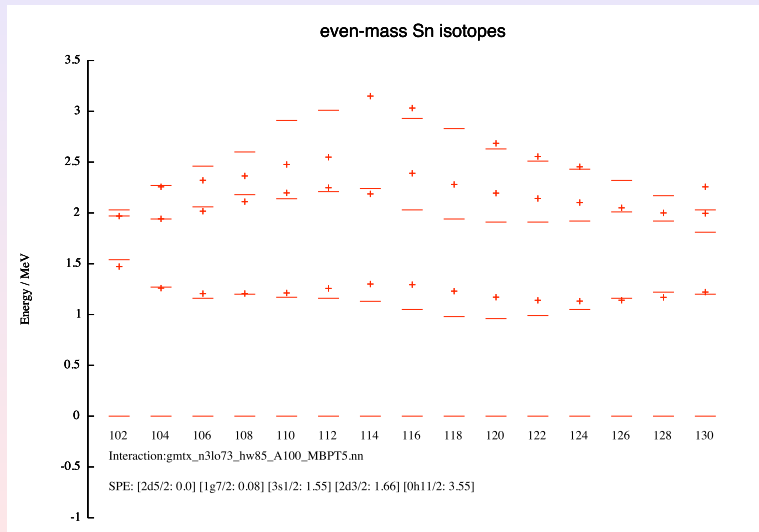
Appendix IV: SM Calculation Details

Theoretical(CDbonn) vs Experimental energy levels



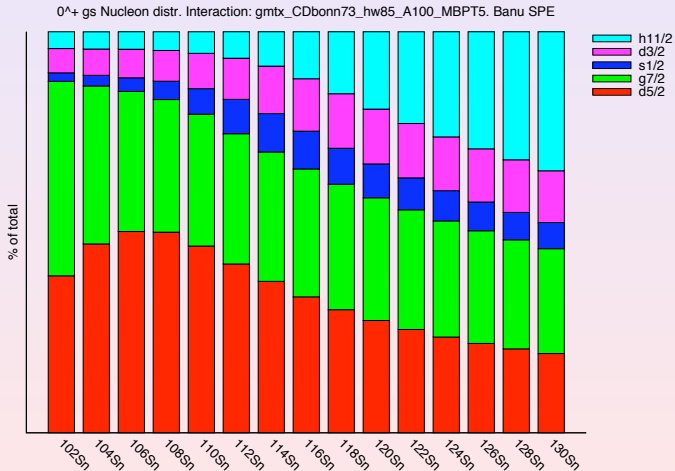
Appendix V: SM Calculation Details

Theoretical(n3lo) vs Experimental energy levels



Appendix VI: SM Calculation Details

Neutron distribution



Appendix VII: Seniority I

Generalized Seniority

If, $[[H, S^+], S^+] = \text{const}(S^+)^2$ I. Talmi NPA 172 1-24 (1971)

where H is the Hamiltonian.

$\Rightarrow E(2^+)$ independent of particle number!

\Rightarrow general n -particle configuration predictions

\Rightarrow truncation schemes

Shell-Model [SM] vs. Generalized Seniority (two states) [GS] (N. Sandulescu PRC 55 (1997))

GS : $|J\rangle = D_J^+(S^+)^{n-1}|0\rangle$, where $S^+ = \sum_j C_j(a^+ j a^+ j)_{J=0}$, and $D^+(J) = \sum_{j_1 j_2} X(j_1, j_2; J)(a_{j_1}^+ a_{j_2}^+)_J$

$E(2^+)$	^{104}Sn	^{106}Sn	^{108}Sn	^{110}Sn	^{112}Sn
SM	1.45	1.42	1.57	1.63	1.65
GS1	1.51	1.56	1.80	2.17	1.65
GS2	1.53	1.54	1.64	1.71	1.72
EXP	1.260	1.206	1.206	1.211	1.256

NOTE: SM in table is based on Bonn A interaction with different single particle energies!

Appendix VIII: Seniority II

The seniority zero/two components of the Shell-Model wavefunction is given by

$$(\nu = 0) |\langle SM(n, J = 0) | (S^+)^{(n)} | 0 \rangle|^2, \quad (\nu = 2) |\langle SM(n, J) | D_J^+ (S^+)^{(n)} | 0 \rangle|^2 \quad (7)$$

(N. Sandulescu PRC 55 (1997))

J^π	^{104}Sn		^{106}Sn		^{108}Sn		^{110}Sn		^{112}Sn	
	GS1	GS2	GS1	GS2	GS1	GS2	GS1	GS2	GS1	GS2
0_1^+	0.950	0.966	0.876	0.938	0.796	0.924	0.742	0.905	0.767	0.909
2_1^+	0.931	0.927	0.787	0.815	0.663	0.780	0.438	0.790	0.420	0.776
4_1^+	0.906	0.906	0.798	0.821	0.482	0.743	0.236	0.764	0.173	0.680
6_1^+	0.918	0.943	0.817	0.895	0.660	0.794	0.401	0.739	0.167	0.695

GS1: amplitude X adjusted to reproduce corresponding two-particle SM state in ^{102}Sn

GS2: amplitude X adjusted for each system separately by diagonalizing the interaction in the $\nu = 2$ space

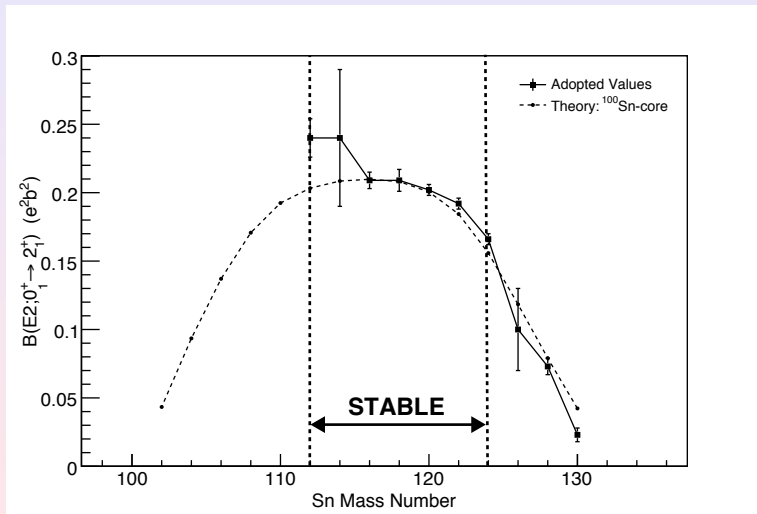
Appendix IX: ^{58}Ni ENSDF

^{58}Ni		Adopted Levels, Gammas				200609
Published: 2000 ENSDF.						
$Q_{\beta^-}=-8565.5$ 14 $S_n=12217.0$ 18 $S_p=8172.5$ 5 $Q_{\alpha}=-6400.2$ 6 2003Au03						
History						
Type	Author	Citation	Cutoff	Date		
Full evaluation Balraj Singh ENSDF 26-Sep-2006						
E _{level}	J ^π	T _{1/2} [#]	XREF	Comments		
0.0 ⁱ	0+	stable	ABCDEFGHIJ KLMNOPQRST UV	T _{1/2} : >7.0×10 ²⁰ y for decay by eβ ⁺ channel to the 0+ g.s. of ⁵⁸ Fe, and >4.0×10 ²⁰ y for decay by the same mode to the 2+, 811-keV level of ⁵⁸ Fe (1993Ya19). Others: 1984No09 , 1982Be20 .		
1454.0 ⁱ 1	2+	0.880 ps 14	ABCDEFGHIJ KLMNOPQRST UV	$\mu=+0.076$ 18 (2001Ke08) $Q=-0.10$ 6 (1989Ra17) $B(E2)=0.0705$ 18 $\langle r^2 \rangle = 3.7748$ fm 14 (2004An14 evaluation). J ^π : 1454γ is E2. T _{1/2} : from 2001Ke08 , Coulomb excitation. Others: 740 fs 40 from B(E2) in (e,e'), 618 fs 16 from B(E2) in Coul. ex., 680 fs 60 from (γ,γ') and 638 fs +98-70 in (p,p'γ). 2001Ra27 evaluation gives 0.627 ps 18 from consideration of about 17 measurements from Coulomb excitation, (γ,γ') and (e,e') published from 1959 to 1983. The B(E2)(↑)=0.0695 20 adopted by 2001Ra27 is agreement with adopted value given above. μ : other: -0.12 24 (1989Ra17). See also 2005St24 compilation.		
2459.1 ⁱ 3	4+	3.7 ps 4	BCDEF HI K MNOPQR UV	J ^π : L(α,α')=4. T _{1/2} : from 2001Ke08 , Coulomb excitation.		
2775.2 2	2+	0.38 ps +12-9	A EG I LMNOP R	J ^π : L(α,α')=2.		

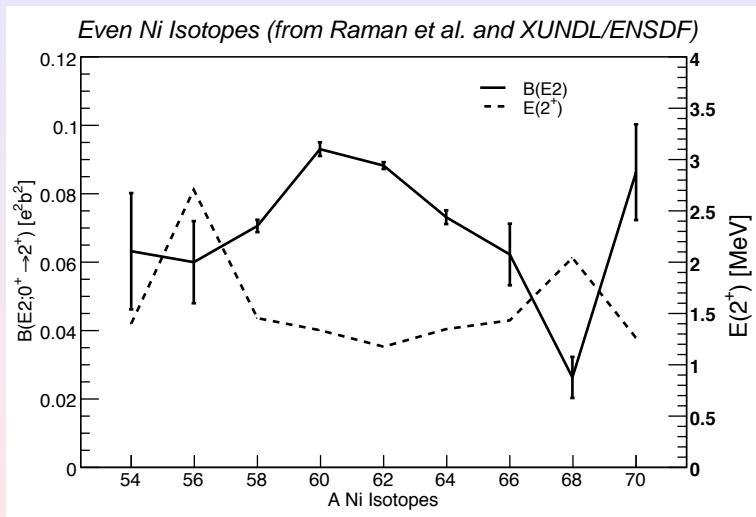
Comment: Target Normalization

- REX $B(E2)$ values normalized against ^{58}Ni
 $B(E2; 0^+ \rightarrow 2^+) = 0.0705(18) e^2b^2$ (ENSDF Adopted Value)
- GSI and MSU data normalized against ^{112}Sn and ^{197}Au , respectively

Sn B(E2) values



The Even-Mass Ni Isotopes



Seniority

