Self-Consistent Description of Exotic Structure and Decay near the N=Z Line in the A~70 Mass Region

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Exotic nuclei near the N = Z line in the A ~ 70 mass region manifest

- shape-coexistence and -mixing
- competition between proton-neutron and like-nucleon pairing correlations
- drastic changes in structure with particle number, angular momentum and excitation energy
- large isospin mixing effect on the *superallowed Fermi β* decay
- *relevant Gamow-Teller β* decay of low-lying excited states in waiting-point nuclei for the rp-process

Requirements for the self-consistent models

- realistic effective interactions in large model spaces
- beyond mean-field approaches

complex VAMPIR approaches

- **the model space is defined by a finite dimensional set of spherical single particle states**
- **the effective many-body Hamiltonian is represented as a sum of one- and two-body terms**
- **the basic buiding blocks are Hartree-Fock-Bogoliubov (HFB) vacua**
- **the HFB transformations are essentially *complex* and allow for proton-neutron, parity and angular momentum mixing being only restricted by time-reversal and axial symmetry**
- **the broken symmetries (s=N, Z, I, p) are restored by projection before variation**

Variational procedures

complex Vampir approach

$$E^s[F_1^s] = \frac{\langle F_1^s|\hat{H}\hat{\Theta}^s_{00}|F_1^s\rangle}{\langle F_1^s|\hat{\Theta}^s_{00}|F_1^s\rangle}$$

$$|\psi(F_1^s); sM\rangle = \frac{\hat{\Theta}^s_{M0}|F_1^s\rangle}{\sqrt{\langle F_1^s|\hat{\Theta}^s_{00}|F_1^s\rangle}}$$

complex Excited Vampir approach

$$|\psi(F_2^s); sM\rangle = \hat{\Theta}^s_{M0}\left\{|F_1^s\rangle\alpha_1^2 + |F_2^s\rangle\alpha_2^2\right\}$$

$$|\psi(F_i^s); sM\rangle = \hat{\Theta}^s_{M0}\sum_{j=1}^{i}|F_j^s\rangle\,\alpha_j^i \qquad \text{for} \quad i = 1, \ldots, n$$

$$|\Psi_\alpha^{(n)}; sM > = \sum_{i=1}^{n}|\psi_i; sM > f_{i\alpha}^{(n)}, \qquad \alpha = 1, \ldots, n$$

$$(H - E^{(n)}N)f^n = 0$$

$$(f^{(n)})^+ N f^{(n)} = 1$$

A$=70-90$ mass region

^{40}Ca - core

model space (π, ν):

$1p_{1/2}\ 1p_{3/2}\ 0f_{5/2}\ 0f_{7/2}\ 1d_{5/2}\ 0g_{9/2}$

(charge-symmetric basis + Coulomb contributions to the π-spe from the core)

renormalized G–matrix (OBEP, Bonn A) (Bonn CD)

- short range Gaussians in the *nn, pp, np channels*
- monopole shifts:

$\langle 0g_{9/2}0f; T=0|\hat{G}|0g_{9/2}0f; T=0\rangle$

$\langle 1p1d_{5/2}; T=0|\hat{G}|1p1d_{5/2}; T=0\rangle$

Superallowed Fermi β Decay

Superallowed Fermi β decay between 0^+ T=1 analog states

test of the CVC hypothesis

test of the unitarity of the CKM matrix

$$ft(1+\delta_R)(1-\delta_c) = \frac{K}{2G_v^2(1+\Delta_R^v)}$$

δc – isospin-symmetry-breaking-correction

A=82 **$_{41}\mathrm{Nb}_{41} \rightarrow {}_{40}\mathrm{Zr}_{42}$** **$0^+ \rightarrow 0^+$**

$T_{1/2}$= 52(6)ms

GANIL, J. Garces Narro, PRC63(2001)044307

Charge-symmetric effective Hamiltonian:

- Bonn A potential
- same single particle energies for π and υ

Isospin-symmetry-breaking contributions:

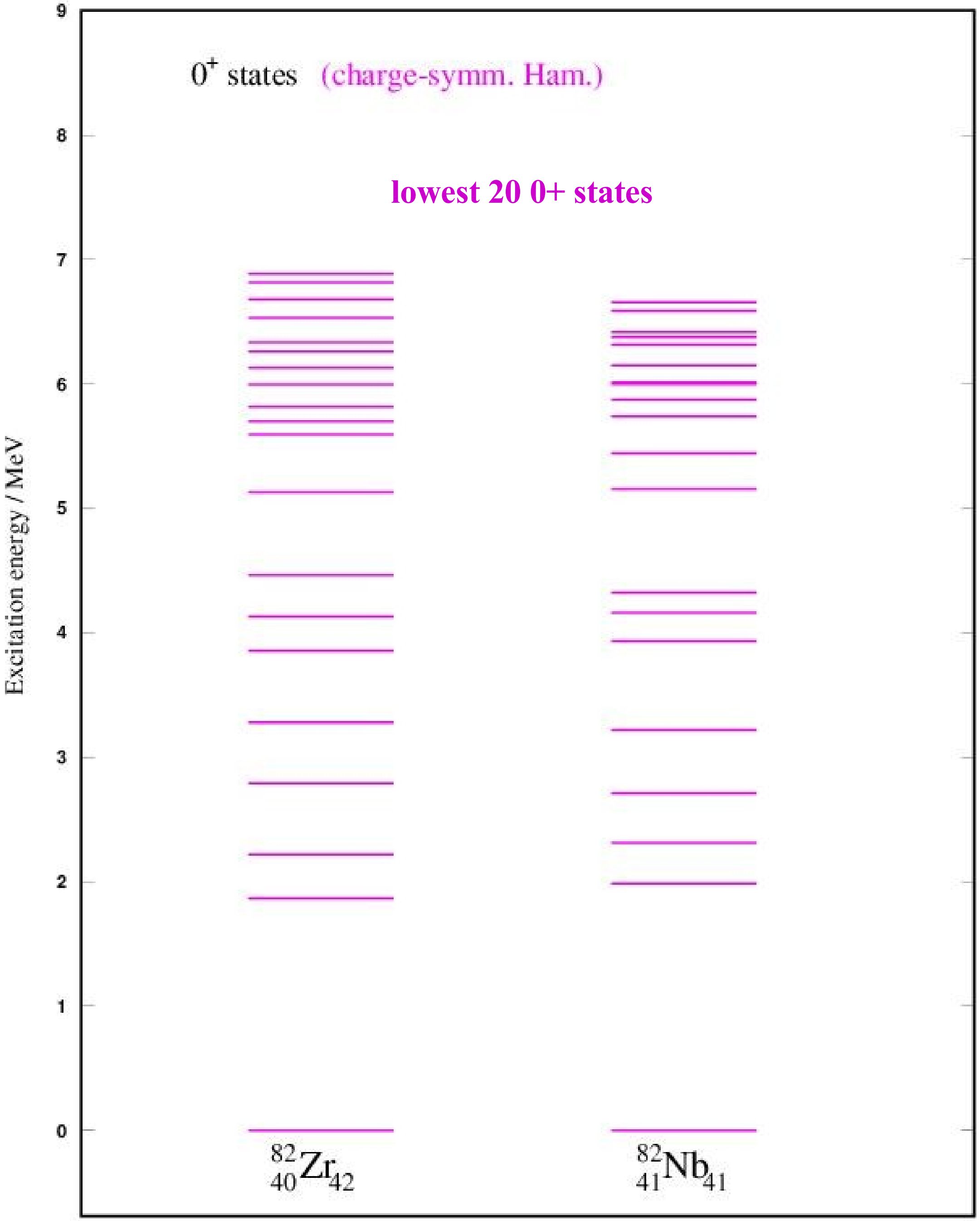
-electromagnetic interaction
- Coulomb two-body matrix elements
- Coulomb contribution to the single particle energies resulting from the Ca core

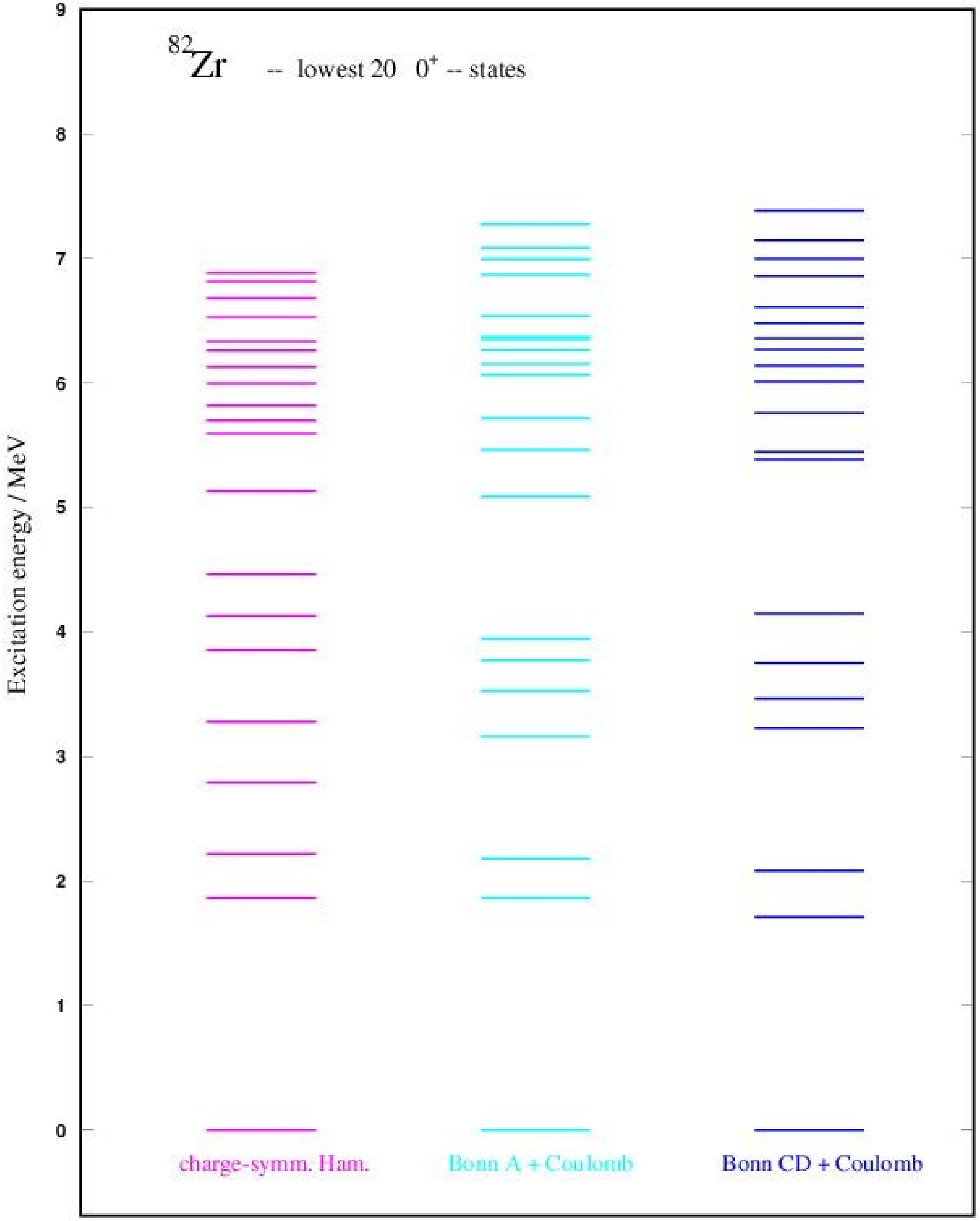
-charge-dependent strong interaction
- Bonn CD potential

Isospin-symmetry-breaking effective Hamiltonians:

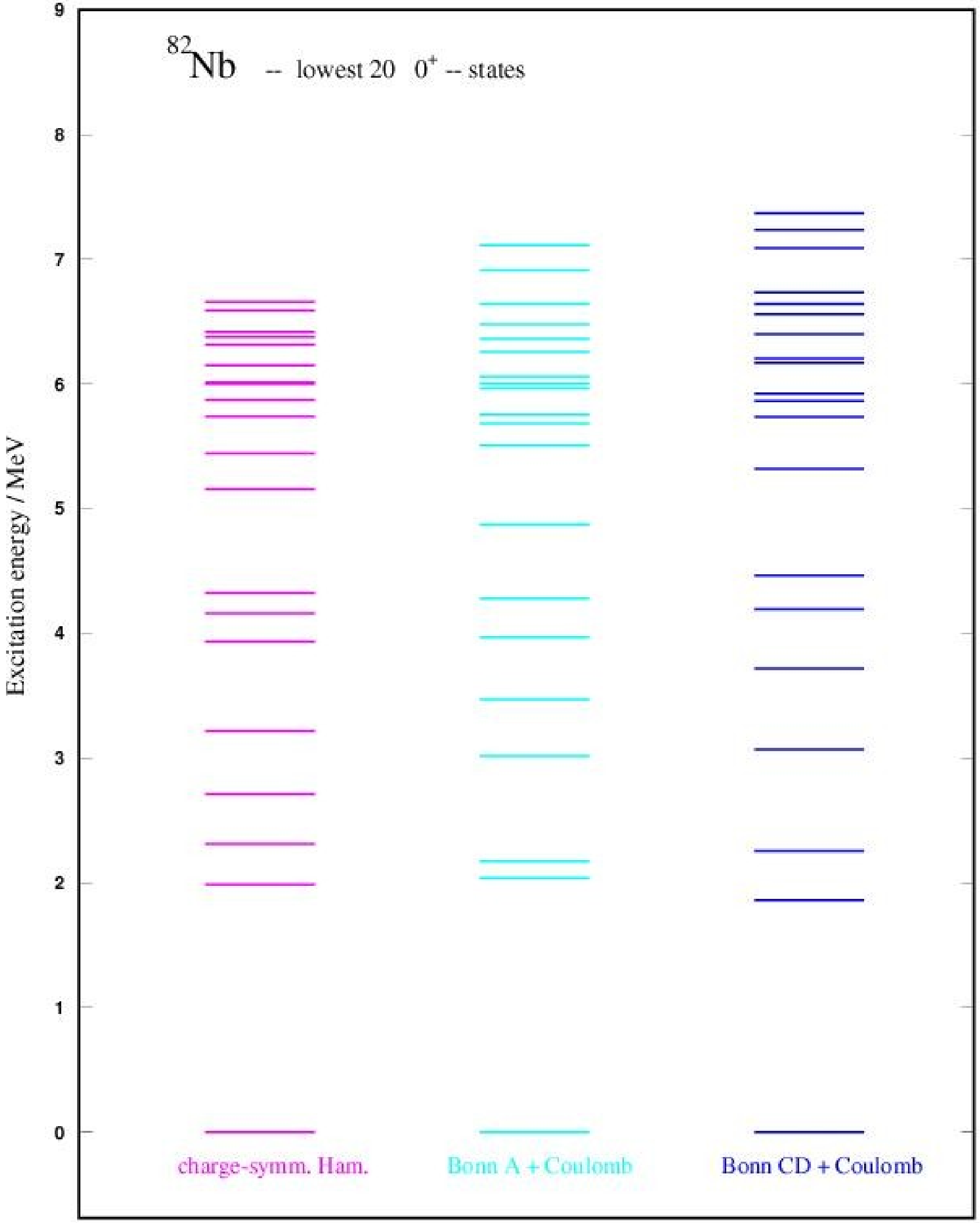
* **Bonn A + Coulomb**

* **Bonn CD + Coulomb**


0^+ states (charge-symm. Ham.)
lowest 20 0+ states
Excitation energy / MeV
9
8
7
6
5
4
3
2
1
0
$^{82}_{40}\mathrm{Zr}_{42}$
$^{82}_{41}\mathrm{Nb}_{41}$



^{82}Zr -- lowest 20 0^+ -- states
Excitation energy / MeV
9
8
7
6
5
4
3
2
1
0
charge-symm. Ham.
Bonn A + Coulomb
Bonn CD + Coulomb



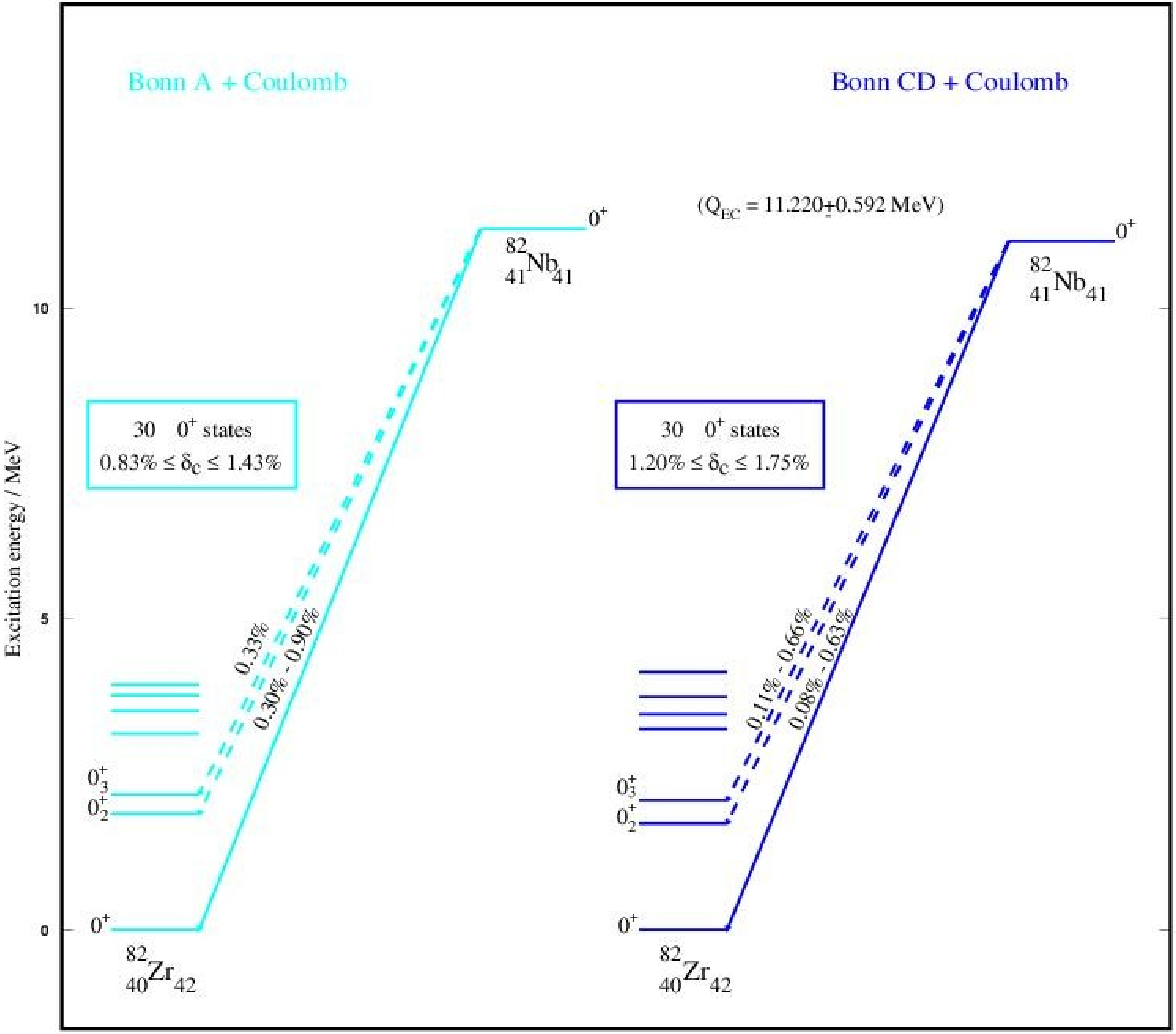
^{82}Nb -- lowest 20 0^+ -- states
Excitation energy / MeV
9
8
7
6
5
4
3
2
1
0
charge-symm. Ham.
Bonn A + Coulomb
Bonn CD + Coulomb

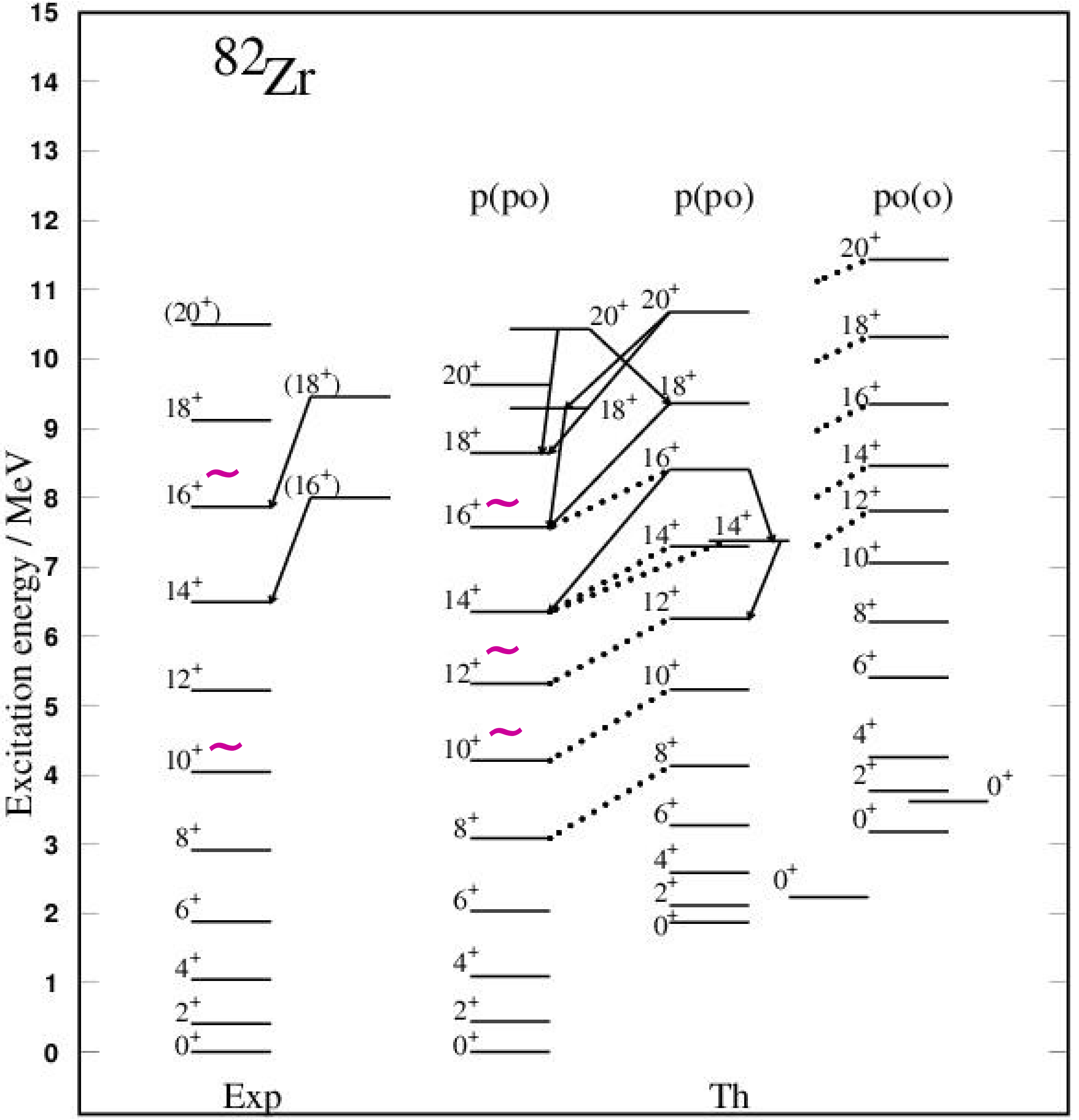
The amount of mixing for the lowest calculated 0^+ states of ^{82}Zr

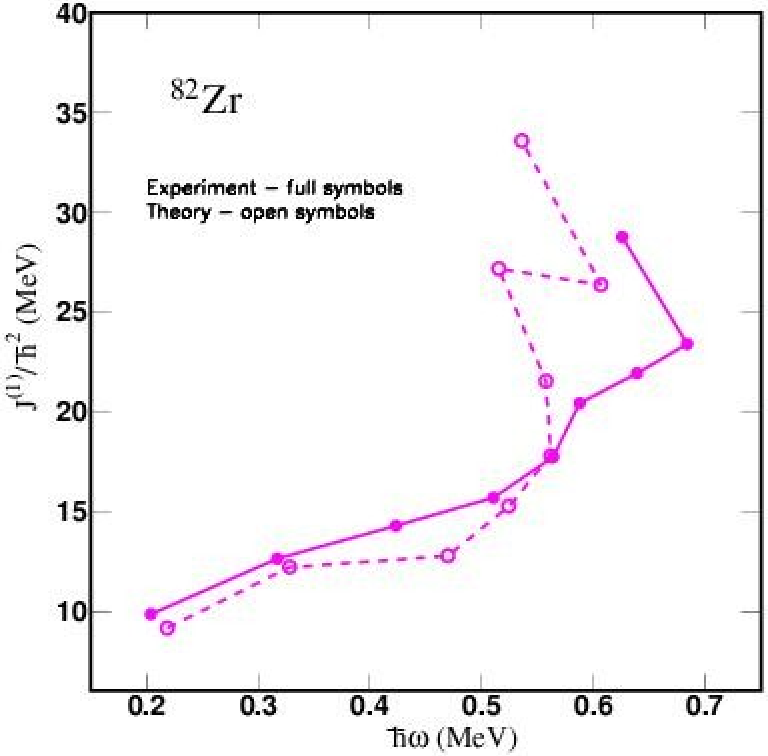
charge-symm. Ham.	Bonn A + Coulomb	Bonn CD + Coulomb
o-mixing /p-mixing	o-mixing /p-mixing	o-mixing /p-mixing
4(2)%91%	3%94%	3%94%
38(15)% 20(16)(5)%	7(2)% 87(2)%	7% 88(2)%
2% 74(17)%	41(10)% 25(8)(5)(5)%	51(4)% 22(8)(6)(4)%
38(35)(2)% 10(6)(5)%	40(10)% 33(10)(3)%	20(14)(2)% 35(18)(3)%
28(7)% 44(7)(4)(2)%	23(2)% 43(16)(5)%	9(6)% 46(17)(14)(2)%

The amount of mixing for the lowest calculated 0^+ states of ^{82}Nb

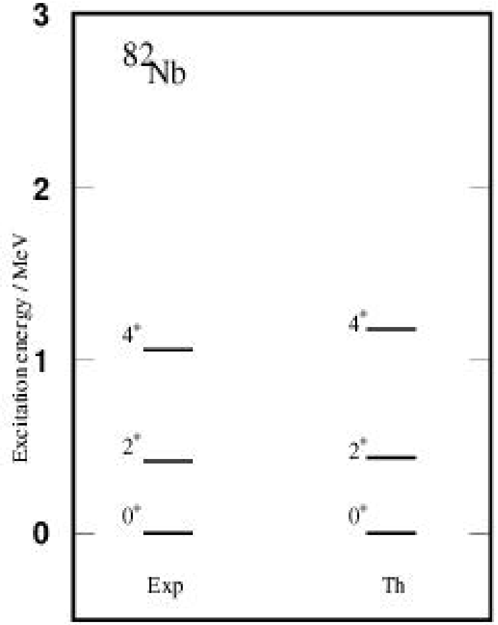
charge-symm. Ham.	Bonn A + Coulomb	Bonn CD + Coulomb
o-mixing /p-mixing	o-mixing /p-mixing	o-mixing /p-mixing
4%91(2)%	3%94%	3%94%
47(21)% 17(8)%	40(9)% 37(5)(3)(2)%	71(4)% 6(5)(4)(3)(3)%
3% 87(3)(2)(2)%	22(3)% 56(10)(3)(2)%	5% 88%
48(32)% 7(6)(3)%	44(18)% 17(5)(5)(4)%	42(7)% 34(3)(3)(2)%
9(6)(2)% 60(6)(5)(3)(2)%	18(2)% 40(26)(6)(2)%	23% 38(27)(5)%

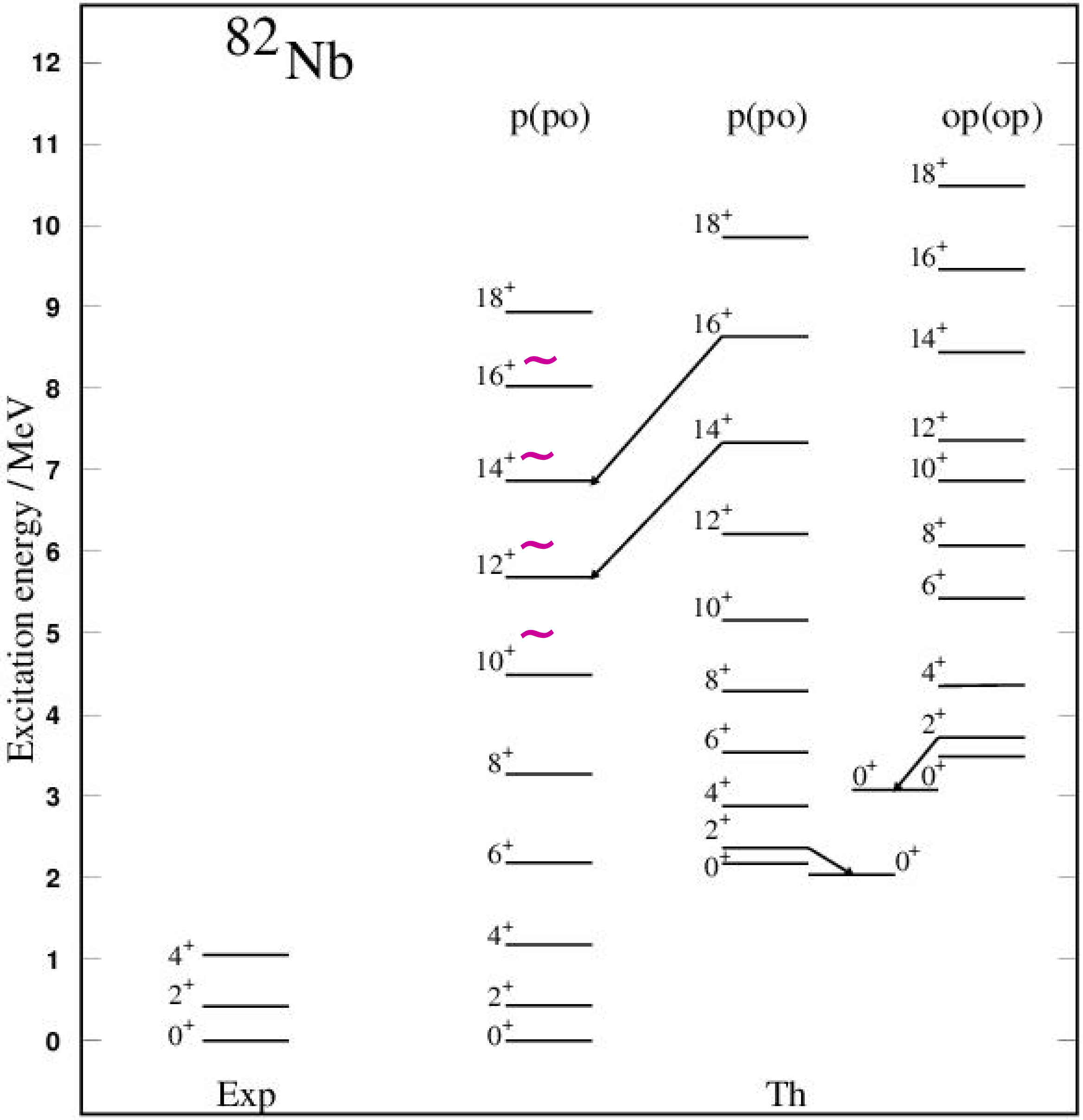

Bonn A + Coulomb
Bonn CD + Coulomb
$(Q_{EC} = 11.220 \pm 0.592$ MeV)
0^+
$^{82}_{41}\mathrm{Nb}_{41}$
0^+
$^{82}_{41}\mathrm{Nb}_{41}$
10
5
0
Excitation energy / MeV
30 0^+ states
$0.83\% \le \delta_C \le 1.43\%$
30 0^+ states
$1.20\% \le \delta_C \le 1.75\%$
0.33%
0.30% - 0.90%
0.11% - 0.66%
0.08% - 0.63%
0^+_3
0^+_2
0^+
$^{82}_{40}\mathrm{Zr}_{42}$
0^+_3
0^+_2
0^+
$^{82}_{40}\mathrm{Zr}_{42}$

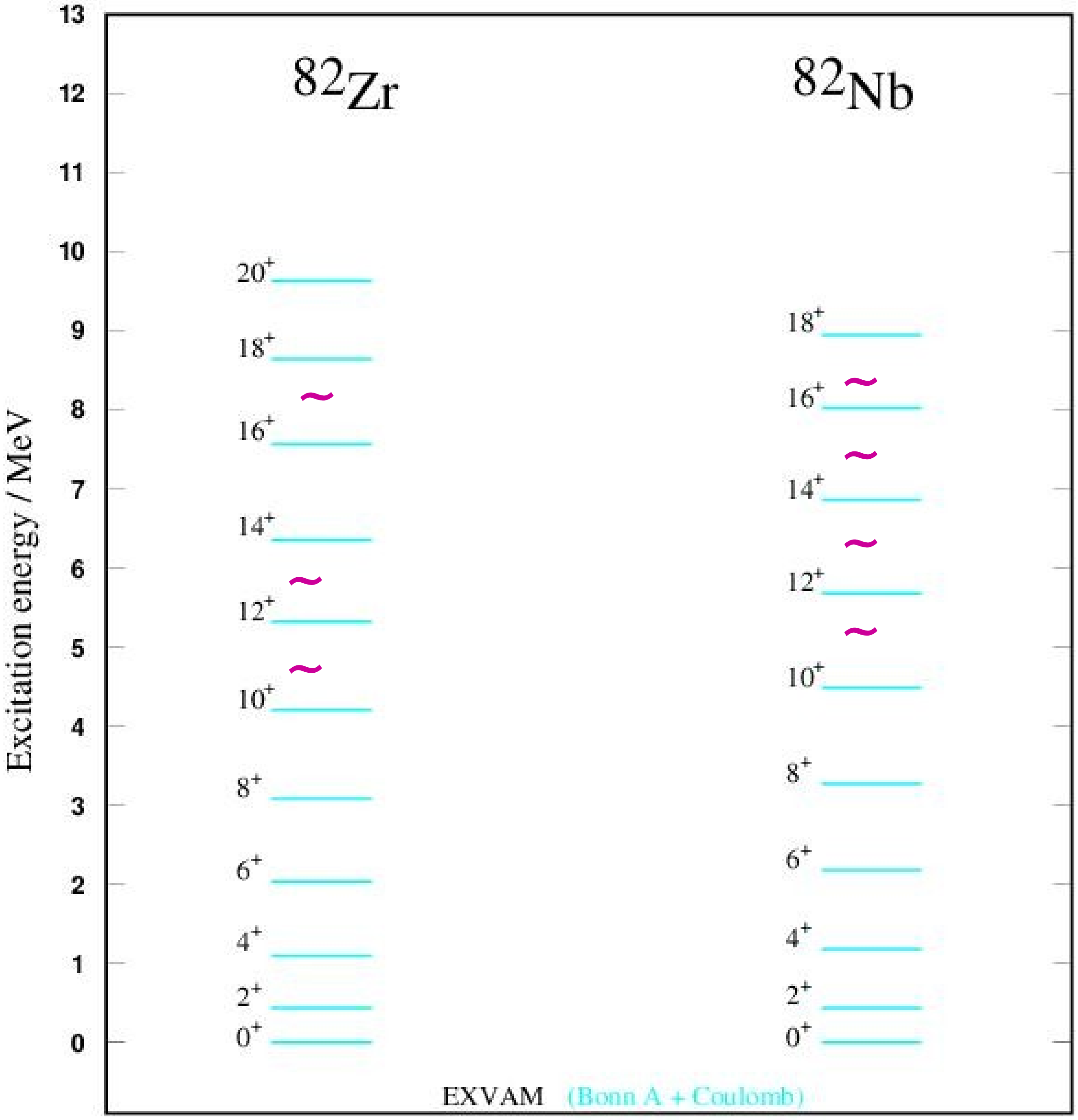

^{82}Zr
Excitation energy / MeV
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Exp
Th
p(po)
p(po)
po(o)
(20+)
18+
(18+)
16+
(16+)
14+
12+
10+
8+
6+
4+
2+
0+
20+
20+
20+
18+
18+
18+
16+
16+
14+
14+
14+
12+
12+
10+
10+
8+
8+
6+
6+
4+
4+
2+
2+
0+
0+
0+
20+
18+
16+
14+
12+
10+
8+
6+
4+
2+
0+
0+



^{82}Zr
Experiment – full symbols
Theory – open symbols
$J^{(1)}/\hbar^2$ (MeV)
$\hbar\omega$ (MeV)
40
35
30
25
20
15
10
0.2
0.3
0.4
0.5
0.6
0.7


82Nb
Excitation energy / MeV
3
2
1
0
4+
2+
0+
4+
2+
0+
Exp
Th


82Nb
Excitation energy / MeV
12
11
10
9
8
7
6
5
4
3
2
1
0
p(po)
p(po)
op(op)
Exp
Th
4+
2+
0+
18+
16+
14+
12+
10+
8+
6+
4+
2+
0+
18+
16+
14+
12+
10+
8+
6+
4+
2+
0+
0+
18+
16+
14+
12+
10+
8+
6+
4+
2+
0+
0+


^{82}Zr
^{82}Nb
Excitation energy / MeV
0
1
2
3
4
5
6
7
8
9
10
11
12
13
20^+
18^+
16^+
14^+
12^+
10^+
8^+
6^+
4^+
2^+
0^+
18^+
16^+
14^+
12^+
10^+
8^+
6^+
4^+
2^+
0^+
EXVAM (Bonn A + Coulomb)

The amount of mixing for the lowest calculated states of ^{82}Zr (Bonn A + Coulomb)

$I^{\pi}[\hbar]$	p(po)-band	p(po)-band	po(op)-band
	o-mixing /p-mixing	o-mixing /p-mixing	o-mixing /p-mixing
0^+	3(1)%94%	4(1)%91(1)(1)%	38(9)%40(10)(1)%
2^+	98%	97%	20(4)%30(21)(18)(4)(2)%
4^+	98(1)%	97%	64(2)(2)%16(11)(2)(1)(1)%
6^+	98(1)%	93(5)(2)%	36%58(4)%
8^+	98(1)%	75(22)(2)%	52(41)(1)%4(2)%
10^+	99%	64(34)%	76(19)(1)%2%
12^+	99%	1%83(15)%	71(25)%4%
14^+	96(2)%	43(2)%48(3)(2)%	64(13)(3)%12(6)(2)%
16^+	14%77(8)%	5(3)%79(12)%	93(2)%4%
18^+	11(11)(2)%43(31)(2)%	47(12)(5)(2)%24(8)(1)%	84%8(6)(1)%
20^+	24%55(14)(4)%	9(2)%59(26)(2)%	80(3)(2)%7(4)(4)%

The amount of mixing for the lowest calculated states of ^{82}Nb (Bonn A + Coulomb)

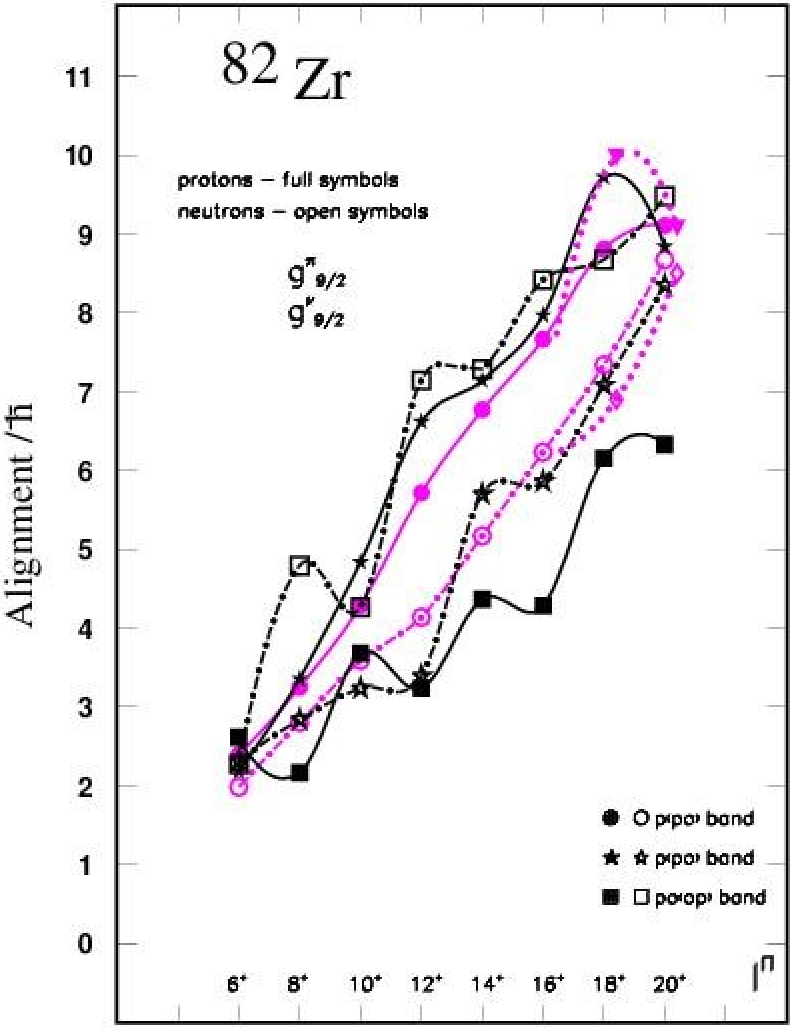
$I^{\pi}[\hbar]$	p(po)-band	p(po)-band	po(op)-band
	o-mixing /p-mixing	o-mixing /p-mixing	o-mixing /p-mixing
0^+	3(1)%95%	30(4)%44(12)(3)(1)(1)%	15(3)%43(23)(7)(2)(2)(1)%
2^+	98%	1(1)%94%	46(1)%27(13)(5)(4)(2)(1)%
4^+	98%	1%97%	58(3)%15(12)(6)(3)(2)%
6^+	98(2)%	95(3)(2)%	70%28%
8^+	95(4)(1)%	95(3)(2)%	63(25)(6)(2)%3%
10^+	98%	96(2)%	62(24)(8)%5%
12^+	99%	2%93(5)%	58(32)(3)%5(1)%
14^+	97(2)%	3%84(10)(2)%	80(8)(5)%4(2)(1)%
16^+	2(1)%89(5)(3)%	4%85(7)(2)%	84(3)%10(2)%
18^+	14(4)(2)(2)%72(4)(2)%	26(2)(1)(1)%57(7)(6)%	77%23%

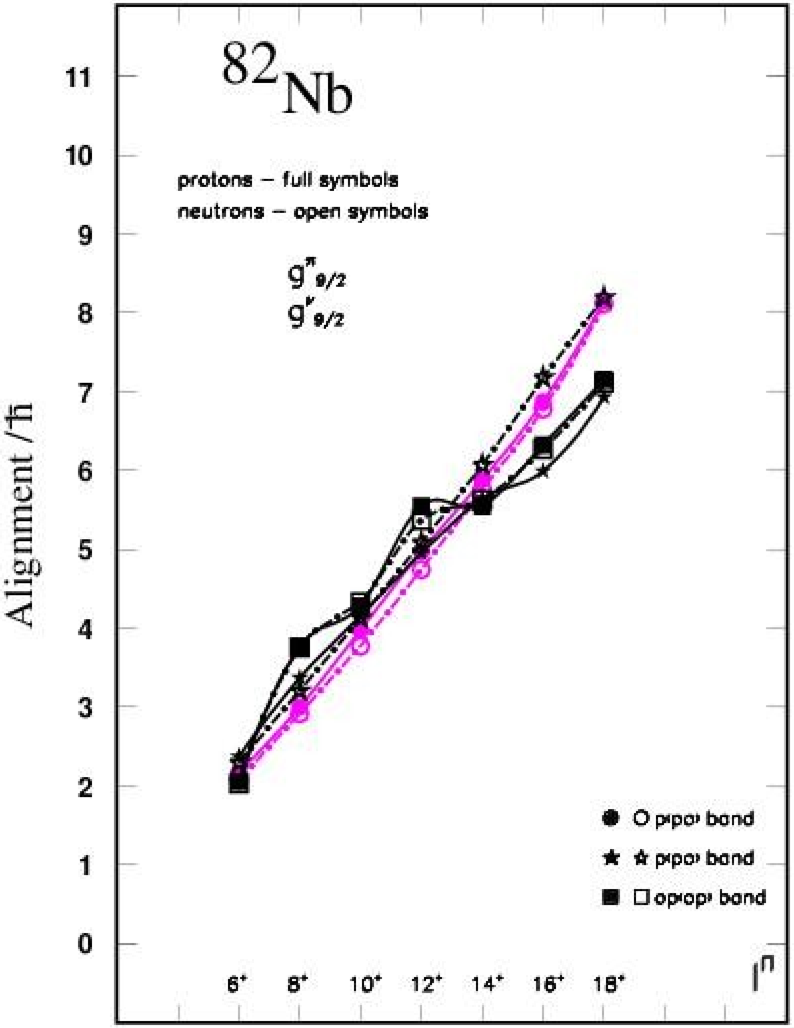
$B(E2; I \rightarrow I-2)$ values (in e^2fm^4) for the yrast states of the nucleus ^{82}Zr and ^{82}Nb

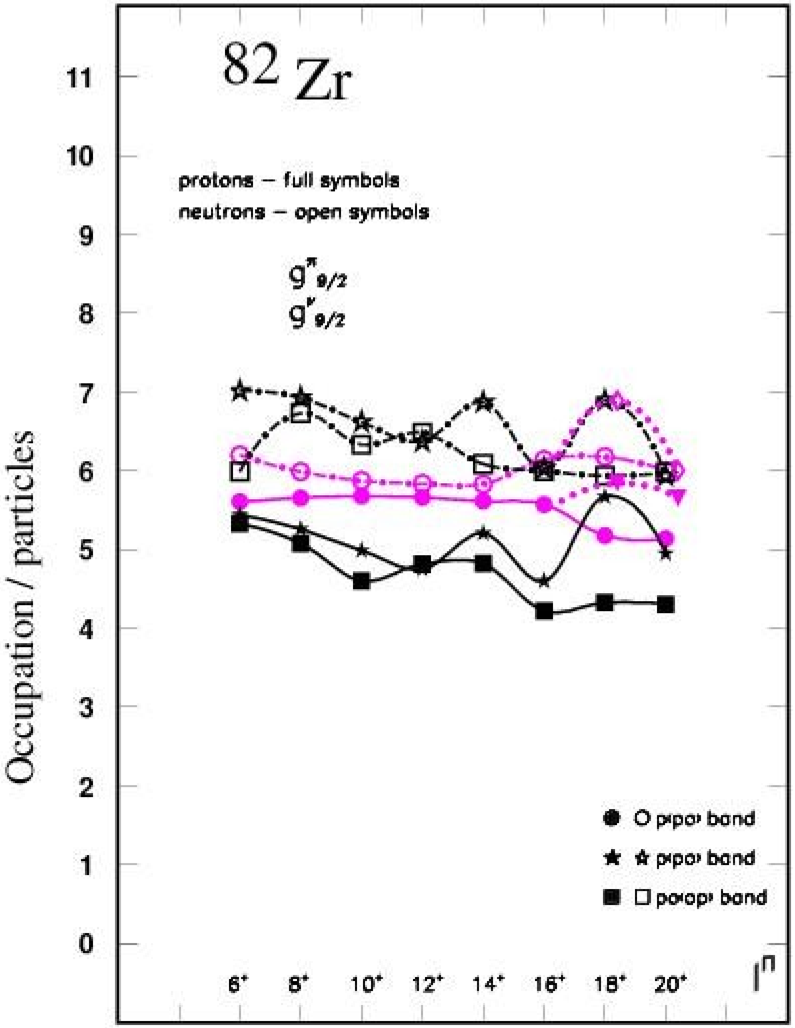
$I^\pi[\hbar]$	^{82}Zr Experiment	Theory	^{82}Nb Theory
2^+	2328(1058)	1322	1274
4^+	1672(360)	1970	1897
6^+	2539(1058)	2138	2064
8^+	2328(635)	2174	2042
10^+	1926(487)	2129	1912
12^+	1904(635)	1974	1824
14^+	> 610	1733	1696
16^+		1472	1479
18^+		809	774
20^+		808	

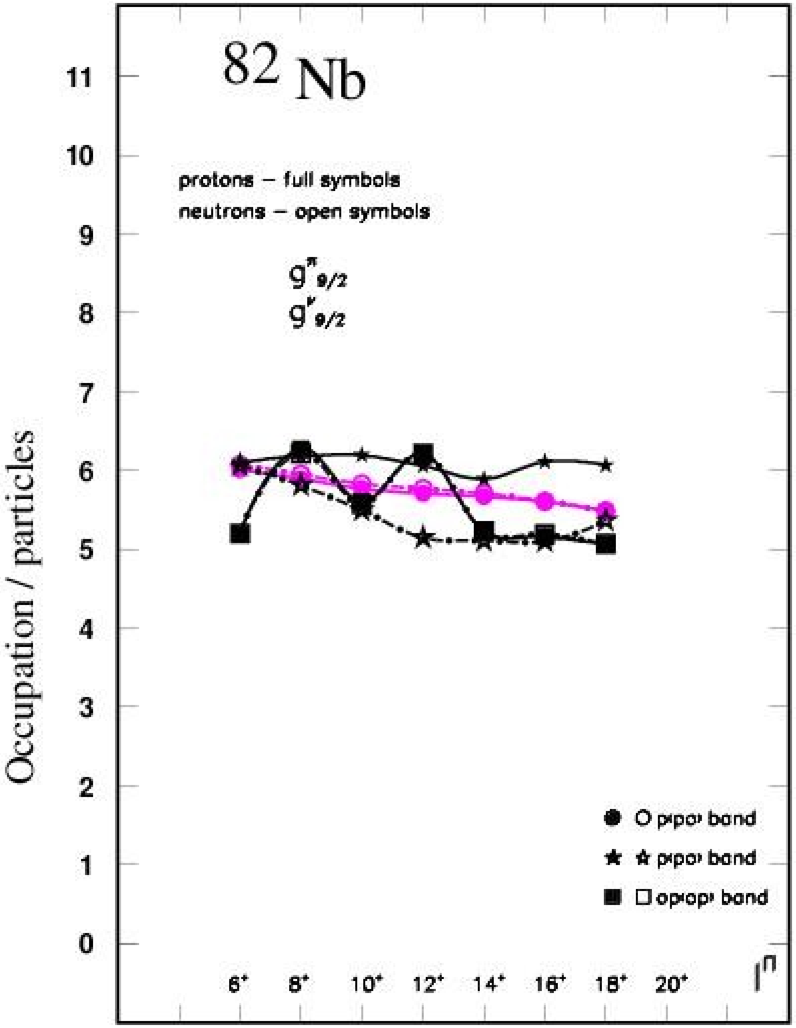
Spectroscopic quadrupole moments Q_2^{sp} (in efm^2)
for selected states of the nucleus ^{82}Zr

I^π	p(po)	$p(po)$	po(op)
2^+	-74.93	-77.23	-38.73
4^+	-95.77	-97.98	22.52
6^+	-106.01	-106.85	-15.73
8^+	-109.72	-105.31	64.64
10^+	-109.54	-94.66	70.57
12^+	-105.08	-82.10	68.24
14^+	-98.58	-10.76	49.33
16^+	-71.42	-62.12	74.31
18^+	-37.36	1.008	55.17
20^+	-23.44	-52.55	57.43


^{82}Zr
protons – full symbols
neutrons – open symbols
$g^{\pi}_{9/2}$
$g^{\nu}_{9/2}$
Alignment /ħ
11
10
9
8
7
6
5
4
3
2
1
0
6^+
8^+
10^+
12^+
14^+
16^+
18^+
20^+
I^{π}
● ○ p›po› band
★ ☆ p›po› band
■ □ po›op› band


^{82}Nb
protons – full symbols
neutrons – open symbols
$g^{\pi}_{9/2}$
$g^{\nu}_{9/2}$
Alignment /ħ
11
10
9
8
7
6
5
4
3
2
1
0
6^+
8^+
10^+
12^+
14^+
16^+
18^+
I^{π}
● ○ p›po› band
★ ☆ p›po› band
■ □ op›op› band


82 Zr
protons – full symbols
neutrons – open symbols
g^π 9/2
g^ν 9/2
Occupation / particles
11
10
9
8
7
6
5
4
3
2
1
0
● ○ pıpo' band
★ ☆ pıpo' band
■ □ popop' band
6+
8+
10+
12+
14+
16+
18+
20+
I^π


82 Nb
protons – full symbols
neutrons – open symbols
g^π 9/2
g^ν 9/2
Occupation / particles
11
10
9
8
7
6
5
4
3
2
1
0
● ○ pıpo' band
★ ☆ pıpo' band
■ □ opop' band
6+
8+
10+
12+
14+
16+
18+
20+
I^π

Gamow-Teller β Decay of ^{72}Kr

CERN/ISOLDE I. Piqueras, Eur. Phys. J. A16(2003)313

$^{72}\mathrm{Kr} \rightarrow {}^{72}\mathrm{Br}$

$Q_{EC} = 5.040 \pm 0.375\ MeV$

$0^{+}_{ground-state} \rightarrow 1^{+}$

$0^{+}_{first-excited} \rightarrow 1^{+}$

$E_{0_2^+} = 0.671\ MeV$

$2^{+}_{yrast} \rightarrow 1^{+}$

$E_{2_1^+} = 0.710\ MeV$

$\rightarrow 2^{+}$

$\rightarrow 3^{+}$

The amount of mixing for the considered states of the ^{72}Kr nucleus (ms3).

	Bonn A		Bonn CD	
$I[\hbar]$	o-mixing	p-mixing	o-mixing	p-mixing
0_1^+	64(2)%	29(2)(1)(1)%	50(3)%	38(5)(3)%
0_2^+	35(2)%	57(3)(1)(1)%	49(2)%	46(3)%
2_1^+	92(1)%	6%	76(1)%	20(3)%

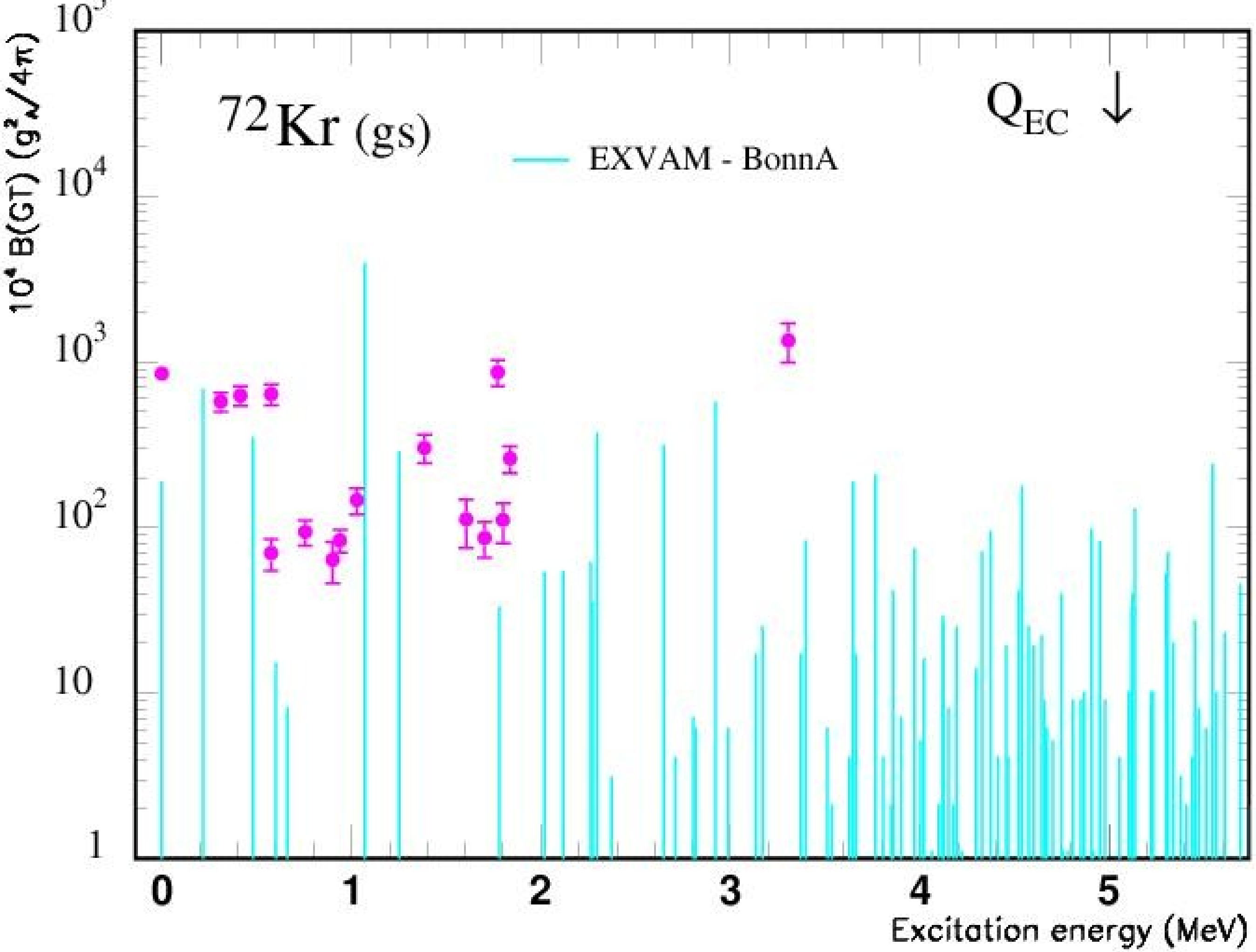
The amount of mixing for the lowest calculated
1^+ states of ^{72}Br with significant B(GT)
(Bonn A/Bonn CD).

o-mixing /p-mixing
85(12)%
81(11)(4)%
87(2)(2)(2)(2)(1)(1)%
81(4)(4)(2)(2)(1)(1)(1)%
78(16)(2)(1)%
78(4)(3)(3)(2)(2)(1)(1)(1)(1)%
49(24)(8)(6)(5)(2)(1)(1)(1)%
32(31)(15)(9)(3)(2)(1)(1)(1)(1)%
79(15)(1)%
31(2)(2)(1)%20(16)(13)(2)(1)(1)(1)(1)(1)(1)(1)%
85(12)(1)%
49(8)(2)(1)% 34(1)(1)%
32(4)(1)(1)%54(2)(1)(1)(1)%
69(26)(1)(1)(1)%
72(6)(4)(4)(3)(3)(2)(2)(1)(1)%
69(24)(3)(1)(1)%
68(18)(8)(1)%
66(16)(5)(2)(1)(1)(1)(1)(1)(1)% 2(1)%
2(1)% 56(23)(5)(2)(2)(2)(1)(1)(1)(1)%
49(26)(9)(5)(3)(1)(1)(1)%

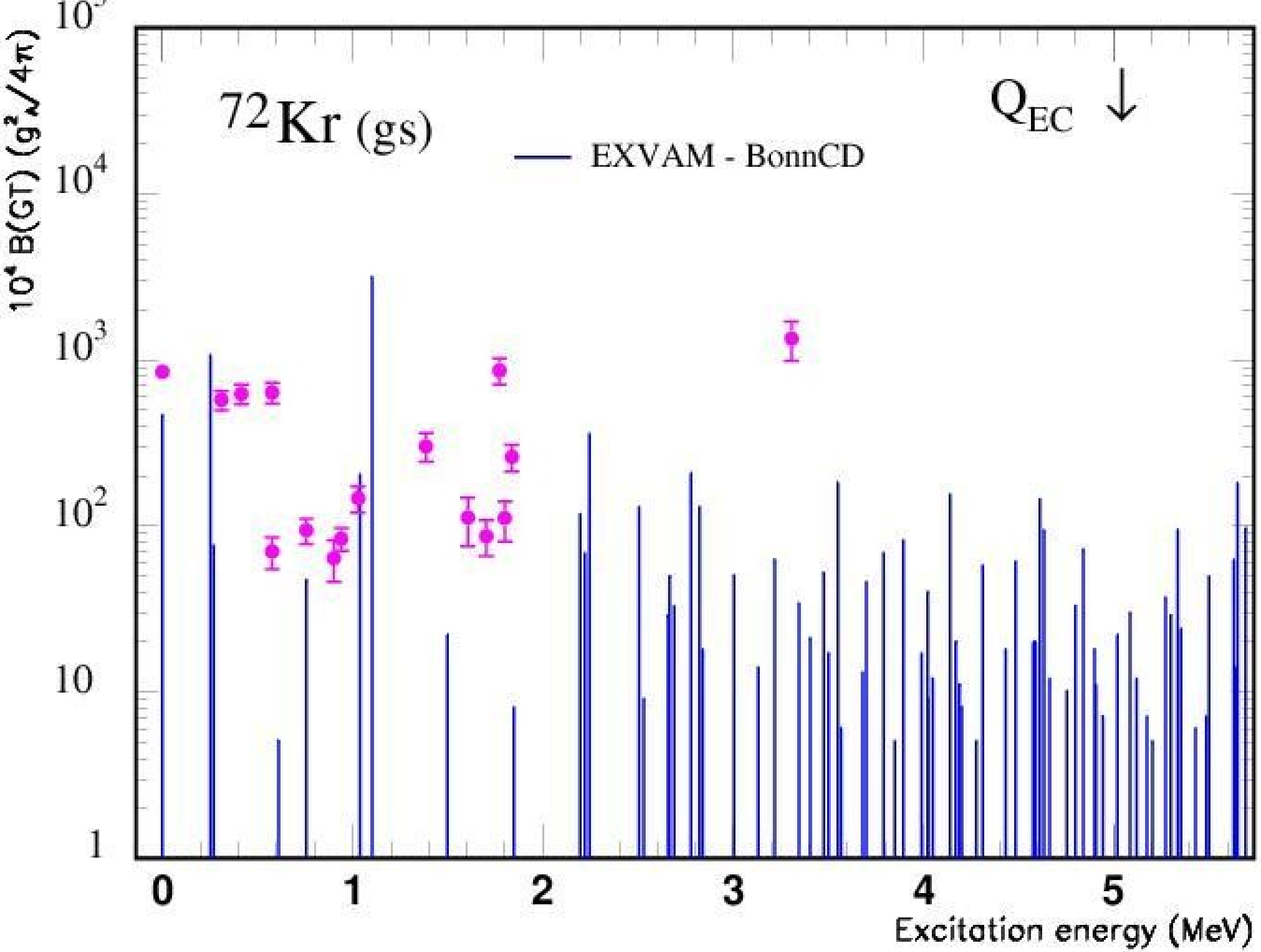
The spectroscopic quadrupole moments Q_2^{sp} (in efm^2) for the lowest 1^+ states of ^{72}Br (Bonn A/BonnCD).

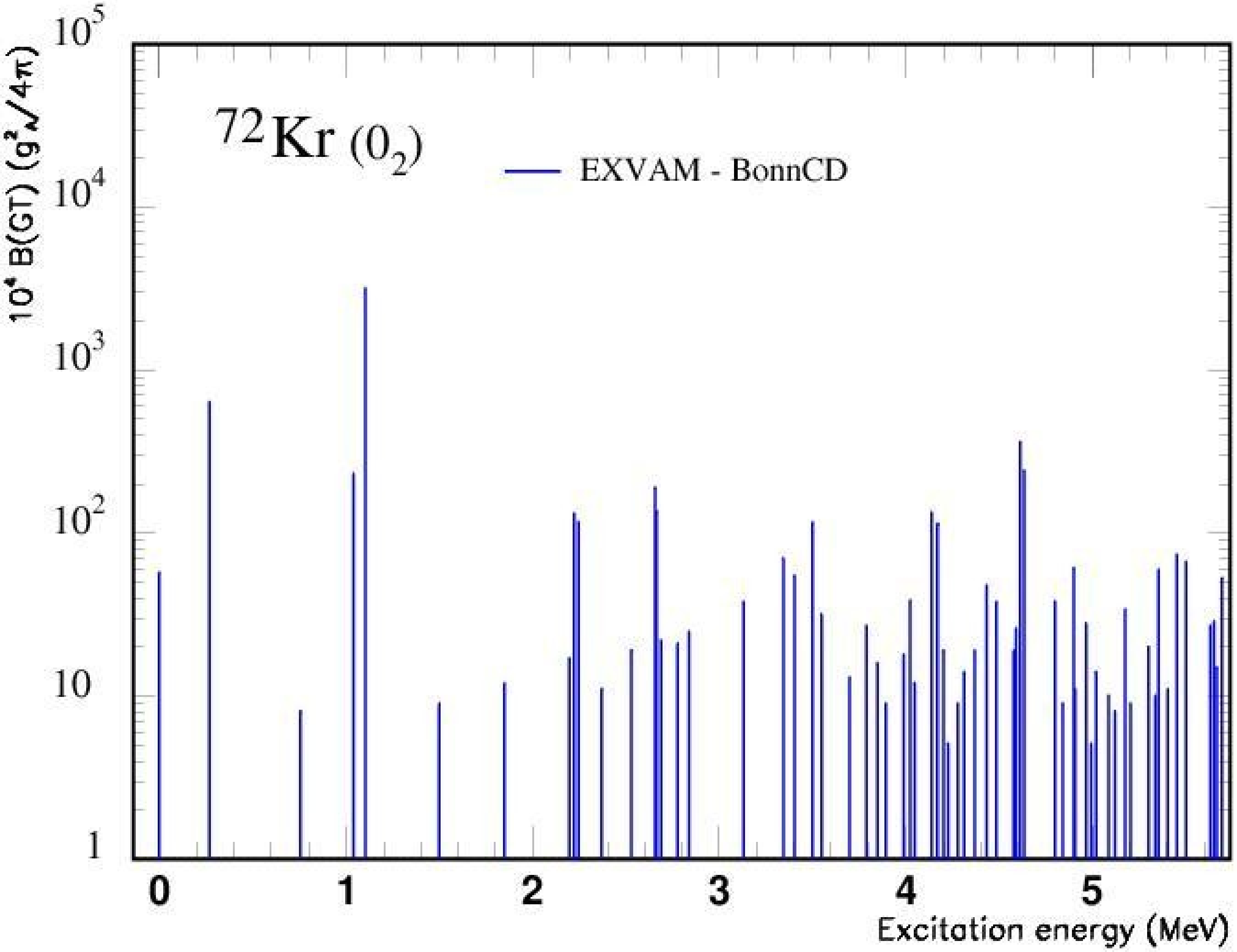
48.5	48.7	-49.9	-49.4	46.5	45.5	-51.6	-50.1	-49.5	46.8
-11.5	8.7	-46.5	-48.7	45.4	44.0	-53.5	-39.1	27.0	41.0
-48.9	-46.5	-49.2	42.5	-39.8	35.8	-46.3	41.8	-45.0	-43.5

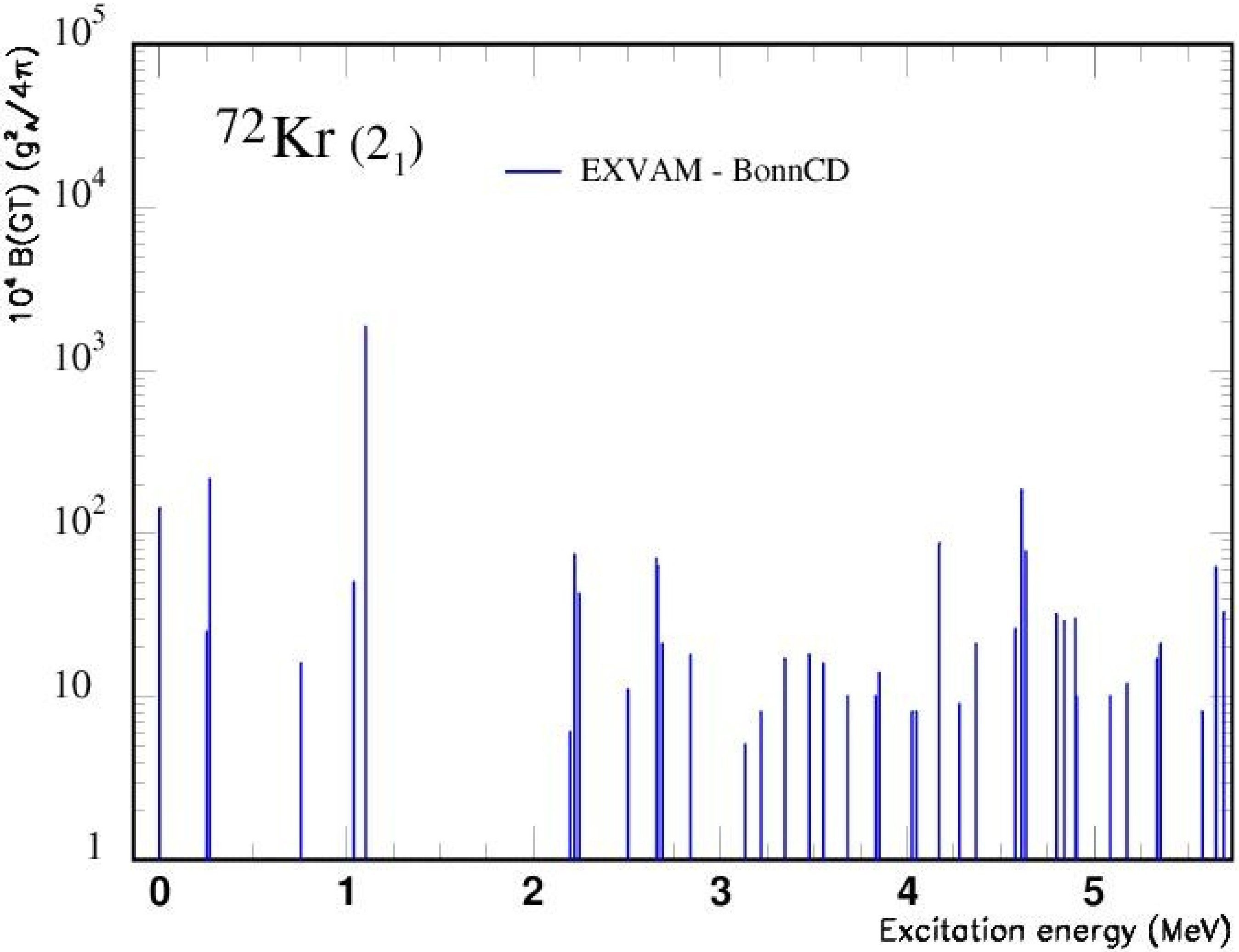
48.2	10.5	-11.5	-49.6	46.6	-51.8	45.6	-50.2	-50.2	-51.8
46.5	43.8	-46.4	-49.2	46.3	-50.1	-9.0	-16.4	-40.8	-40.6
7.8	-18.4	44.3	-45.8	42.8	42.6	-47.7	-34.4	27.3	-43.8

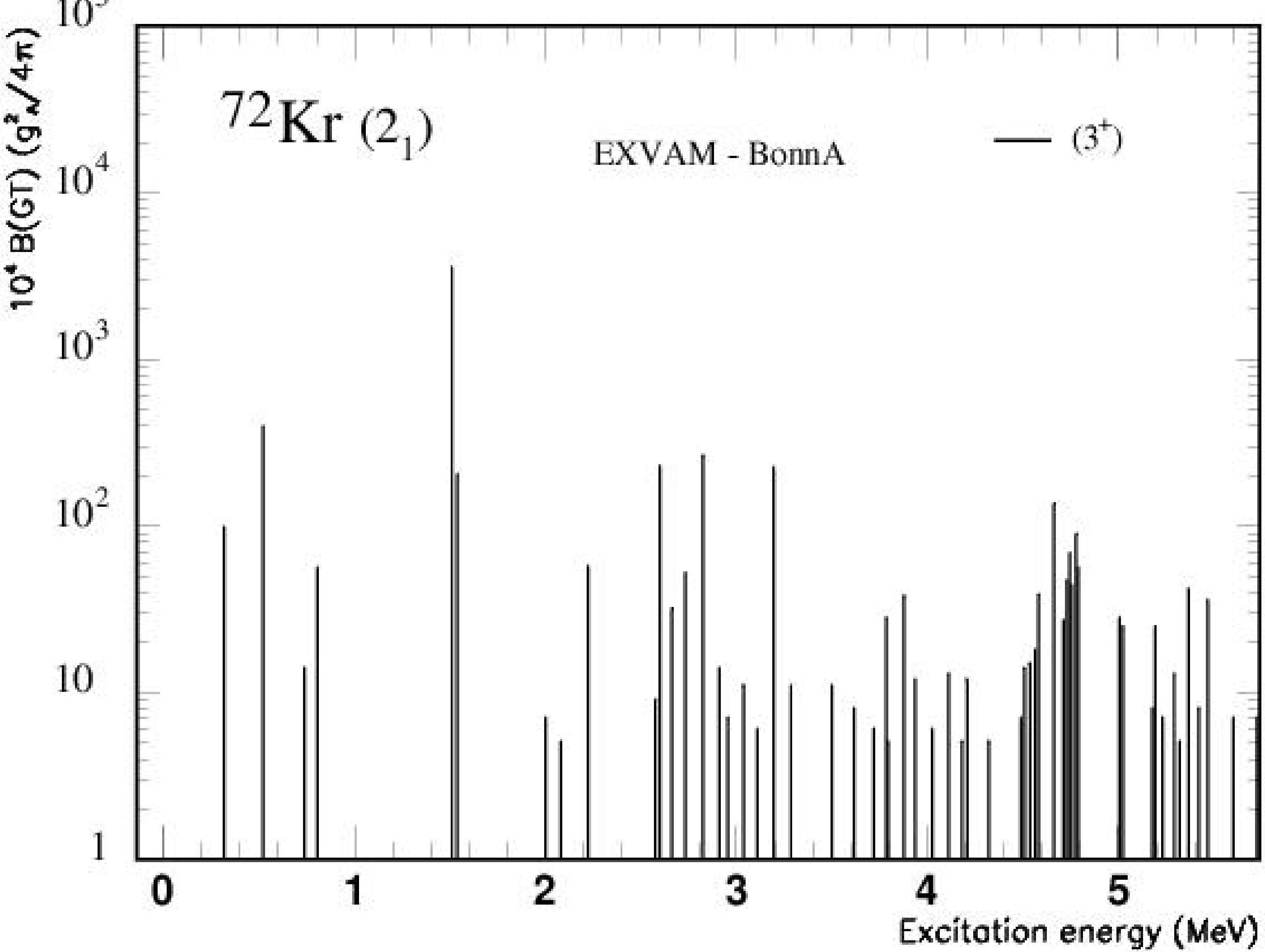


^{72}Kr (gs)
Q_{EC} ↓
EXVAM - BonnA
10^4 B(GT) ($g_A^2/4\pi$)
10^5
10^4
10^3
10^2
10
1
0
1
2
3
4
5
Excitation energy (MeV)

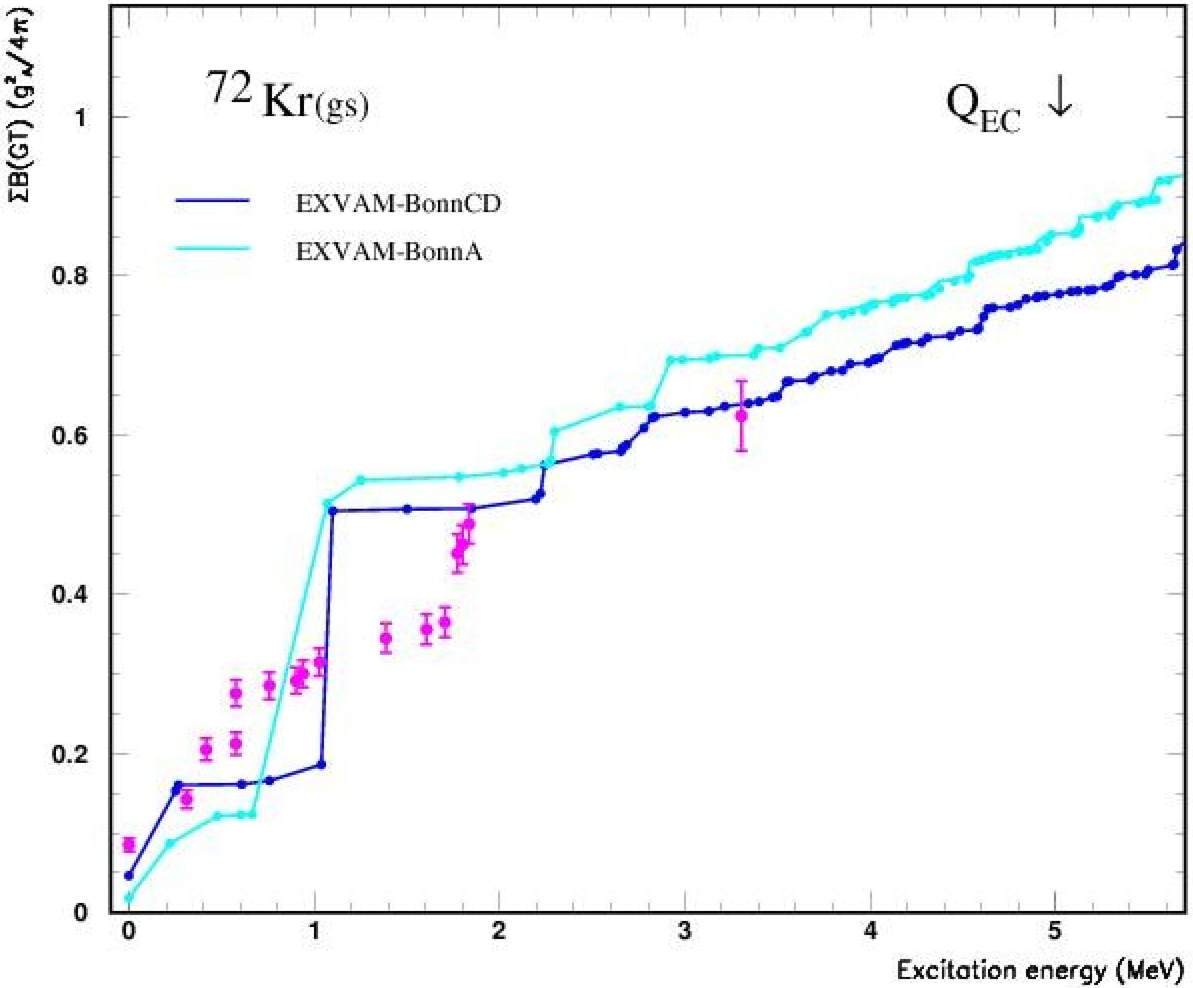

10^5
10^4
10^3
10^2
10
1
10^4 B(GT) $(g_A^2/4\pi)$
^{72}Kr (gs)
Q_{EC} ↓
EXVAM - BonnCD
0
1
2
3
4
5
Excitation energy (MeV)

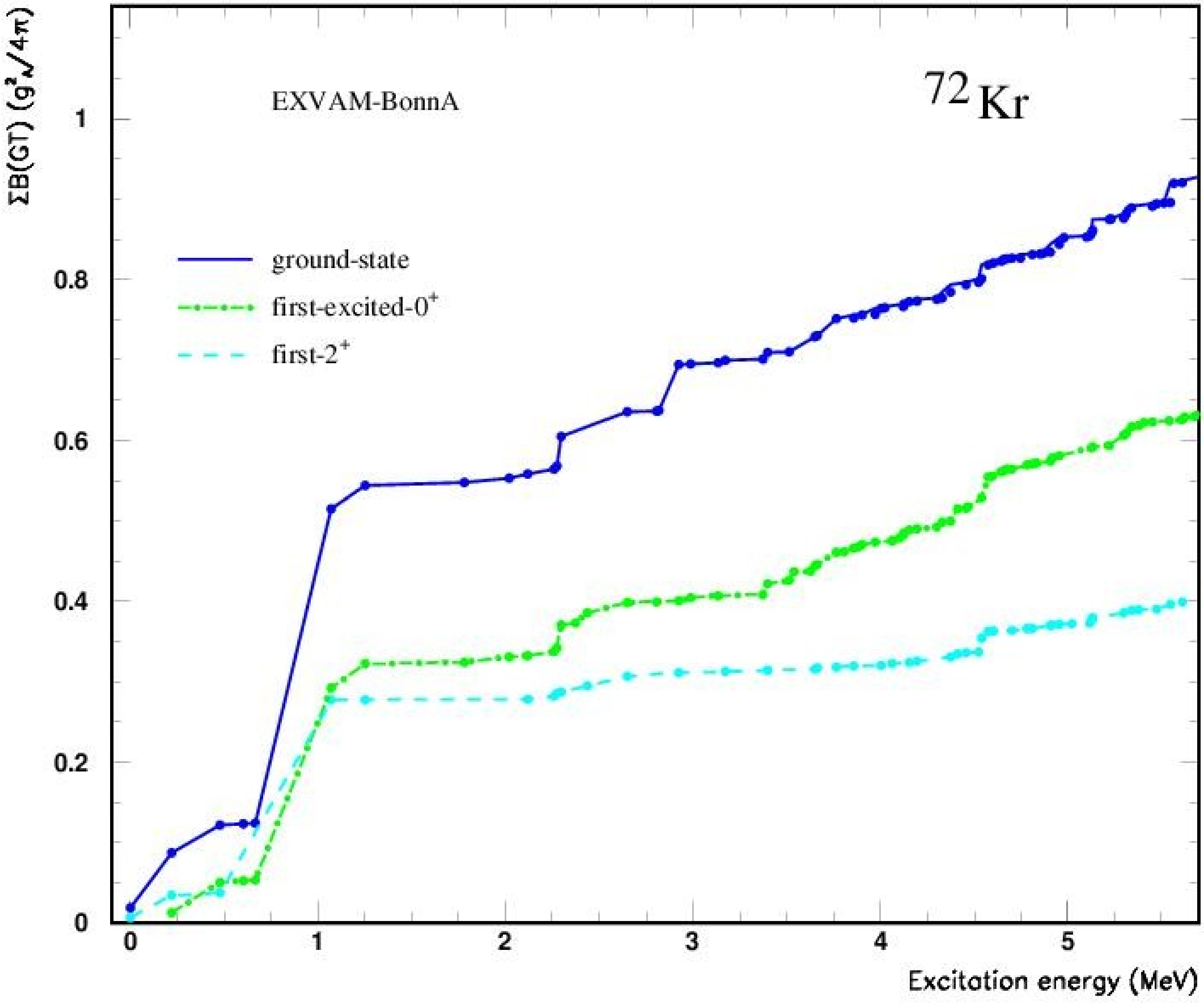

^{72}Kr (0_2)
EXVAM - BonnCD
10^4 B(GT) $(g_A^2/4\pi)$
10^5
10^4
10^3
10^2
10
1
0
1
2
3
4
5
Excitation energy (MeV)


^{72}Kr (2_1)
EXVAM - BonnCD
10^4 B(GT) $(g_A^2/4\pi)$
10^5
10^4
10^3
10^2
10
1
0
1
2
3
4
5
Excitation energy (MeV)

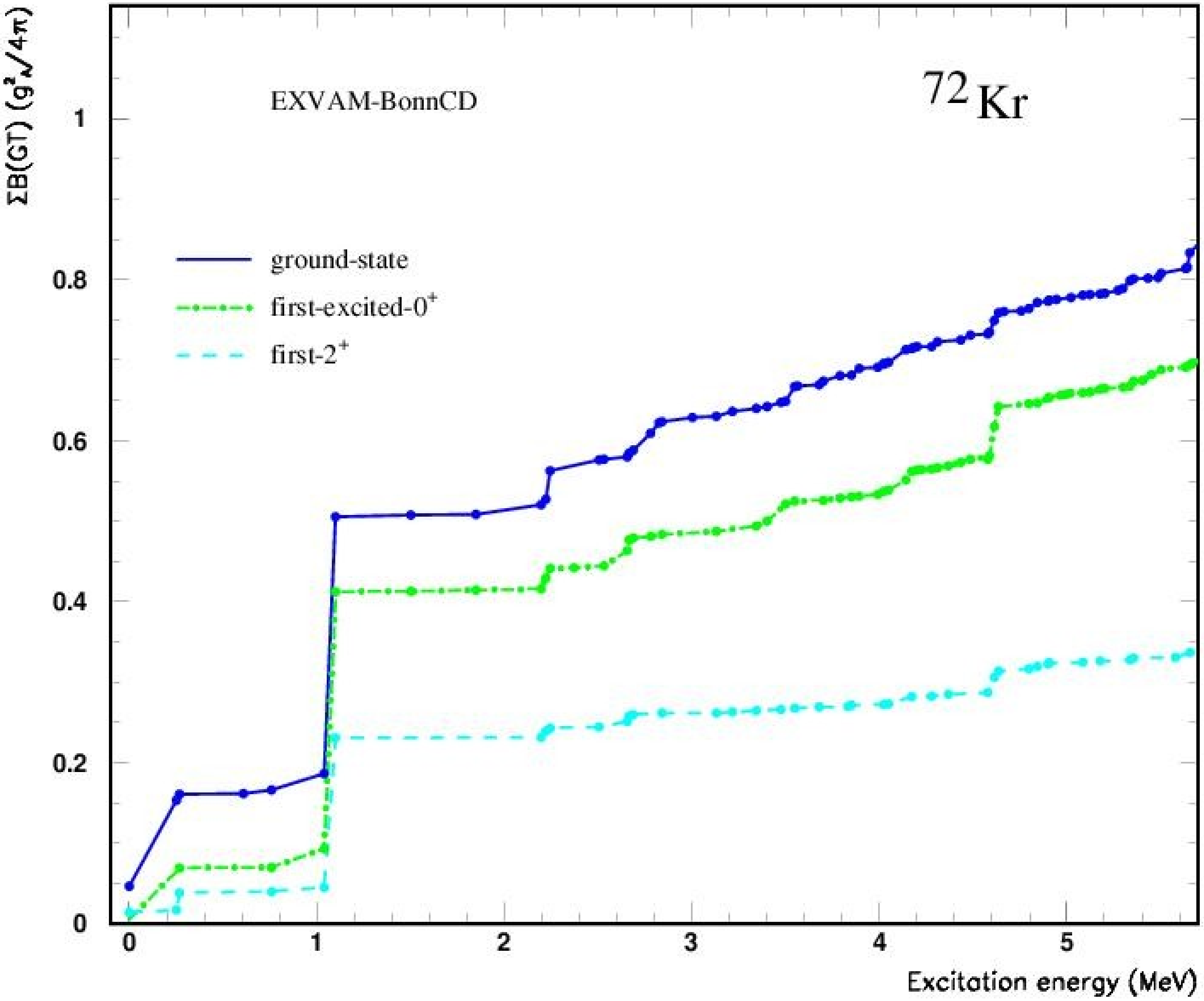

^{72}Kr (2_1)
EXVAM - BonnA
(3^+)
10^4 B(GT) $(g_A^2/4\pi)$
10^5
10^4
10^3
10^2
10
1
0
1
2
3
4
5
Excitation energy (MeV)

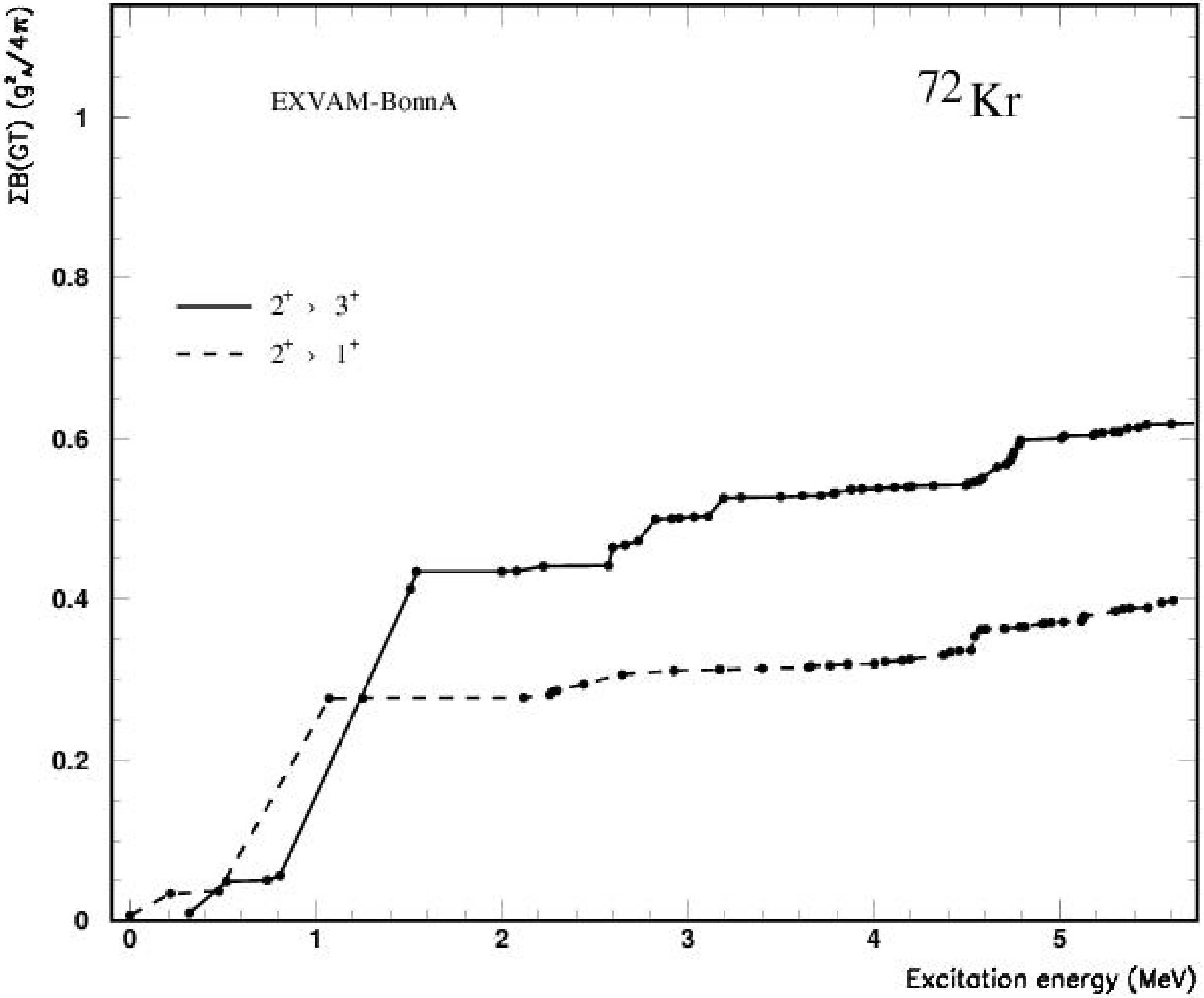
A. Petrovici et al., Phys. Rev. C - accepted





EXVAM-BonnA
^{72}Kr
ground-state
first-excited-0^+
first-2^+
$\Sigma B(GT)$ $(g_A^2/4\pi)$
0
0.2
0.4
0.6
0.8
1
0
1
2
3
4
5
Excitation energy (MeV)


$\Sigma B(GT)$ ($g_A^2/4\pi$)
EXVAM-BonnCD
^{72}Kr
ground-state
first-excited-0^+
first-2^+
0
0.2
0.4
0.6
0.8
1
0
1
2
3
4
5
Excitation energy (MeV)


$\Sigma B(GT)$ $(g^2_A/4\pi)$
EXVAM-BonnA
^{72}Kr
2^+ › 3^+
2^+ › 1^+
0
0.2
0.4
0.6
0.8
1
0
1
2
3
4
5
Excitation energy (MeV)

Summary and outlook

- the isospin-symmetry-breaking effect on the superallowed Fermi β decay of ^{82}Nb →^{82}Zr was investigated for the first time within the *complex* Excited Vampir model describing self-consistently both the analogue and non-analogue Fermi branches. Using this approach most of the 'radial mismatch problem' is avoided.

- the *complex* Excited Vampir description of the properties of low and high spins in even-even and odd-odd members of the T=1 multiplet for the A=82 nuclei is in good agreement with the available data

- the Gamow-Teller strength distributions as well as the accumulated strengths for the decay of the ground state, first-excited 0^+ and yrast 2^+ of ^{72}Kr to the 1^+ (and for yrast 2^+, also to the 2^+ and 3^+) states in the β window in ^{72}Br are self-consistently described for the first time. Good agreement with the available data is revealed. For the temperatures of the X-ray bursts the decay of the lowest excited states will not influence the halh-life of the ^{72}Kr

- improvements require extension of the single-particle and many-body model spaces
- uncertainties in the effective interaction require systematic investigations

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