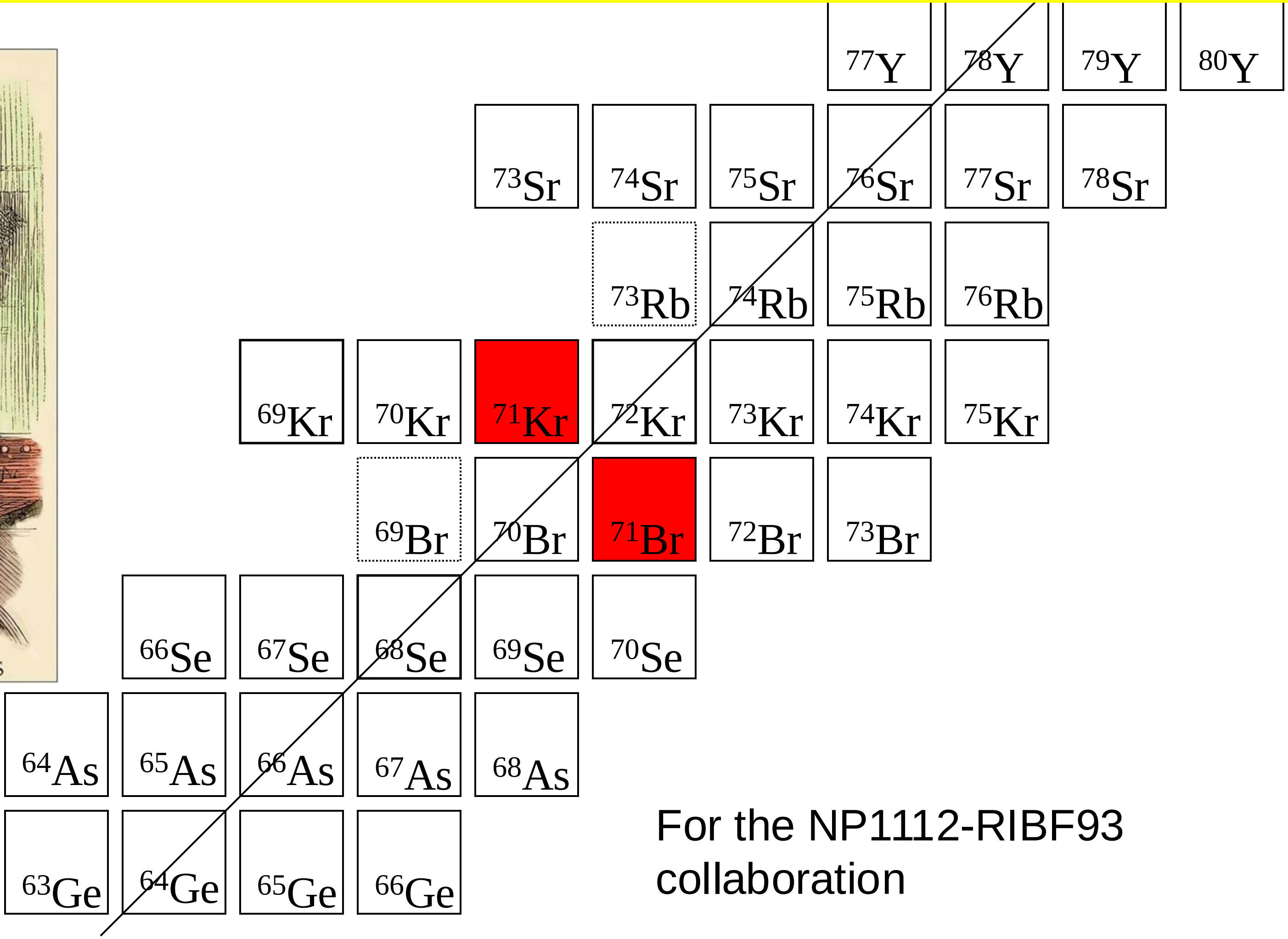
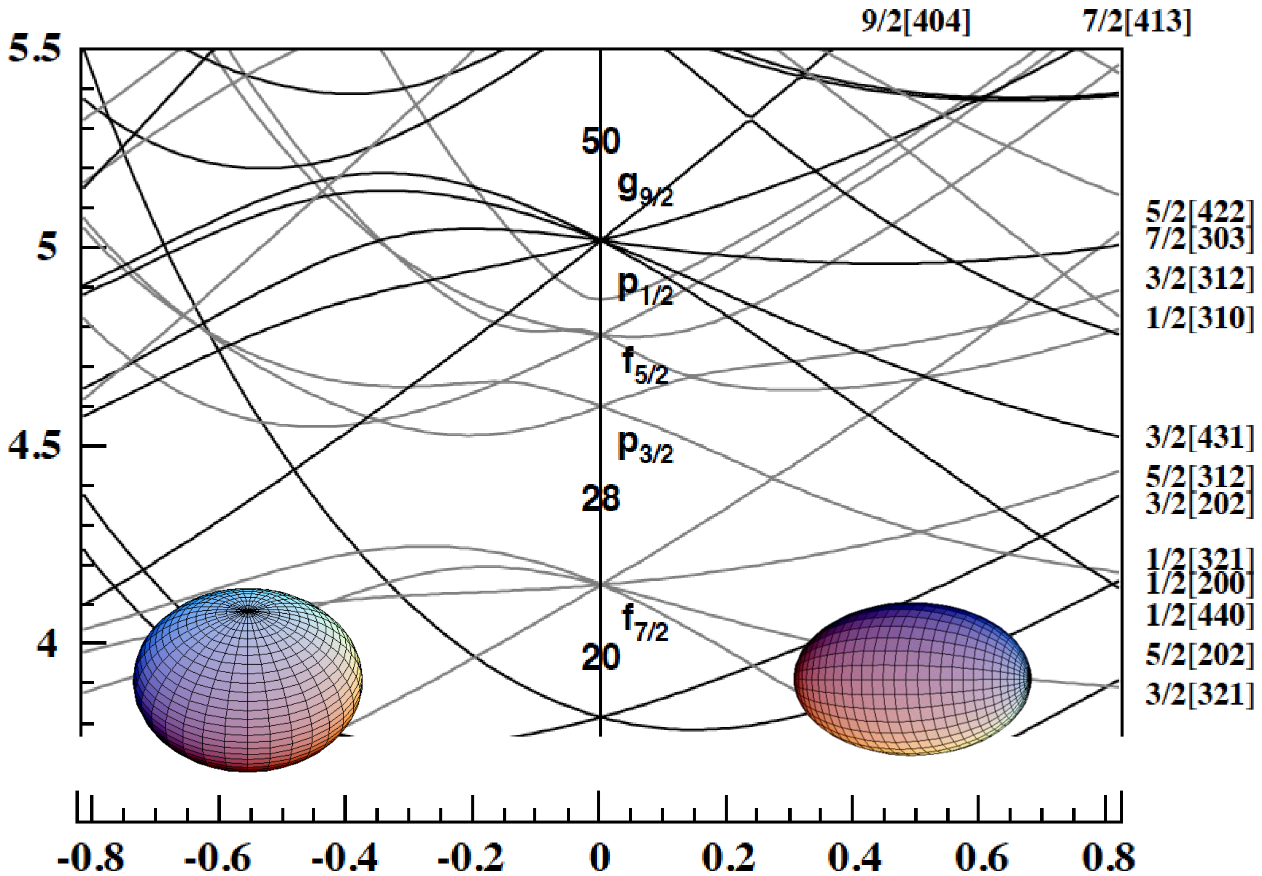
Deformation and isospin effects in the beta decay of ^{71}Kr

A. Algora
(IFIC, CSIC-Univ. Valencia; HUN-REN Atomki, Debrecen)



For the NP1112-RIBF93 collaboration

The N≈Z region around Z=34-38



This region is of particular interest in phenomena related to

- deformation
- shape co-existence
- isospin symmetry
- np pairing

Main reason: drastic shape and structural changes depending on the occupation of orbitals in a region of relatively low-level density

Study of isospin symmetry and isoscalar pn-pairing beyond the $f_{7/2}$ shell

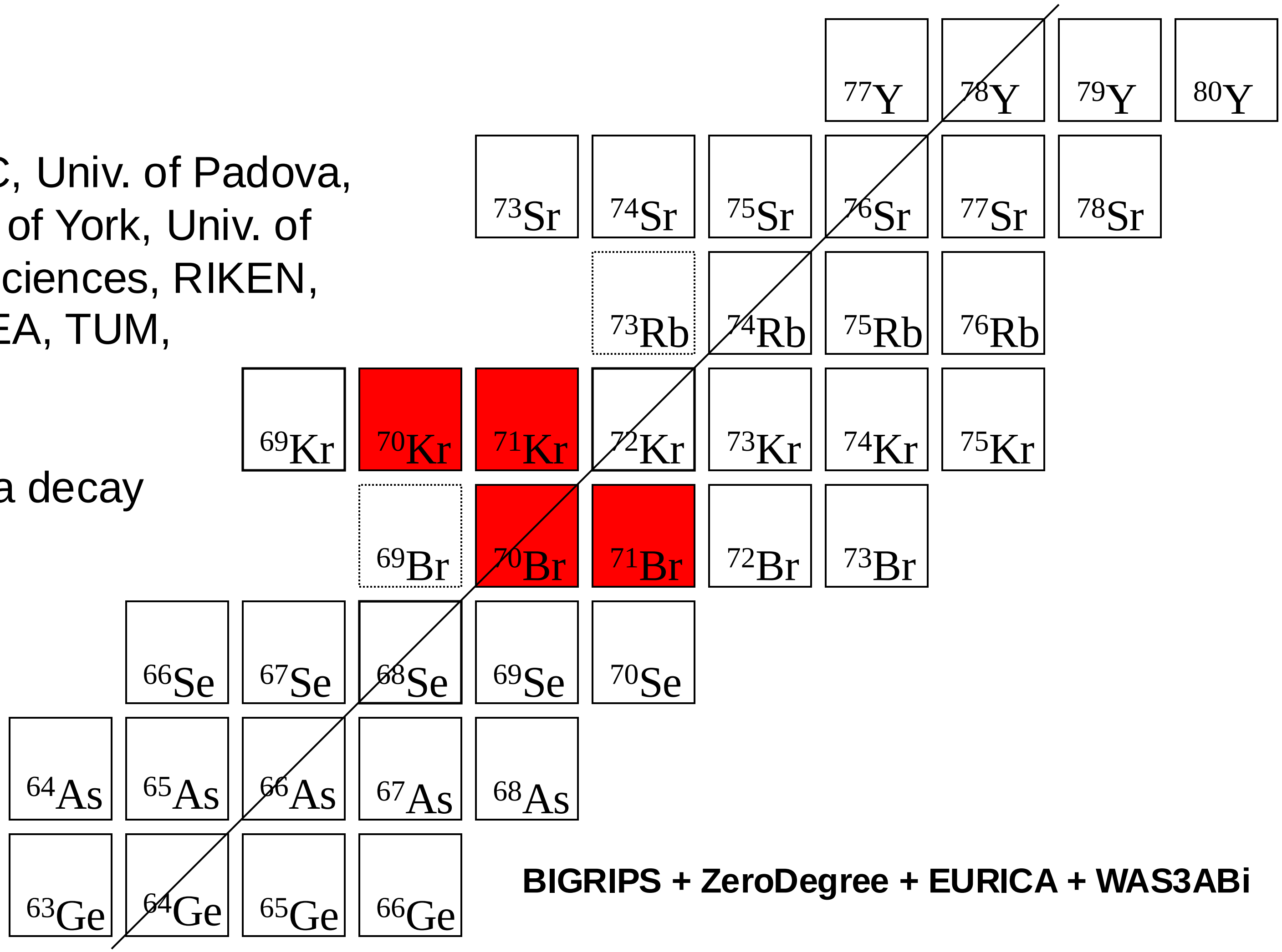
Spokespersons: G. De Angelis, A. Algora, F. Recchia, B. Rubio

Experiment NP1112-RIBF93

Collaboration:

LNL-INFN, IFIC-CSIC, Univ. of Padova, IEM-CSIC, IKP, Univ. of York, Univ. of Surrey, Tokyo Univ. Sciences, RIKEN, GSI, ANL, NIPNE, CEA, TUM, MTA ATOMKI

Main goal: ^{70,71}Kr beta decay



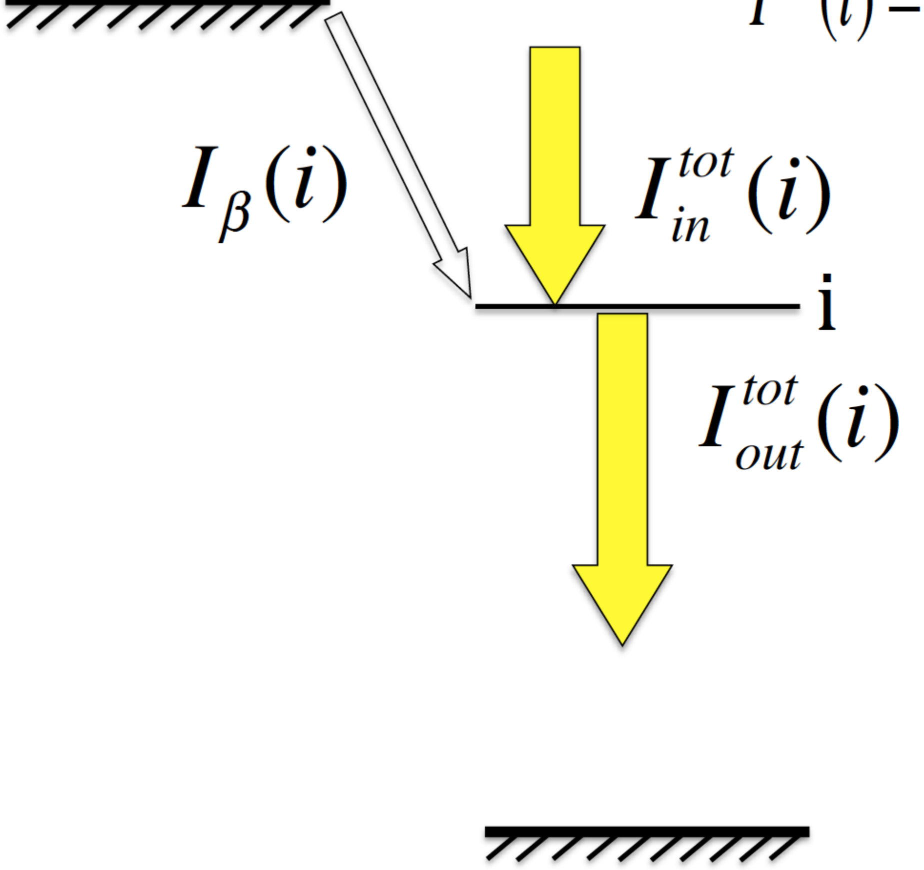
BIGRIPS + ZeroDegree + EURICA + WAS3ABi

A few words about beta decay: beta feedings

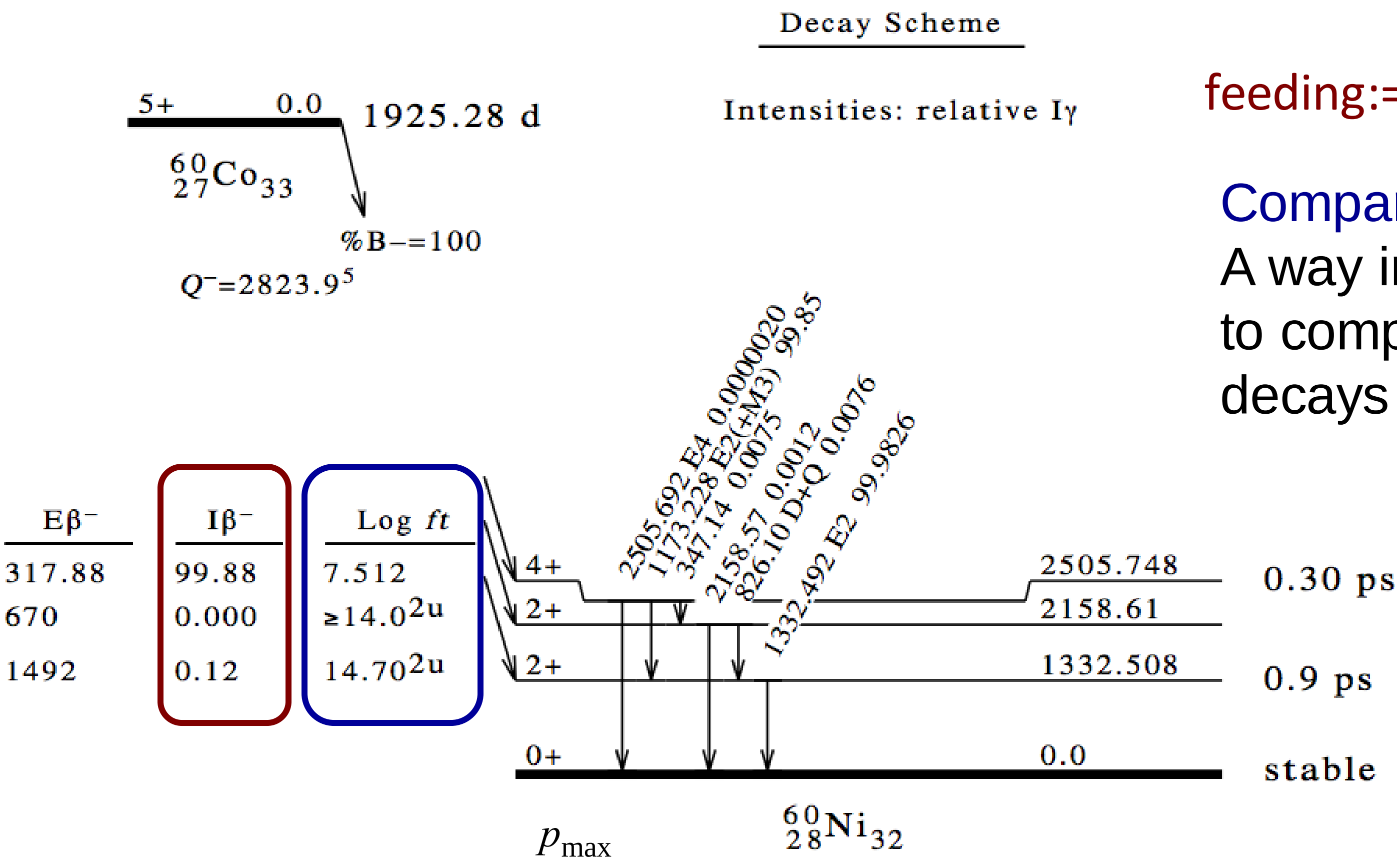
(for excited states)

$$0 = I_{out}^{tot}(i) - I_{in}^{tot}(i) - I_{\beta}(i)$$

$$I^{tot}(i) = \sum_{k} I_{\gamma_k} + I_{CE_k}$$



Example: ^{60}Co decay from http://www.nndc.bnl.gov/



feeding:= $I_\beta = P_f$*100

Comparative half-life: ft

A way introduced by Fermi to compare the different decays (Q, Z')

$$f(Z',Q) = const \times \int_0^{p_{max}} F(Z',p)\,p^2 (Q - E_e)^2\,dp, \qquad t_f = \frac{T_{1/2}}{P_f}$$

$$ft_f = const' \frac{1}{|M_{if}|^2} \qquad B(GT) \sim |M_{if}^{st}|^2 \qquad T_{1/2} = \frac{\ln(2)}{\lambda} = \tau \ln(2)$$

Mirror nuclei and fundamental applications

$${}^{A}_{Z}X_{N} \quad \Big| \quad {}^{A}_{N}Y_{Z}$$

Why their study is relevant:

Provides a way to test how good the isospin concept/symmetry is valid (if the strong force between protons and neutrons is the same then their spectrum should be very similar,once the Coulomb force and other distortions are taken into account).

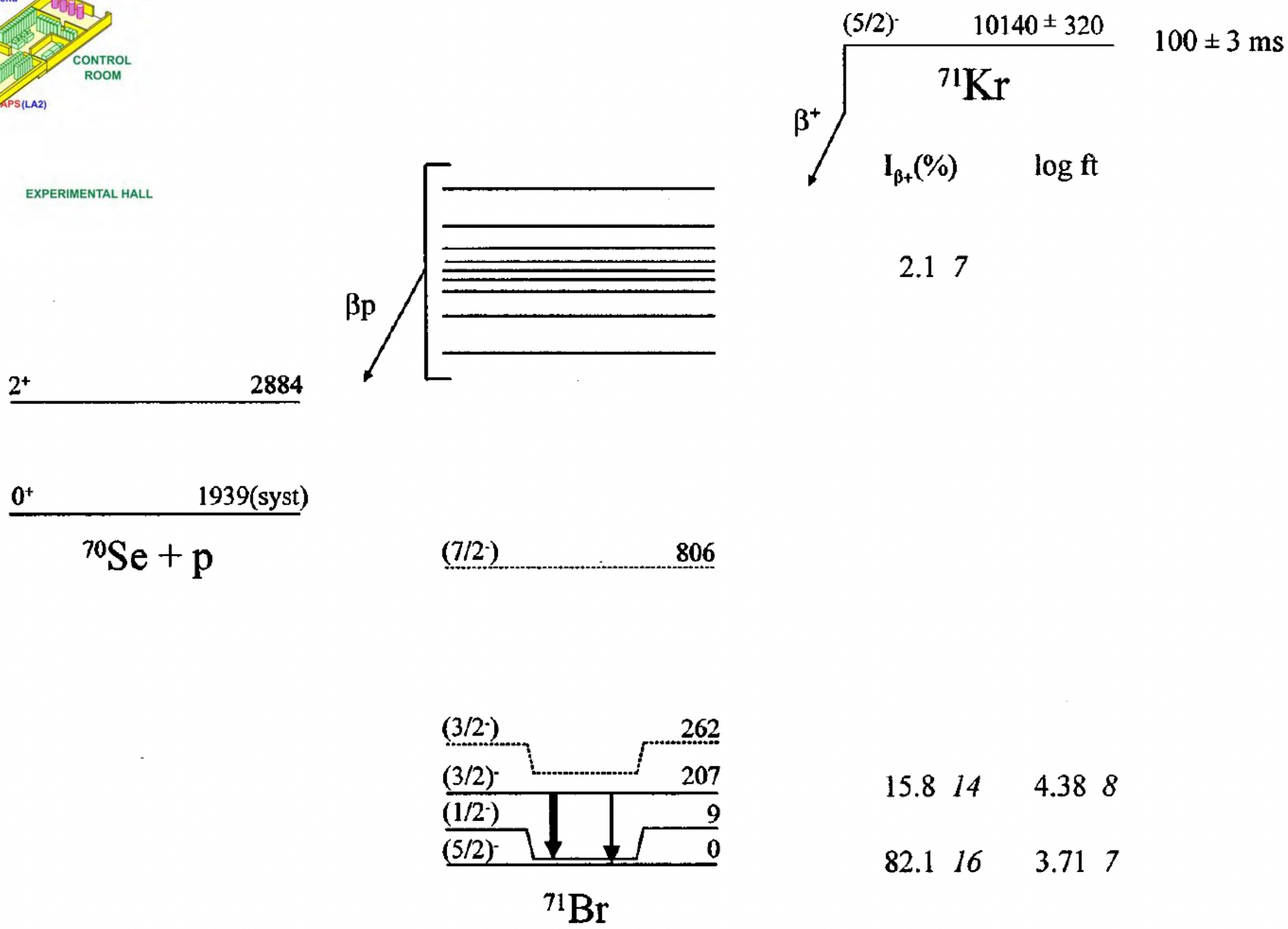
It also provides independent data to test the unitarity of the CKM matrix and the CVC hypothesis.

See Naviliat-Cuncic, Severijns, PRL 102, 142302 (2009)
(Fermi transitions between IAS)

Beta decay of ^{71}Kr: the first detailed study

ISOLDE, CERN

$$^{71}_{36}Kr_{35} \rightarrow {}^{71}_{35}Br_{36}$$



M. Oinonen, Phys. Rev. C 56, 745 (1997)

Mirror nuclei for fundamental applications

TABLE II. Branching ratios, BR, for the $T = 1/2$ mirror β transitions. References to data listed here are given in Table IV. References to rejected data are listed in Table VI.

Parent nucleus	Measured branching ratio, BR (%) 1		2		3		Average value BR%	scale S
^{3}H	100	[Ti87]					100	
^{11}C	100	[Aj75]					100	
^{13}N	100	[Aj70]					100	
^{15}O	100	[Aj70]					100	
^{17}F	100	[Aj70]					100	
^{19}Ne	BR(1.55 MeV):		0.0021 ± 0.0003	[Al76]	0.0023 ± 0.0003	[Ad83]		
	BR(0.11 MeV):		0.012 ± 0.002	[Ad81]	0.011 ± 0.009	[Sa93]	99.9858 ± 0.0020	1
^{21}Na	94.9 ± 0.2	[Al74]	95.8 ± 0.2	[Az77]	94.98 ± 0.13	[Wi80]		
	95.26 ± 0.04	[Ia06]	95.15 ± 0.12	[Ac07]			95.235 ± 0.069	2.0
^{23}Mg	90.9 ± 0.5	[Ta60]	91.4 ± 0.4	[Go68a]	90.9 ± 0.4	[Al74]		
	91.9 ± 0.4	[Ma74]	92.2 ± 0.2	[Az77]			91.78 ± 0.26	1.8
^{25}Al	99.16 ± 0.07	[Ju71]	99.1 ± 0.2	[Ma69]	99.11 ± 0.08	[Ma76]		
	99.16 ± 0.04	[Az77]					99.151 ± 0.031	1
^{27}Si	99.90 ± 0.02	[Go64]	99.80 ± 0.07	[De71]	99.82 ± 0.05	[Be71]		
	99.77 ± 0.02	[Ma74]	99.81 ± 0.01	[Az77]			99.818 ± 0.022	2.8
^{29}P	98.4 ± 0.3	[Lo62]	98.11 ± 0.30	[Az77]	98.29 ± 0.03	[Wi80]	98.290 ± 0.030	1
^{31}S	98.9 ± 0.1	[Ta60]	99.2 ± 0.4	[De71]	98.75 ± 0.06	[Al74]		
	98.89 ± 0.20	[Az77]	98.86 ± 0.04	[Wi80]			98.837 ± 0.031	1
^{33}Cl	98.3 ± 0.2	[Ba70]	98.58 ± 0.19	[Wi80]			98.45 ± 0.14	1
^{35}Ar	98.32 ± 0.07	[Wi69]	98.55 ± 0.05	[De71]	98.3 ± 0.2	[Ge71]		
	98.0 ± 0.2	[Az77]	98.24 ± 0.05	[Wi80]	98.24 ± 0.10	[Ad84]	98.358 ± 0.066	2.2
^{37}K	98.0 ± 0.4	[Ka64]	98.5 ± 0.2	[Ma76]	97.8 ± 0.2	[Az77]		
	97.89 ± 0.11	[Ha97]					97.99 ± 0.14	1.7
^{39}Ca	99.9975 ± 0.0002	[Ha94]					99.9975 ± 0.0002	
^{41}Sc	99.963 ± 0.003	[Wi80]					99.963 ± 0.003	
^{43}Ti	90.2 ± 0.8	[Ho87]					90.2 ± 0.8	
^{45}V	95.7 ± 1.5	[Ho82]					95.7 ± 1.5	
^{47}Cr	96.3 ± 1.2	[Bu85]					96.3 ± 1.2	
^{49}Mn	93.6 ± 2.6	[Ha80]	91.9 ± 2.8	[Ho89]			92.8 ± 1.9	1
^{51}Fe	95.0 ± 1.3	[Ay84]	93.8 ± 1.3	[Ho89]			94.40 ± 0.92	1
^{53}Co	94.4 ± 1.7	[Ho89]					94.4 ± 1.7	
^{57}Cu	89.9 ± 0.8	[Se96]					89.9 ± 0.8	
^{59}Zn	93.0 ± 3.0	[Ho81]	94.1 ± 0.8	[Ar84]			94.03 ± 0.77	1
^{61}Ga	94 ± 1	[We02]					94 ± 1	
^{71}Kr	82.1 ± 1.6	[Oi97]					82.1 ± 1.6	
^{75}Sr	$90.3^{+1.9}_{-2.8}$	[Hu03][a]					89.6 ± 2.4	

N. Severijns et al., PRC 78, 055501, (2008)

Beta decay of ^{71}Kr: Urkedal and Hamamoto

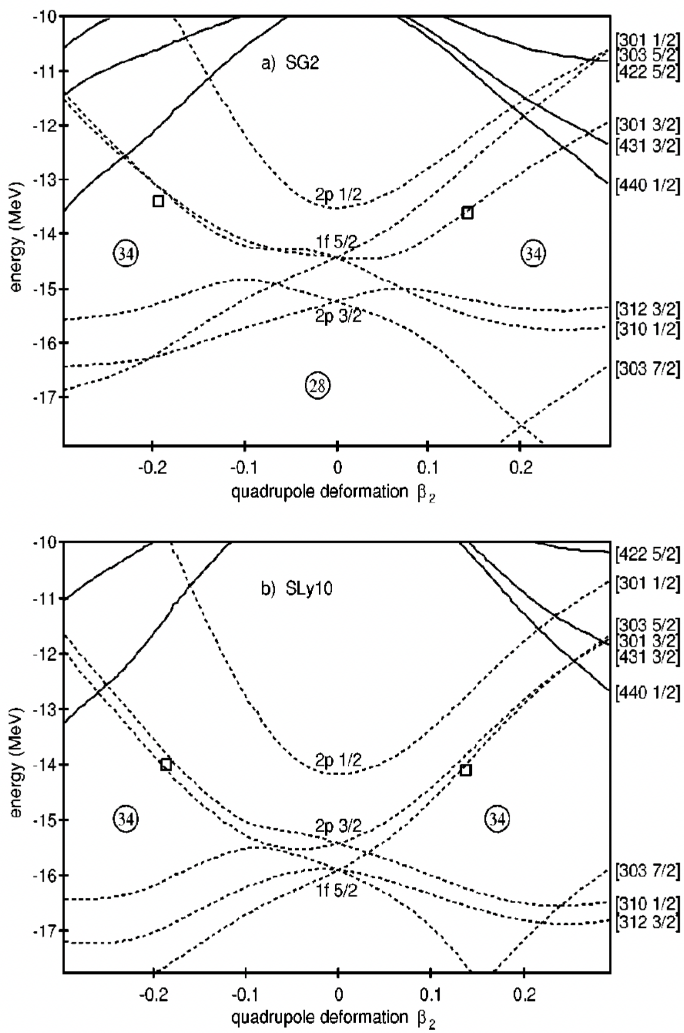


FIG. 2. Nilsson diagrams for neutron one-particle orbits in ^{72}Kr, based on calculations using (a) the SG2 and (b) the SLy10 interactions. The $N=36$ Fermi levels at the prolate and oblate HF minima are denoted by open squares. Asymptotic quantum numbers $[Nn_z\Lambda\Omega]$ are shown on the right. Negative (positive) parity orbits are drawn by dashed (solid) lines.

Premises:

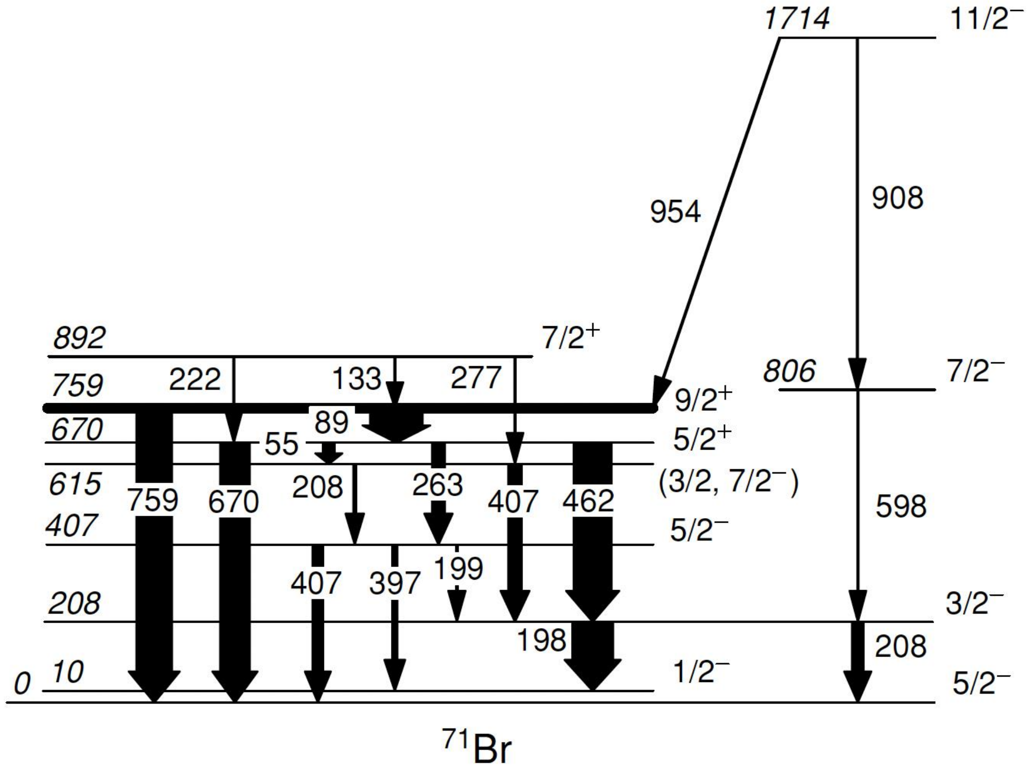
- The assignment of 5/2- to the gs of 71Br seems solid
- Deformation might be an issue
- Hartree-Fock calculations. Analysis of possible configurations in ^{71}Br. In their interpretation ^{71}Br is preferably prolate, but requires smaller spin-orbit splitting than conventional to get 5/2- as gs
- B(GT) calculations in asymptotic limit.

Conclusion of the work:

- Considering the magnitude of the B(GT)-s, the gs state of ^{71}Kr probably has the same deformation than his mirror counter part ^{71}Br, but it is a different state (3/2-).
- The same 5/2- can not account for the exp. B(GT) value.

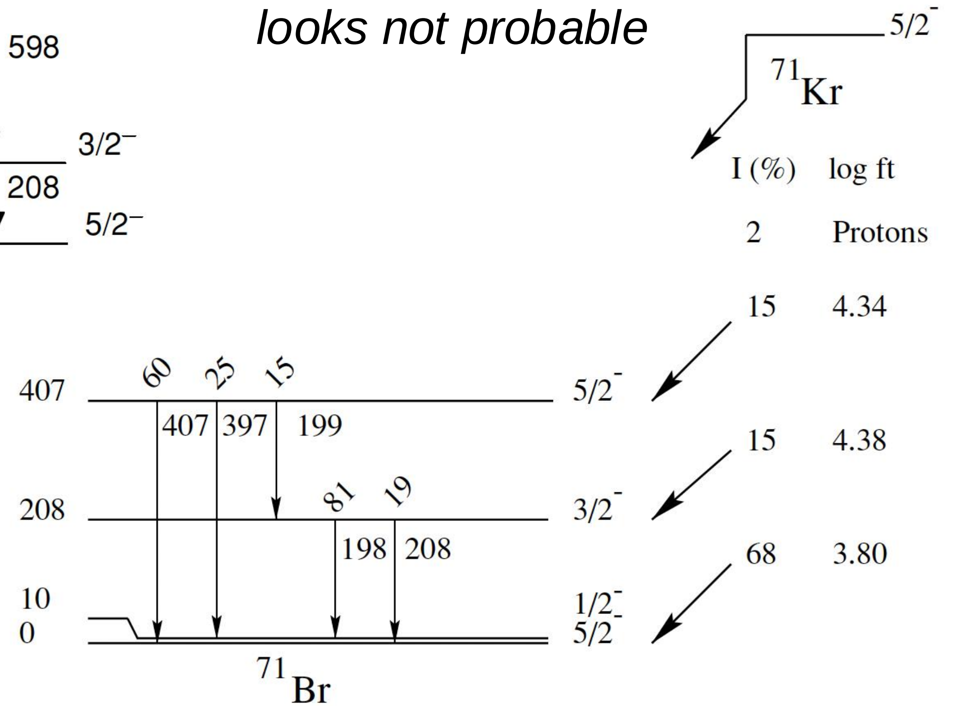
Urkedal, Hamamoto, PRC 58, R1889 (1998)

Beta decay of ^{71}Kr: infered from in-beam?



Revisited conclusions of Oinonen, based on a careful work in in-beam for 71Br (ATLAS, Gammasphere). Redistribution of gamma intensities, implies different feeding patterns.

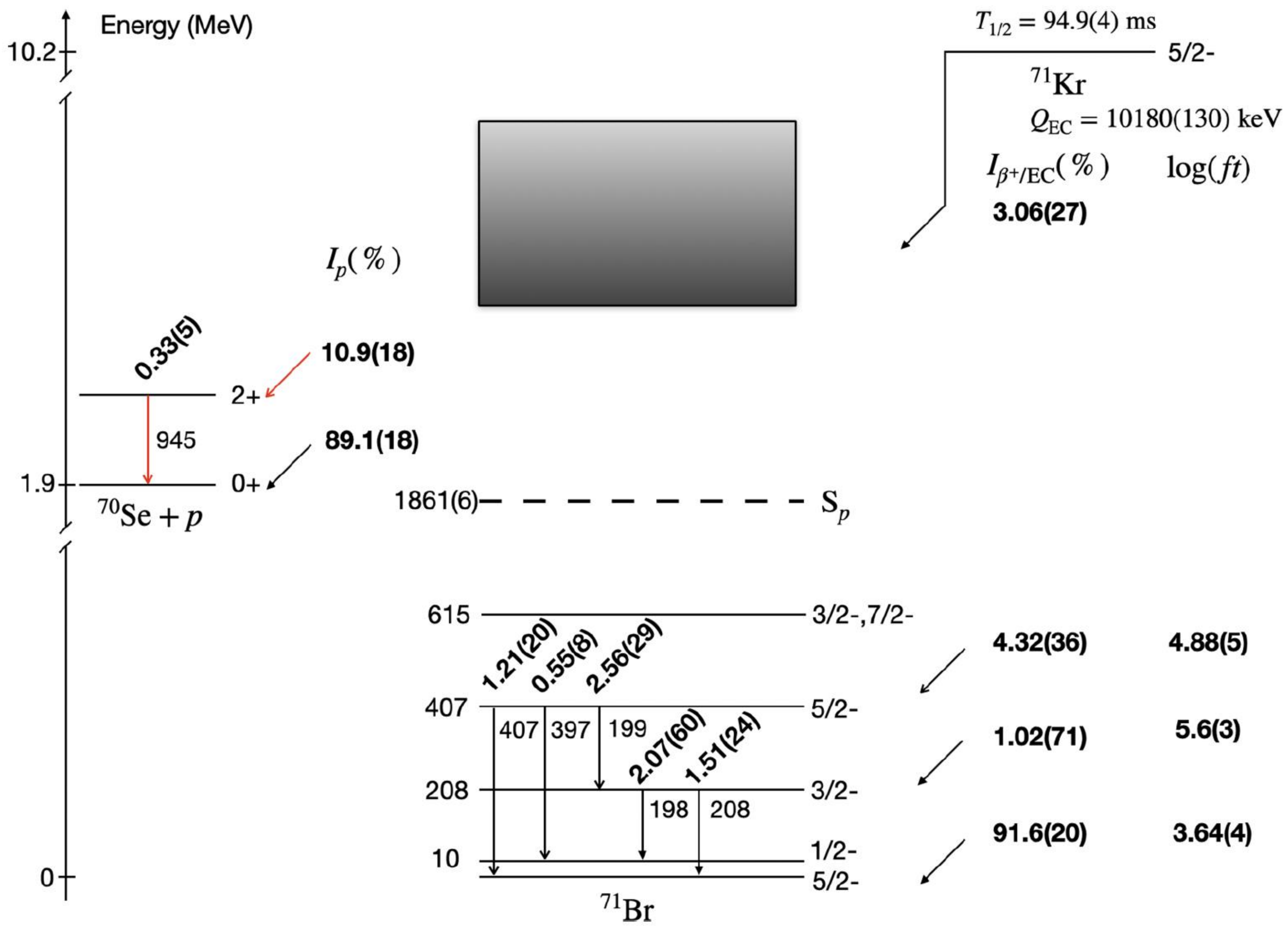
Compared to other mirror decays looks not probable



S.M. Fischer *et al.*, PRC72, 024321 (2005)

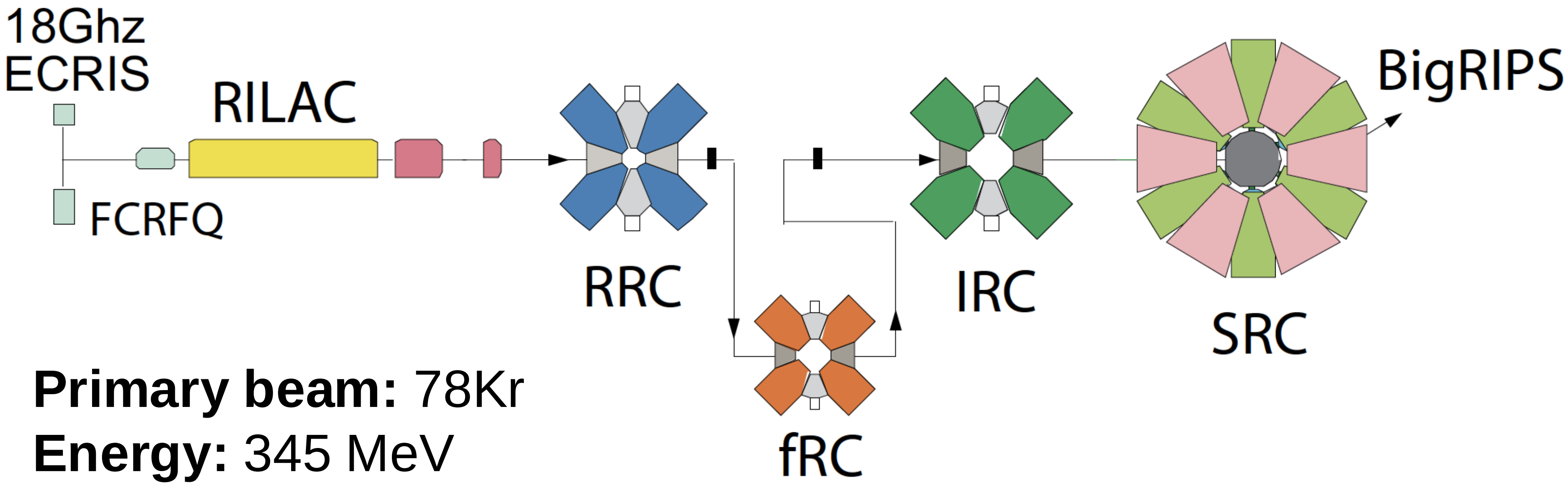
FIG. 10. The modified β-decay scheme for ^{71}Kr.

Beta decay of ^{71}Kr: Waniganeththi et al.

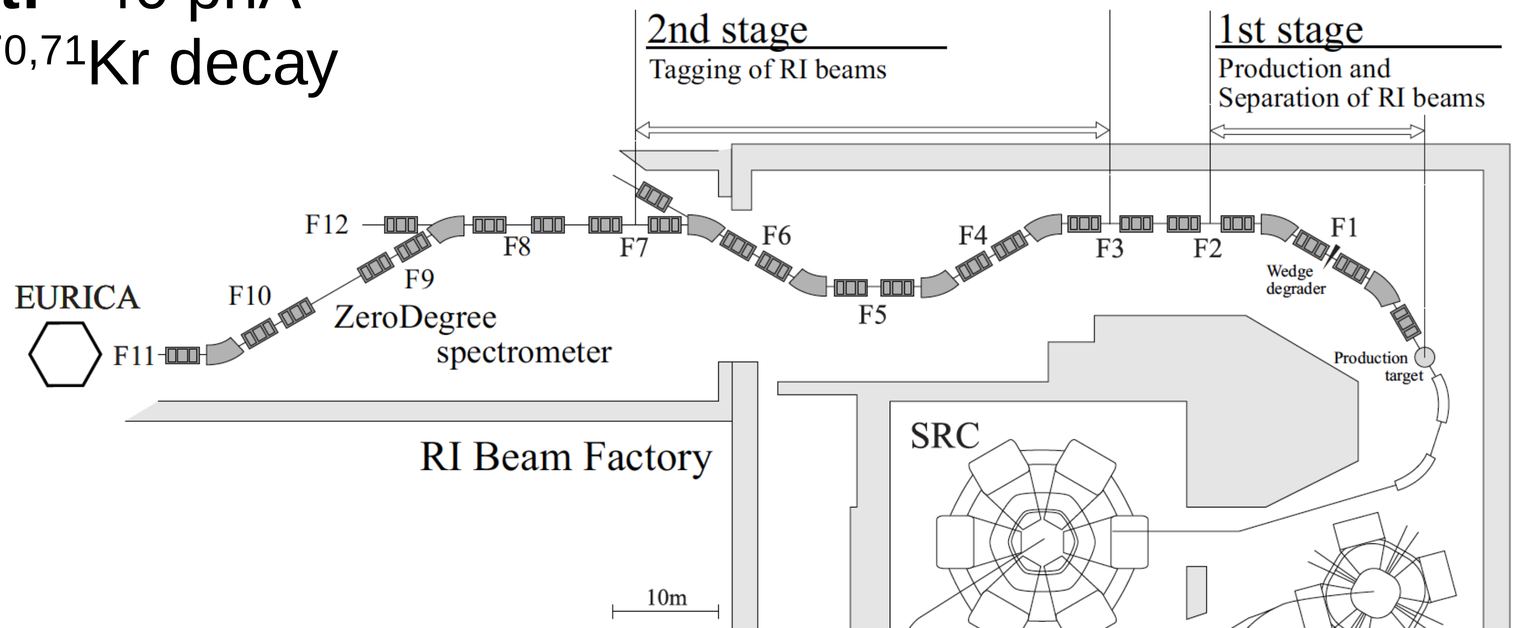


S. Waniganeththi *et al.*, PRC 106, 044317 (2022)

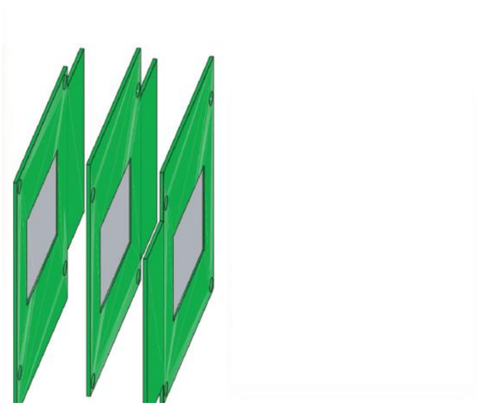
Beta decay of ^{71}Kr: our experiment



Primary beam: 78Kr
Energy: 345 MeV
Typ. Int: ~40 pnA
Goal: ^{70,71}Kr decay



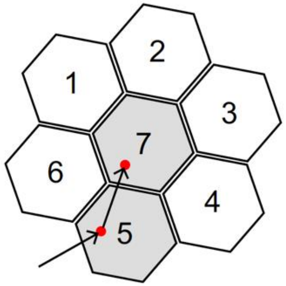
Beta decay of ^{71}Kr: our experiment

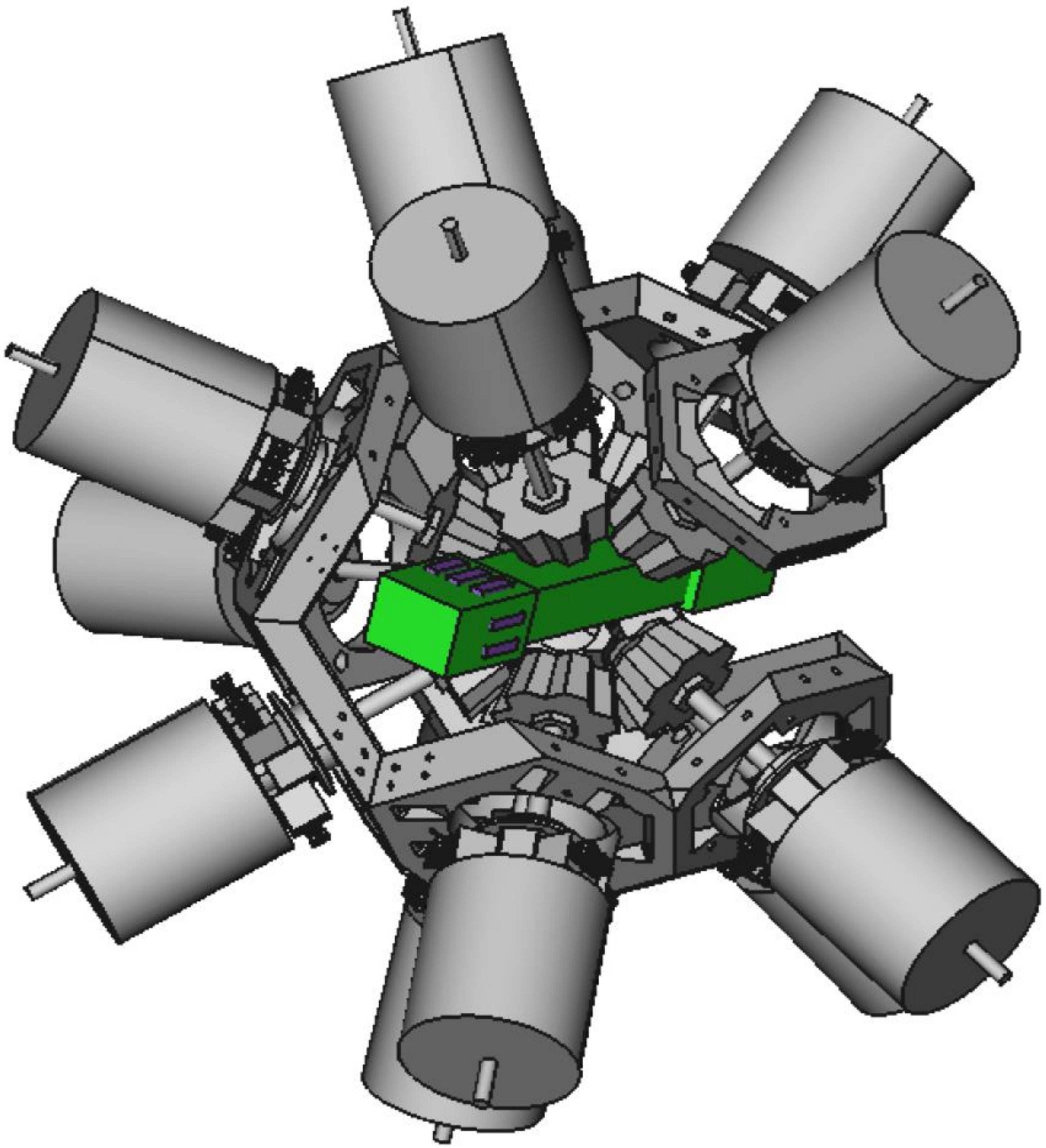


Implantation detector
WAS3ABI + EURICA

84 capsules
(12 cluster detectors of 7 capsules)

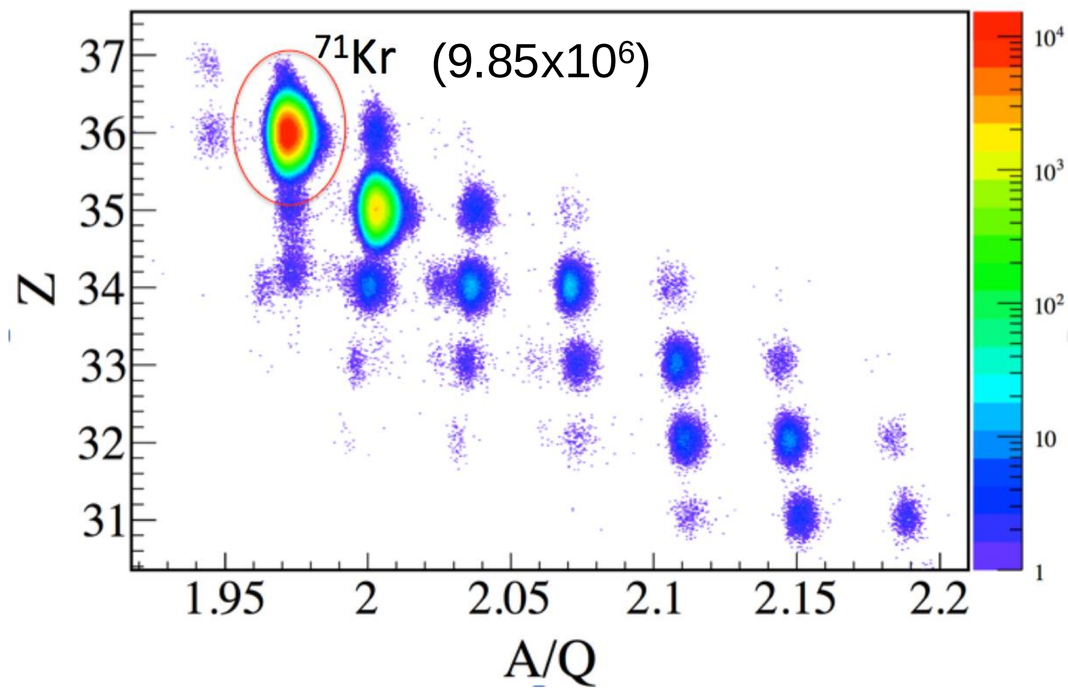
Singles eff 4.5 % at 1 MeV
Addback eff 6 % at 1 MeV





Beta decay of ^{71}Kr: our experiment

PID of the fragments using BigRIPS (Bρ-ΔE-TOF method)

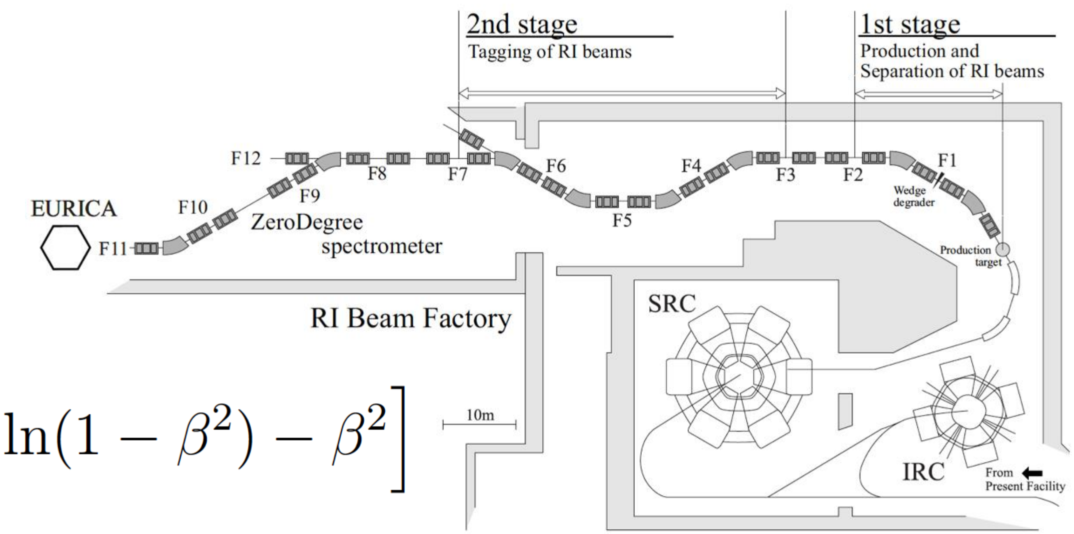


In the Eurica exp:
TOF between F3 and F7
Bro measured (or extrapolated)
Z identifed from the energy loss in MUSIC detectors
Correlations are needed for the analysis of the experiment

$$\mathrm{TOF} = \frac{L}{\beta c}$$

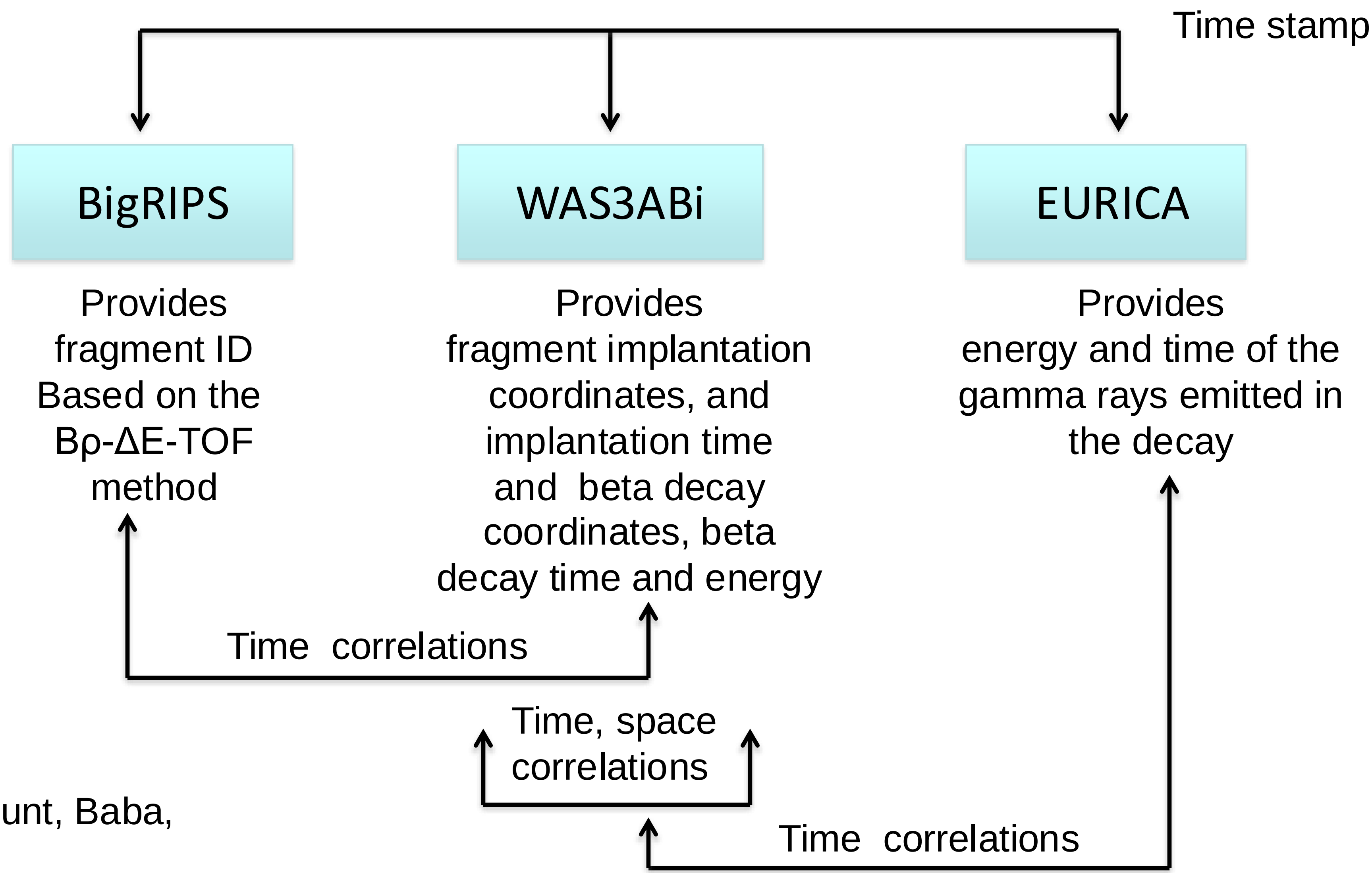
$$\frac{A}{Q} = \frac{B\rho}{\beta\gamma}\frac{c}{m_u}$$

$$\frac{dE}{dx} = \frac{4\pi e^4 Z^2}{m_e v^2} N z \left[\ln\frac{2 m_e v^2}{I} - \ln(1-\beta^2) - \beta^2\right]$$



The complexity of the experiments: correlations

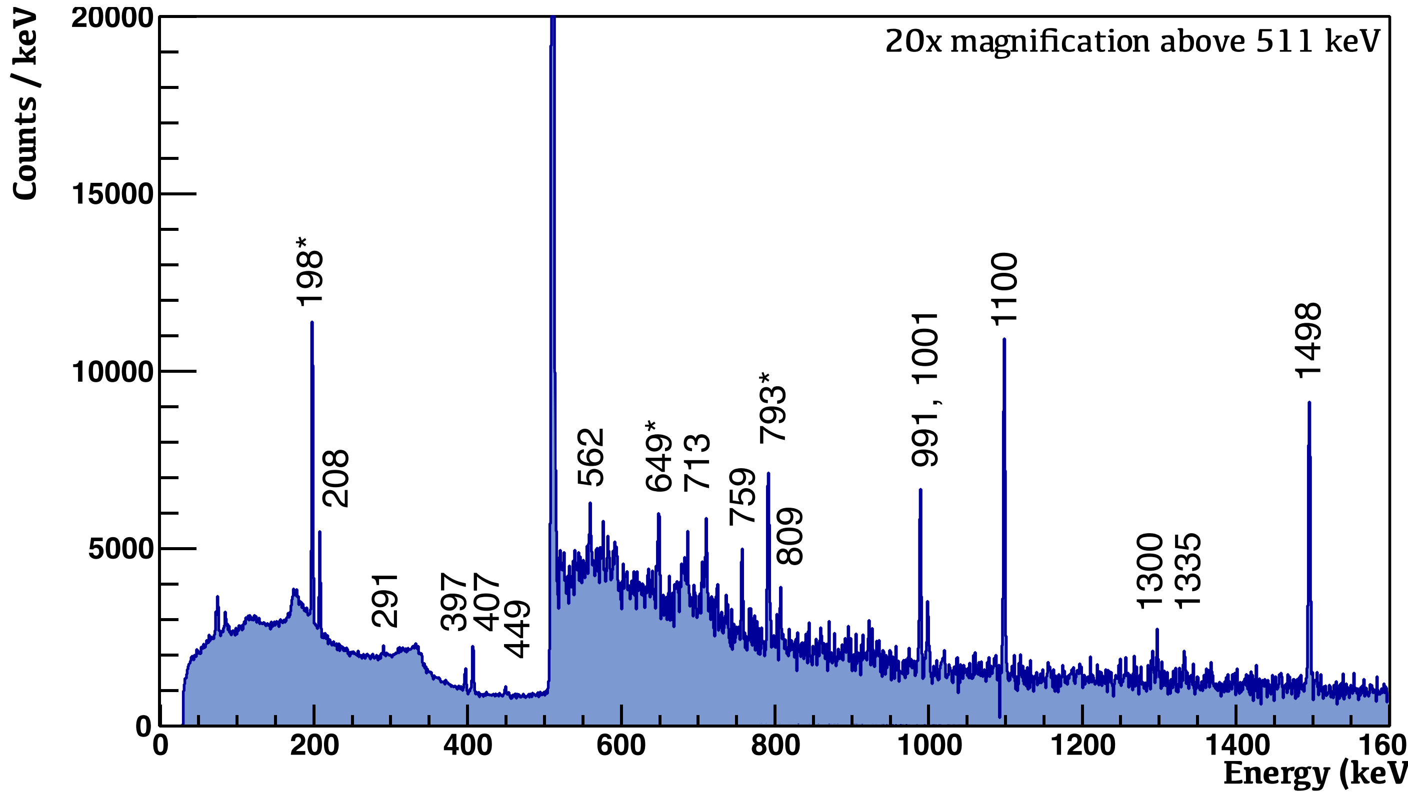
Three independent data acquisition systems



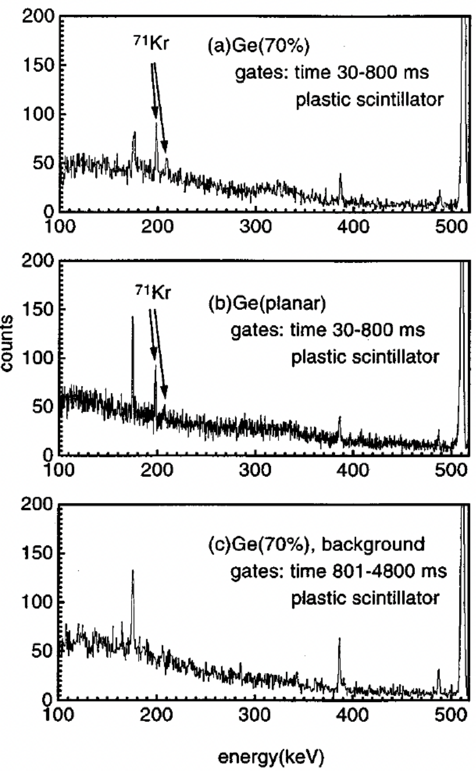
Agramunt, Baba, et al.

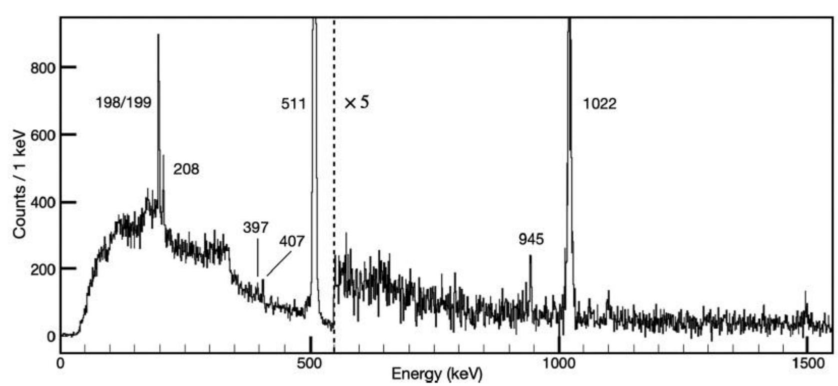
Beta decay of ^{71}Kr: our experiment

Our high stat. data



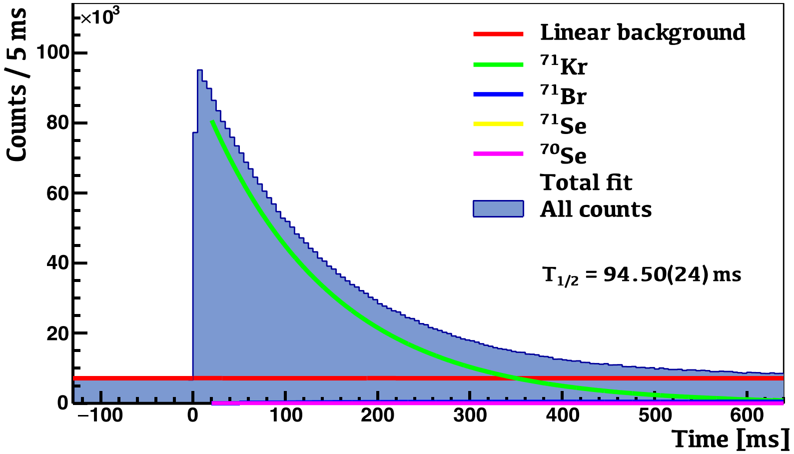
Oinonen et al.





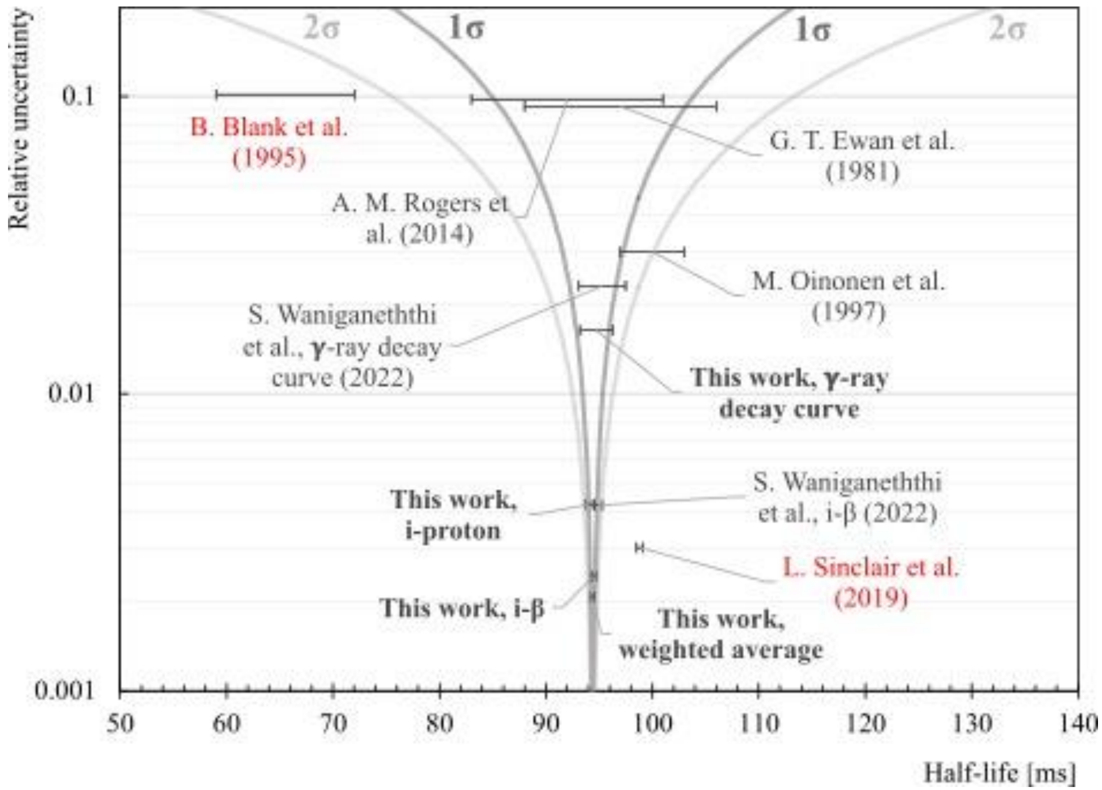
Waniganeththi et al.

Beta decay of ^{71}Kr: half-life

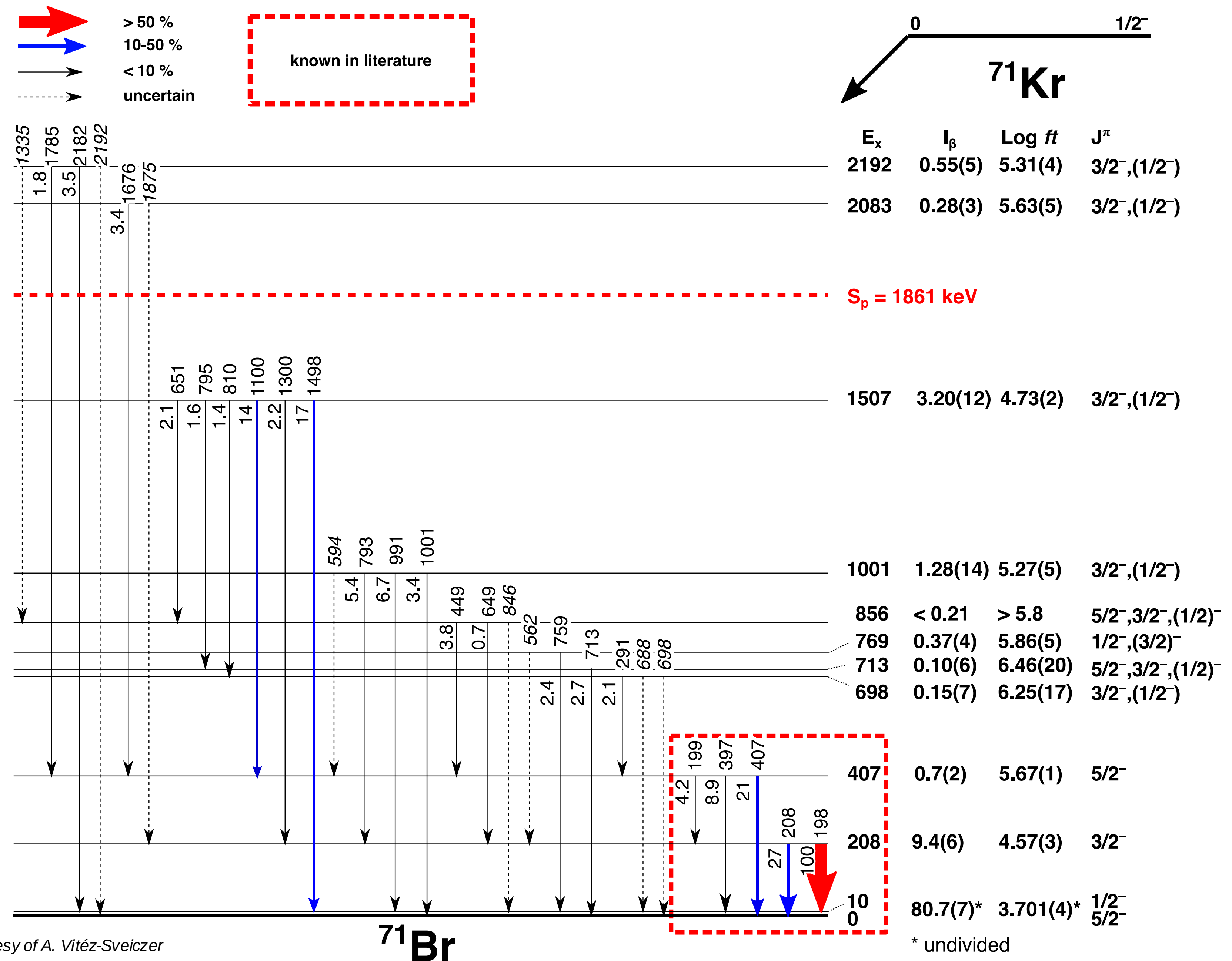


Method	$T_{1/2}$(ms)
i-β	95.5 ± 0.06 (stat)$^{+0.21}_{-0.23}$(sys.)
i-β-γ	94.7 ± 0.5 (stat)$^{+1.6}_{-1.5}$(sys.)
i-β-p	94.1 ± 0.2 (stat)$^{+0.3}_{-0.3}$(sys.)

Courtesy of A. Vitéz-Sveiczer



Beta decay of ^{71}Kr: level scheme



Courtesy of A. Vitéz-Sveiczer

Beta decay of ^{71}Kr: Shell model calculations

Framework: large scale shell model calculations (SM-CI)
Interaction: PFSDG-U
Valence space: orbits 1p3/2, 1p1/2, 0f5/2, 0g9/2, and 1d5/2.

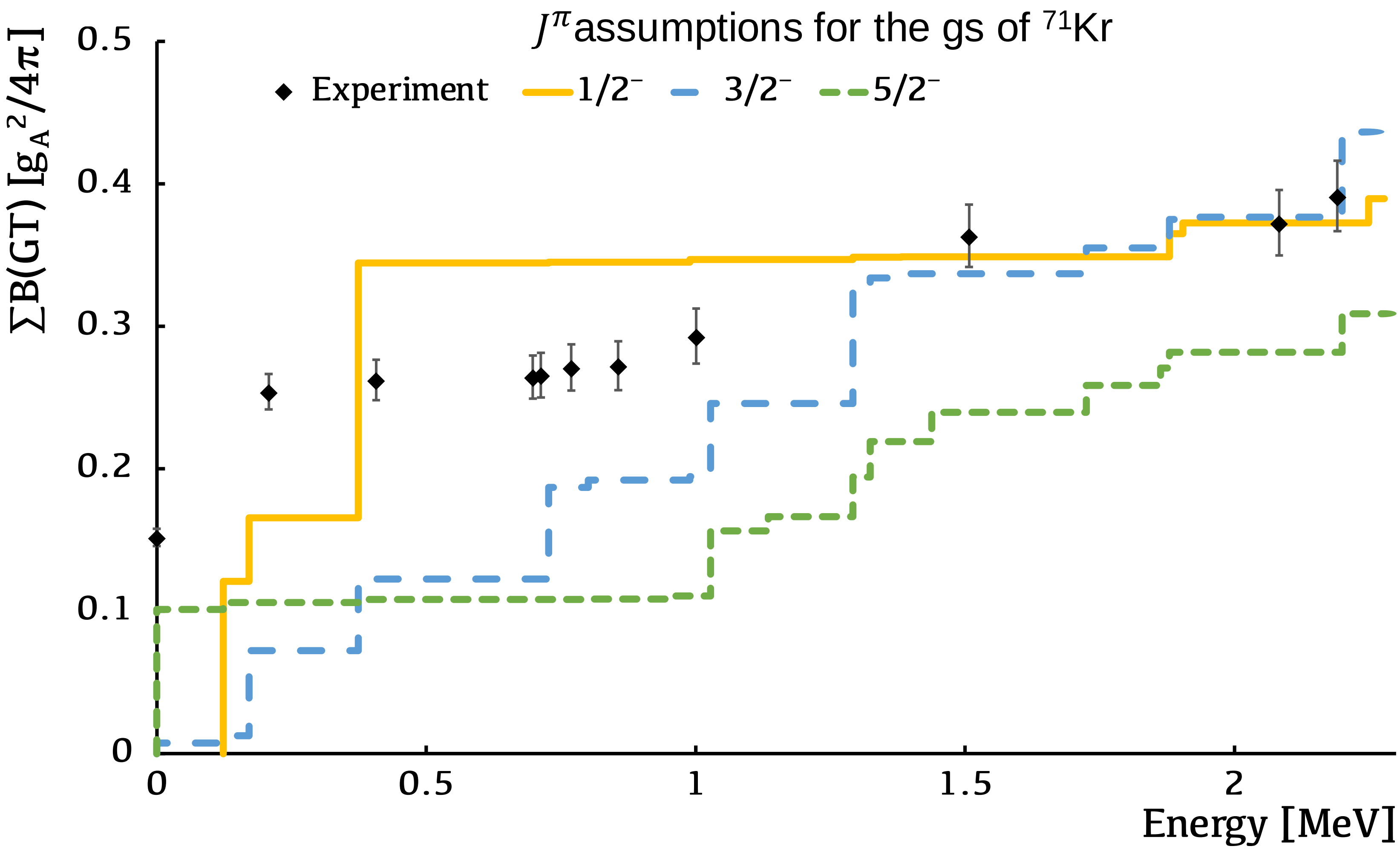
B(GT) calculated for different assumptions of J^{π} assignments to the ground state.

In addition, Coulomb and other charge symmetry breaking (CSB) terms were evaluated

Same model was recently used to explain the gs inversion in the A=73 case (see next slides)

Calculations by Alfredo Poves

Beta decay of ^{71}Kr: accumulated beta strength



Beta decay of ^{71}Kr: Shell model calculations

Framework: large scale shell model calculations (SM-CI) using the interaction
Interaction: PFSDG-U
Valence space: orbits 1p3/2, 1p1/2, 0f5/2, 0g9/2, and 1d5/2.

In addition, Coulomb and other charge symmetry breaking (CSB) terms were evaluated

TABLE I. Calculated energy levels with the PFSDG-U interaction (A=71 column) and considering in successive approximations the electromagnetic and nuclear charge symmetry breaking (CSB) terms (see reference [25] for more details): (a) Nuclear plus Coulomb two body plus the electromagnetic $\vec{l}\cdot\vec{l}$ and $\vec{l}\cdot\vec{s}$ contributions to the single particle energies of protons and neutrons; (b)=(a) plus the nuclear CSB correction; (c)=(b) plus the radial correction to the mirror energy differences (MED) assigned to ^{71}Kr. All energies are given in keV.

J^π	A=71	^{71}Kr (a)	^{71}Kr (b)	^{71}Kr (c)	^{71}Br (a)	^{71}Br (b)	^{71}Br (exp)
$5/2^-$	0	0	0	0	0	0	0
$1/2^-$	171	45	50	23	33	26	10
$3/2^-$	123	131	136	137	182	189	208
$9/2^+$	1047	975	998	902	882	877	759

Calculations by Alfredo Poves

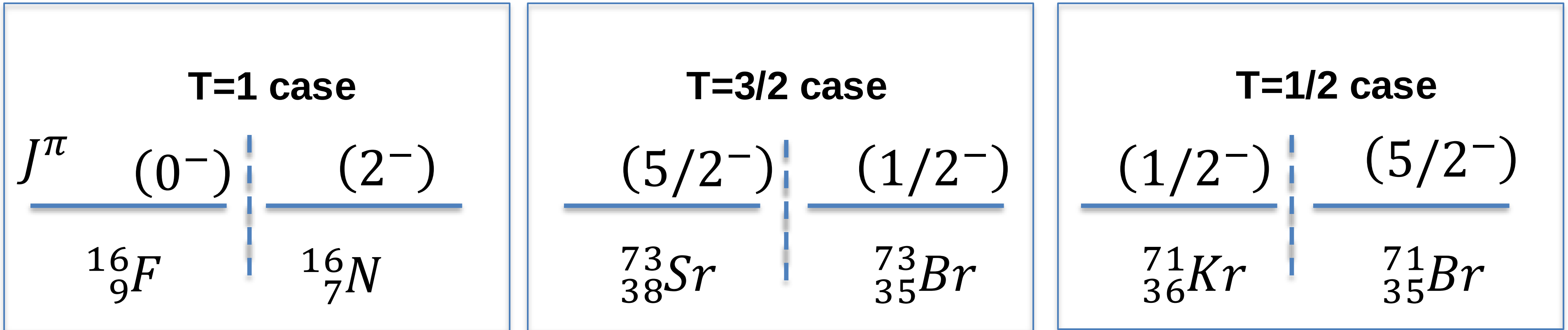
Rare case of ISOSPIN symmetry breaking

We infer an ISOSPIN breaking in the ground state of mirror A=71 nuclei (^{71}Kr vs ^{71}Br). First time in the literature for a T=1/2 case (Algora, Vitéz-Sveiczer et al.), which is the possible simplest case.

Identified cases before:

T=1 case. (^{16}F-^{16}N) mirror pair, a special system where ^{16}F is particle unbound and ^{16}N is particle bound. The symmetry breaking in this case is explained as a consequence of the Coulomb interaction, by an effect known as the Thomas-Ehrmann shift (Stefan et al. Phys. Rev. C 90, 014307 (2014)).

T=3/2 case. (^{73}Sr-^{73}Rb) This last case was identified indirectly by studying the proton emission of states in ^{73}Rb that indicates the assignment of Jπ =(5/2−) to the ground state of ^{73}Sr, to be compared with the Jπ=1/2− assignment to ^{73}Br in its ground state (Hoff et al., Nature 580, 52 (2020))



Beta decay of ^{71}Kr: shapes, some partial conclusions

Final shape conclusion from SM not so clear, but clearly there is and inversion in the lowest states.

I quote (short version): ...if you can not speak, remain silent

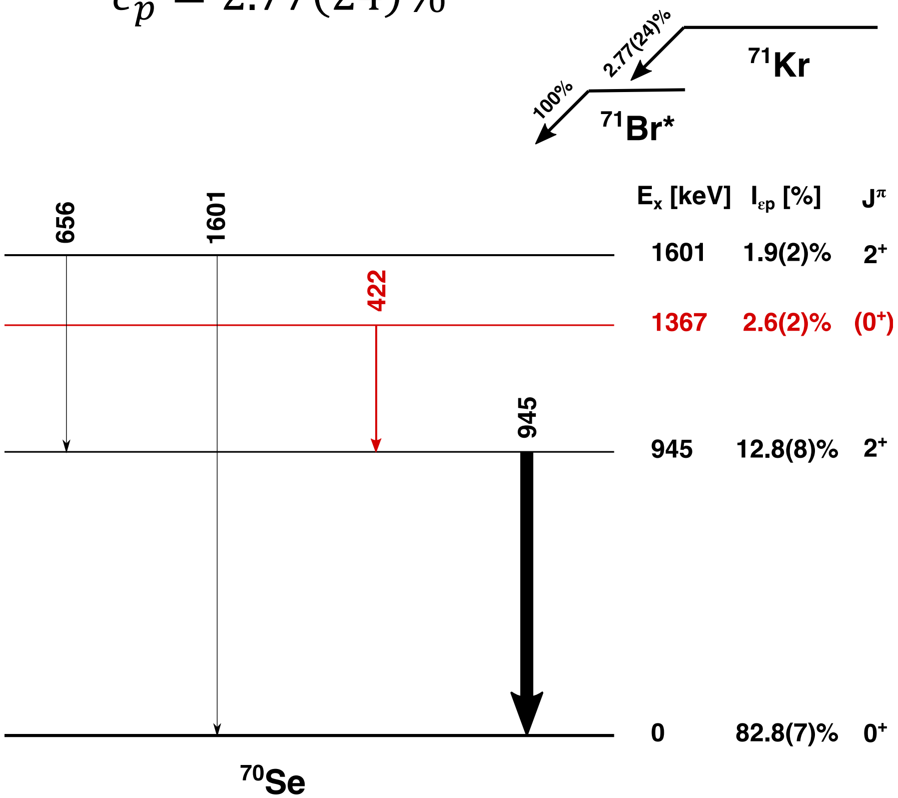
In the mean field approach based on the Skyrme SLy4 interaction the ground state corresponds to an oblate minimum consistent with the 1/2− assignment with a deformation β=-0.18. In the prolate side the various local minima correspond to a 3/2− state with β=0.14 and to slightly excited states 5/2− and 1/2− with deformation β=0.09.

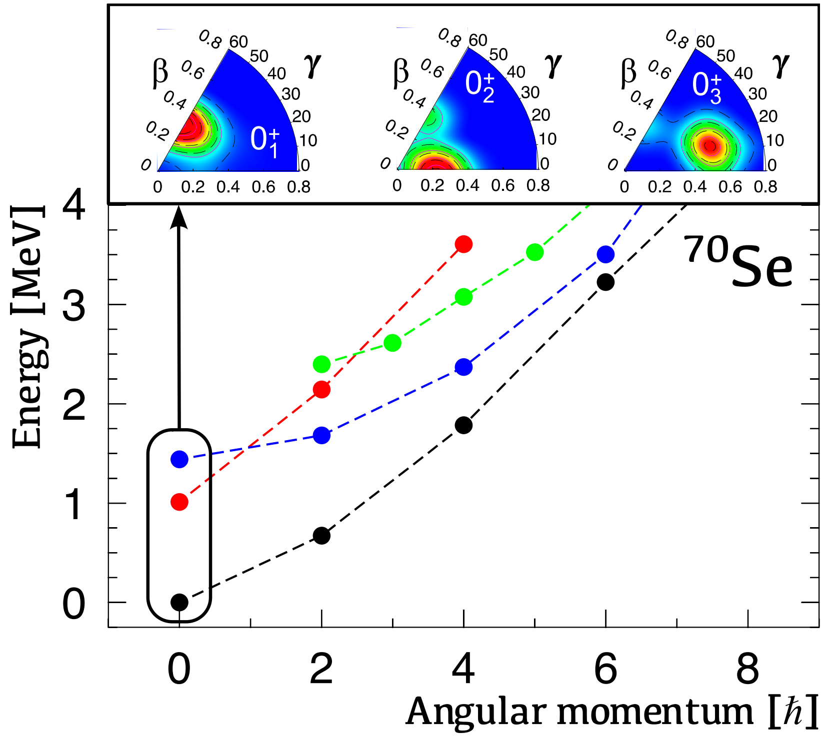
Private comm. Pedro Sarrigurren

Beta decay of ^{71}Kr: beta delayed protons

Beta delayed p branch

$$\epsilon_p = 2.77(24)\%$$





Calculations by T. Rodriguez (SCCM calculations, Gogni D1S)

Possible coexisting state in ^{70}Se, long sought.

See recent publication by Smallcombe et al. PRC 110, 024318 (2024)

Some final conclusions

Beta decay of ^{71}Kr has been a challenging case, and possibly not all questions are answered.

First case of T=1/2 isospin breaking in the gs.

Probably ^{71}Kr is ”oblate” in its ground state.

We see evidence of a new 0+ state in ^{70}Se, which has been interpreted as a long sought coexisting state.

THANK YOU
for your attention

A. Algora,[1,2,*] A. Vitéz-Sveiczer,[2,3] A. Poves,[4] G. G. Kiss,[2,5,†] B. Rubio,[1] G. de Angelis,[6] F. Recchia,[7,8] S. Nishimura,[5] T. Rodriguez,[9] P. Sarriguren,[10] J. Agramunt,[1] V. Guadilla,[1,11] A. Montaner-Pizá,[1] A. I. Morales,[1] S. E. A. Orrigo,[1] D. Napoli,[6] S. M. Lenzi,[7,8] A. Boso,[7,8] V. H. Phong,[5,12] J. Wu,[5] P.-A. Söderström,[5] T. Sumikama,[5] H. Suzuki,[5] H. Takeda,[5] D. S. Ahn,[5] H. Baba,[5] P. Doornenbal,[5] N. Fukuda,[5] N. Inabe,[5] T. Isobe,[5] T. Kubo,[5] S. Kubono,[5] H. Sakurai,[5] Y. Shimizu,[5] S. Chen,[5] B. Blank,[13] P. Ascher,[13] M. Gerbaux,[13] T. Goigoux,[13] J. Giovinazzo,[13] S. Grévy,[13] T. Kurtukián Nieto,[10,13] C. Magron,[13] W. Gelletly,[1,14] Zs. Dombrádi,[2] Y. Fujita,[15,16] M. Tanaka,[16] P. Aguilera,[7,17] F. Molina,[17] J. Eberth,[18] F. Diel,[18] D. Lubos,[19] C. Borcea,[20] E. Ganioglu,[21] D. Nishimura,[22] H. Oikawa,[23] Y. Takei,[23] S. Yagi,[23] W. Korten,[24] G. de France,[25] P. Davies,[26] J. Liu,[27] J. Lee,[27] T. Lokotko,[27] I. Kojouharov,[28] N. Kurz,[28] H. Schaffner,[28] and A. Kruppa[2]

Algora, Vitéz-Sveiczer, Poves, Kiss, Rubio et al., arXiv:2411.00509[nucl-ex nucl-th]