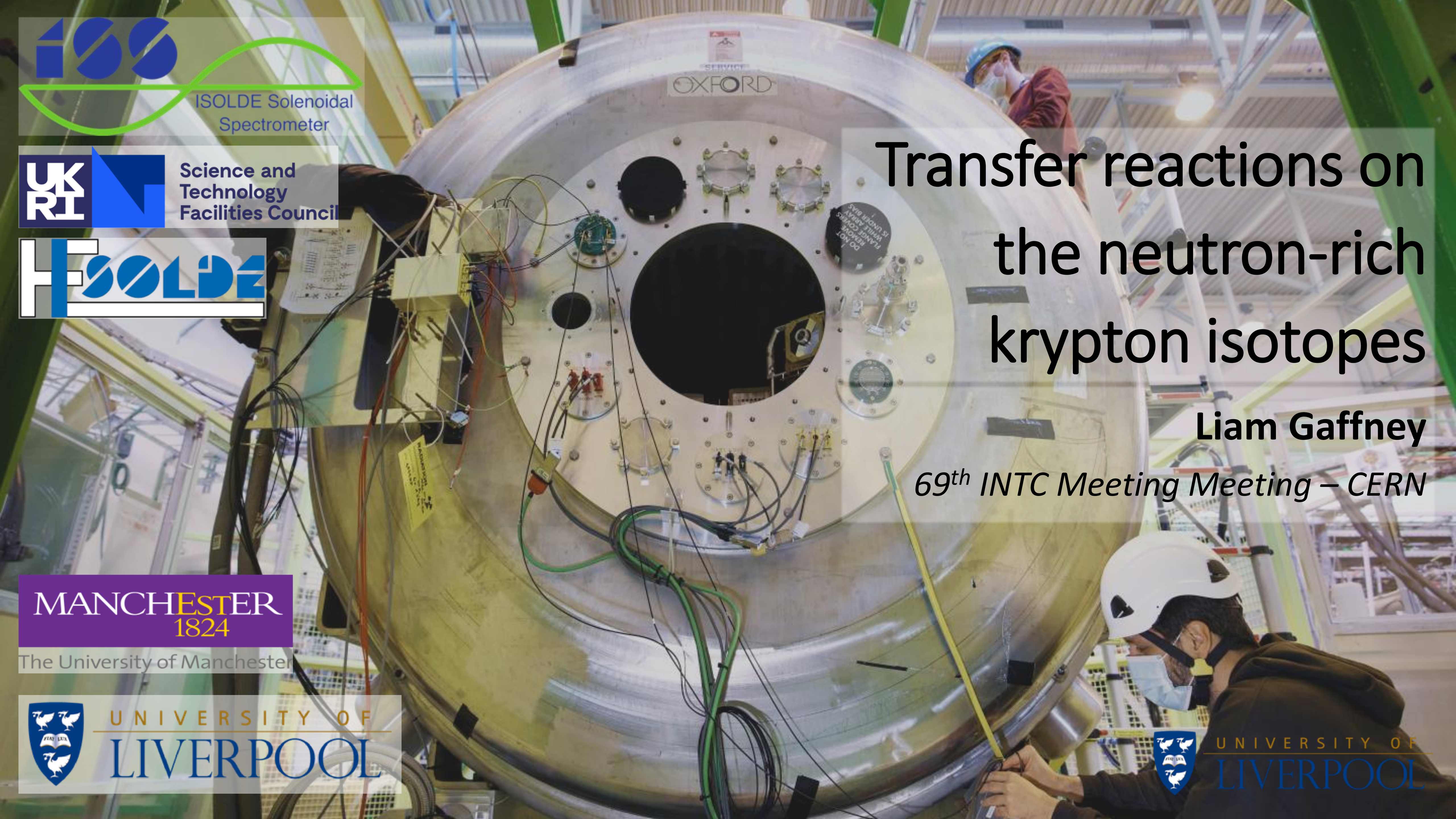
Transfer reactions on the neutron-rich krypton isotopes

Liam Gaffney

69th INTC Meeting Meeting – CERN



ISOLDE Solenoidal Spectrometer

Science and Technology Facilities Council

The University of Manchester

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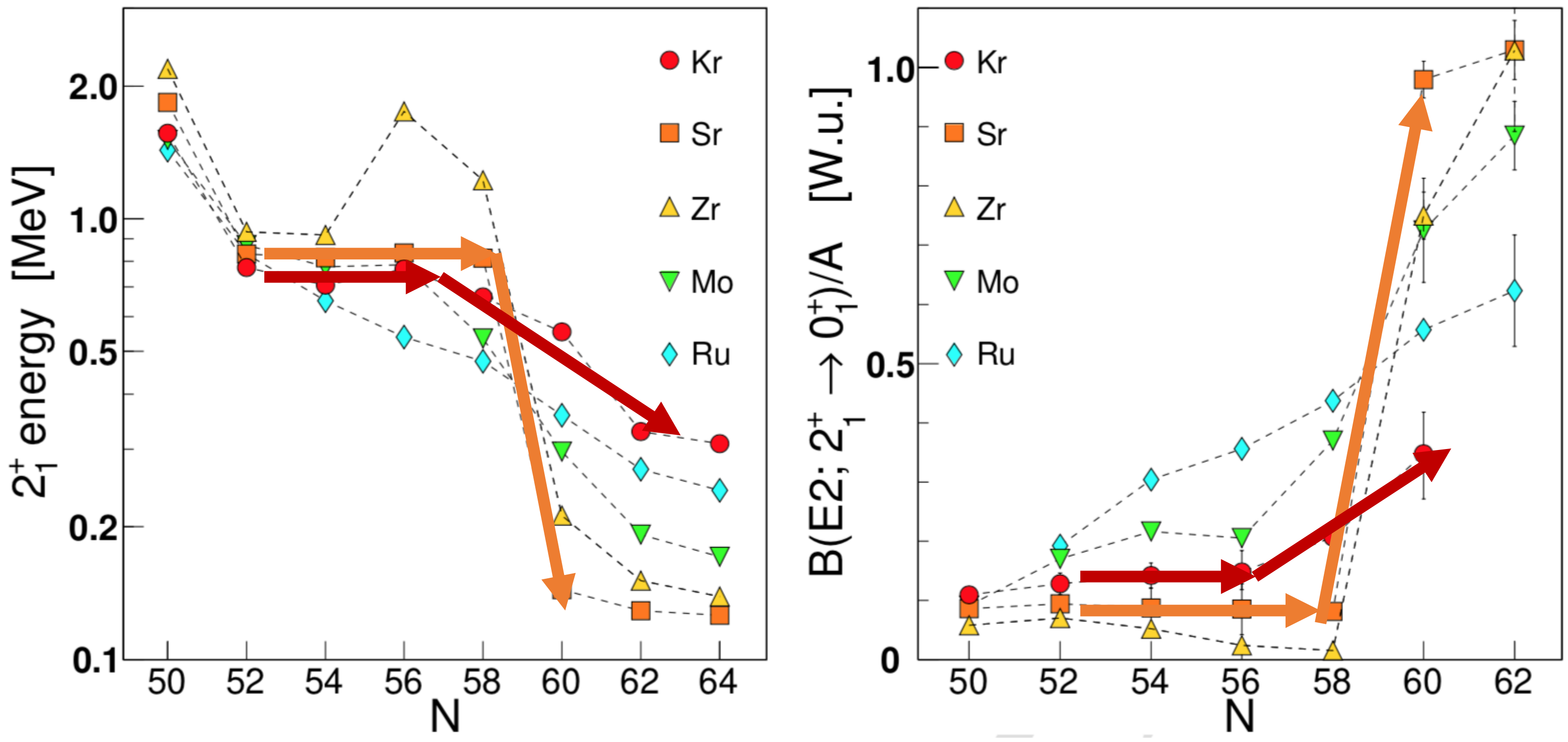
Onset of deformation at *N*=60

- Sr and Zr show rapid and **dramatic onset** of deformation at *N*=60.
- **Smooth increase** for the Kr isotopic chain[1].
- Low-lying intruder configurations → **shape coexistence**[2,3]

[3] P.E. Garrett, M. Zielińska, and E. Clément, Prog. Part. Nucl. Phys. **163**, 103931 (2021).



[1] M. Albers, et al., Phys. Rev. Lett. **108**, 062701 (2012).
[2] J.E. García-Ramos and K. Heyde, Phys. Rev. C **100**, 044315 (2019).

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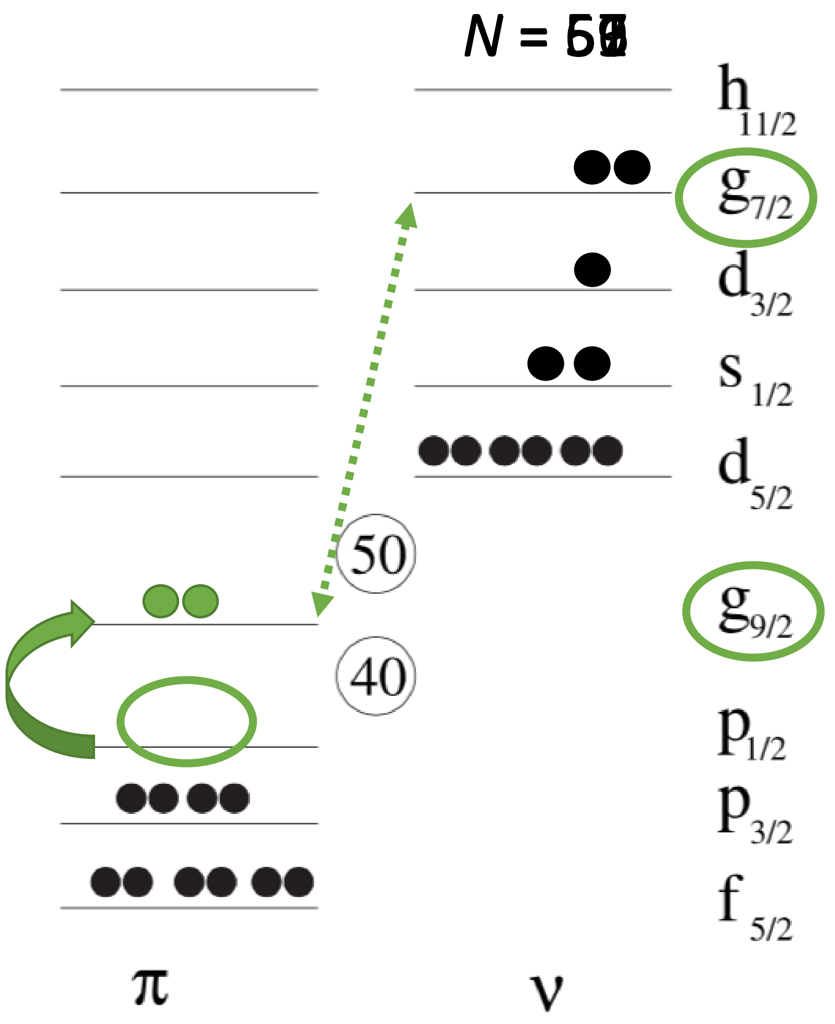
Deformation-driving orbitals

- Proton **excitations across $Z = 40$** to $\pi g_{9/2}$ orbital.
  - Ground-state configuration at $N = 60$.
- Filling neutron orbitals lowers energy of $\pi g_{9/2}$.
  - Large overlap of $\pi g_{9/2}$ and $\nu g_{7/2}$… (lesser extent $\nu h_{11/2}$)
  - Tensor force[1] → **Type-II shell evolution**[2]
- Close proximity of $\nu s_{1/2}$, $\nu d_{3/2}$, $\nu g_{7/2}$, $\nu h_{11/2}$ orbitals.
  - Enhanced quadrupole interaction from coherent contributions of configurations → **deformation**



[1] P. Federman and S. Pittel, Phys. Lett. B **69**, 385 (1977).

[2] T. Togashi, Y. Tsunoda, T. Otsuka, and N. Shimizu, Phys. Rev. Lett. **117**, 172502 (2016).

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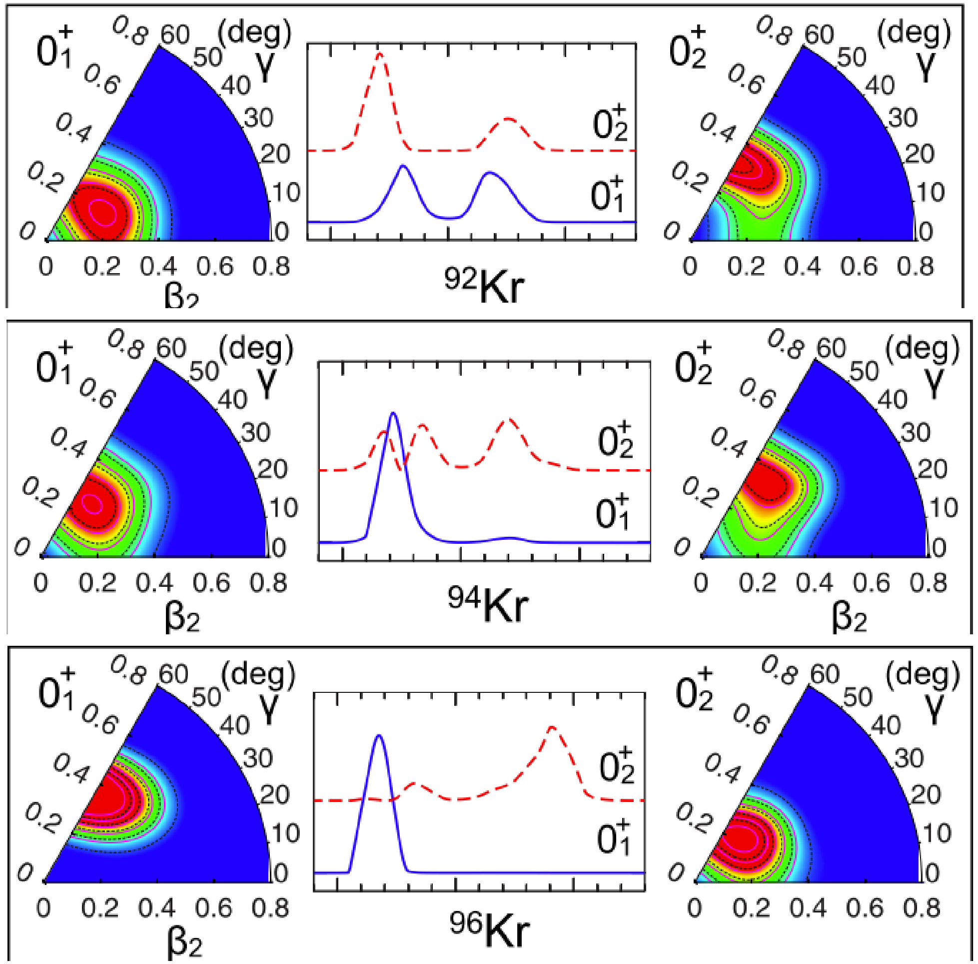
The neutron-rich krypton isotopes

- Evolution of shape change is not as dramatic as Zr and Sr, but **occurs smoothly**.
- Mean-field based models[1] and IBM "mapping"[2,3] show **configuration mixing**.
    - Not present in Zr and Sr…
- How do the **single-particle orbitals** and their occupancies evolve in the Kr isotopes?



[1] T.R. Rodríguez, Phys. Rev. C **90**, 034306 (2014).
[2] K. Nomura, et al., Phys. Rev. C **96**, 034310 (2017).
[3] R.-B. Gerst, et al., Phys. Rev. C **105**, 024302 (2022).

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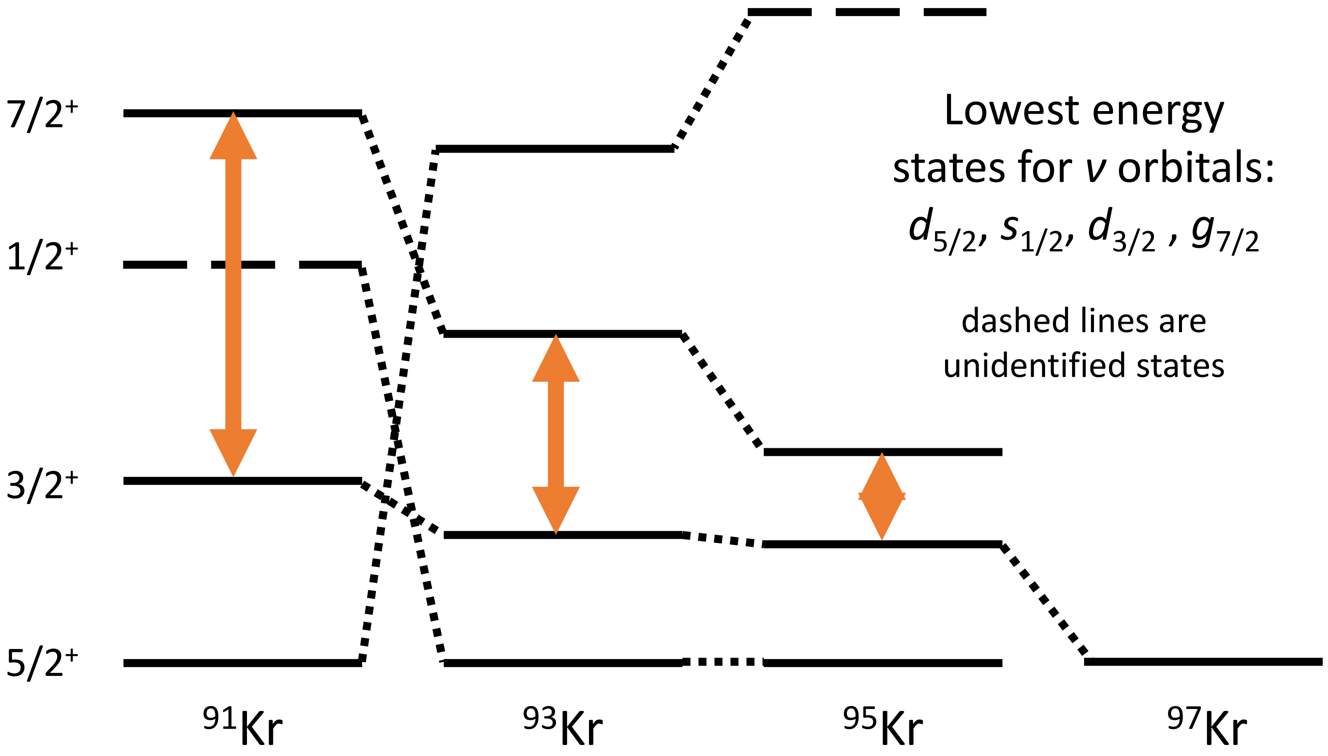
[1] T. Rząca-Urban, et al., Phys. Rev. C **95**, 064302 (2017).
[2] G. Lhersonneau, et al., Phys. Rev. C **63**, 034316 (2001).
[3] R.-B. Gerst, et al., Phys. Rev. C **105**, 024302 (2022).

Odd-mass Kr isotopes

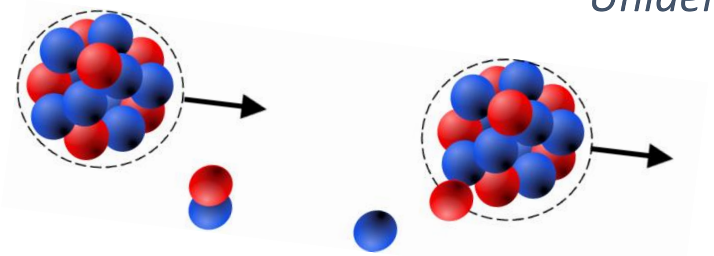
- Energy gap of $\nu d_{3/2}$ - $\nu g_{7/2}$ is reduced with increasing N.
- Occupancy of each orbital drives change in $\pi g_{9/2}$ energy.
  - $\nu g_{7/2}$ and $\nu h_{11/2}$ most important.

Use **one-neutron transfer:**

- Determine ℓ of the states.
- Relative occupancies of key orbitals.
- Identify fragmentation of SP strength.
- Determine centroid – related to ESPEs.



But we have collectivity and fragmentation!
Unidentified $h_{11/2}$ states?



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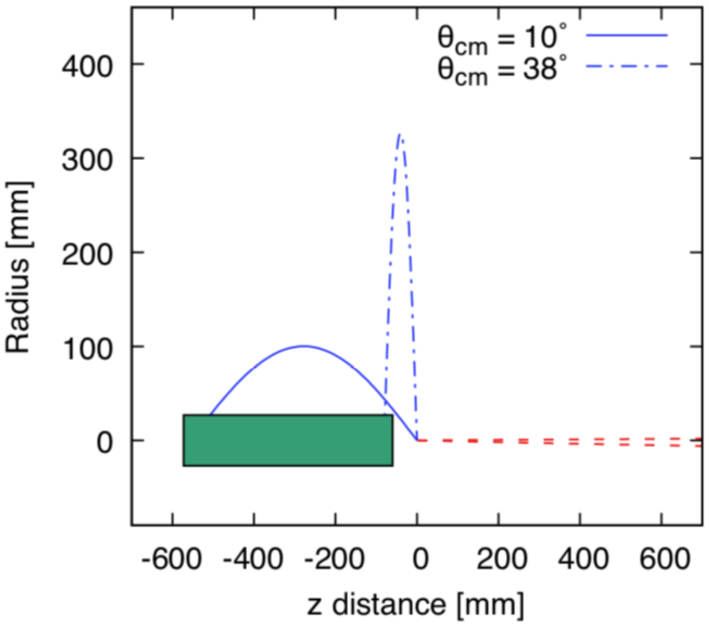
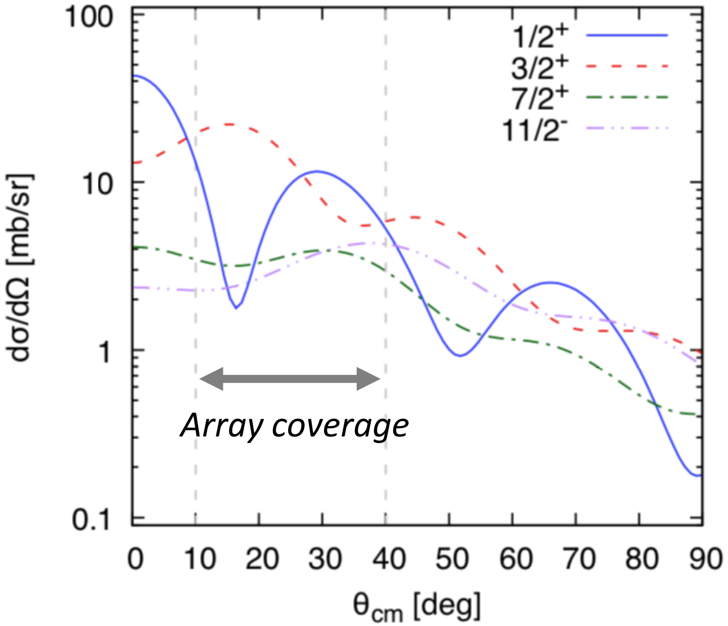
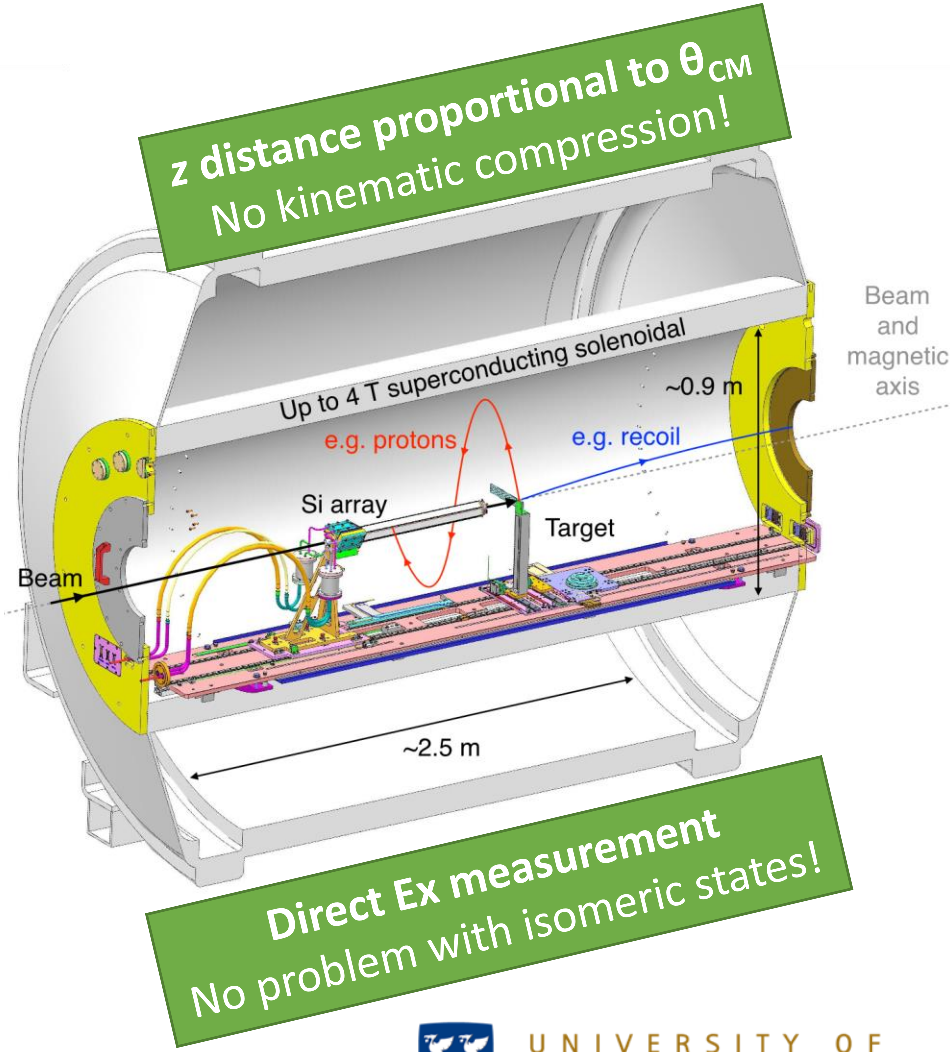
Transfer reactions at ISS - ^{92,94}Kr(d,p)

- “Standard” setup with new array, plus gas recoil detector.
- Kinematics with array at 60 mm and magnetic field = 2.05 Tesla.
- Maximum possible beam energy from HIE-ISOLDE ~7.5 MeV/u.
- DWBA calculations with PTOLEMY + global optical model parameters[1,2].
- Monitor detector for (d,d) normalisation → extraction of C^2S







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[1] H. An and C. Cai, Phys. Rev. C **73**, 054605 (2006).
[2] A.J. Koning and J.P. Delaroche, Nucl. Phys. A **713**, 231 (2003).

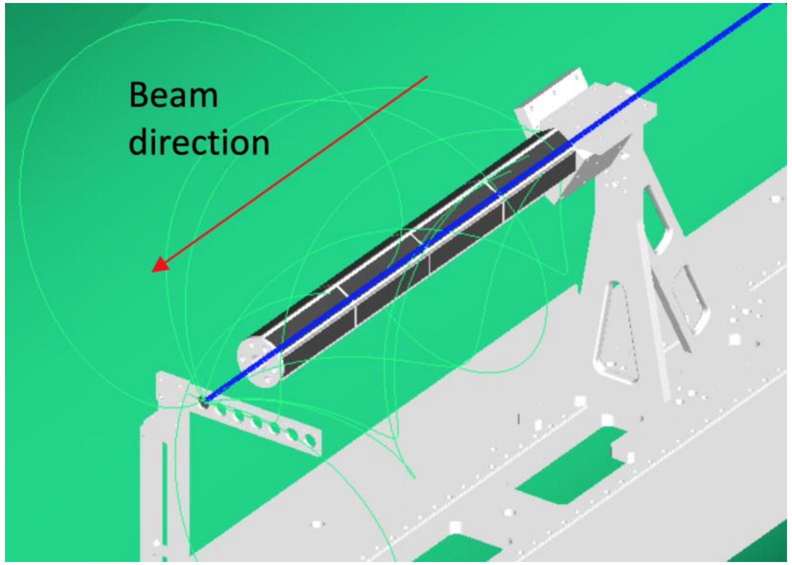
Beam intensity and availability

- Experience from runs in 2009, 2010 (REX) and 2018 (HIE).
- Requires Mo-free ion source to reduce contaminants.
- ^{92,94}Kr otherwise "easy", but ^{96}Kr has short half-life (80 ms).
  - Synchronisation of TRAP and EBIS, plus T1 timing in analysis.
  - **Extra shift requested** to test this for future feasibility.
  - TAC comments inline with expectations and proposed plan.

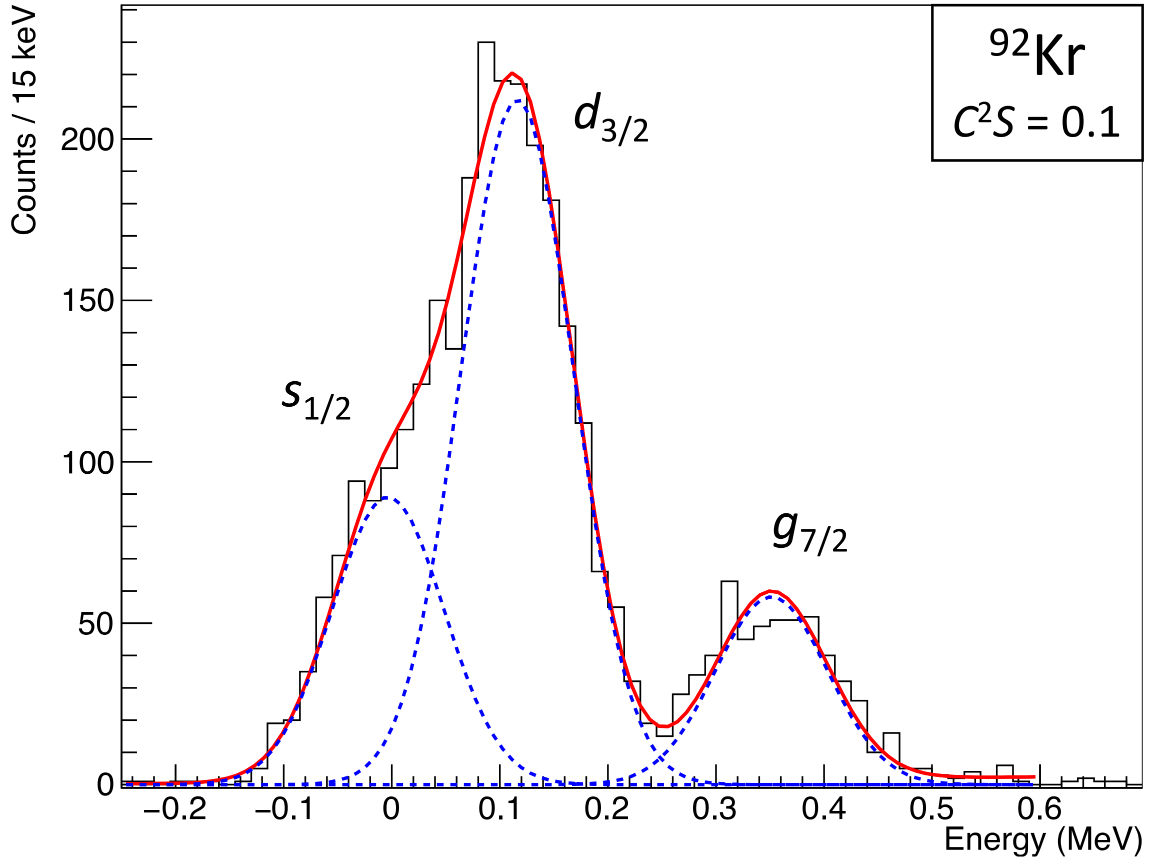
Isotope	$T_{1/2}$	Primary yield	Yield at ISS	
^{92}Kr	1.84 s	1.0×10^8 ions/μC	5.2×10^6 pps	10 shifts for physics
^{94}Kr	212 ms	3.3×10^6 ions/μC	1.7×10^5 pps	10 shifts for physics
~~^{96}Kr~~	~~80 ms~~	~~1.3×10^5 ions/μC~~	~~6.8×10^3 pps~~	1 shifts for EBIS tests

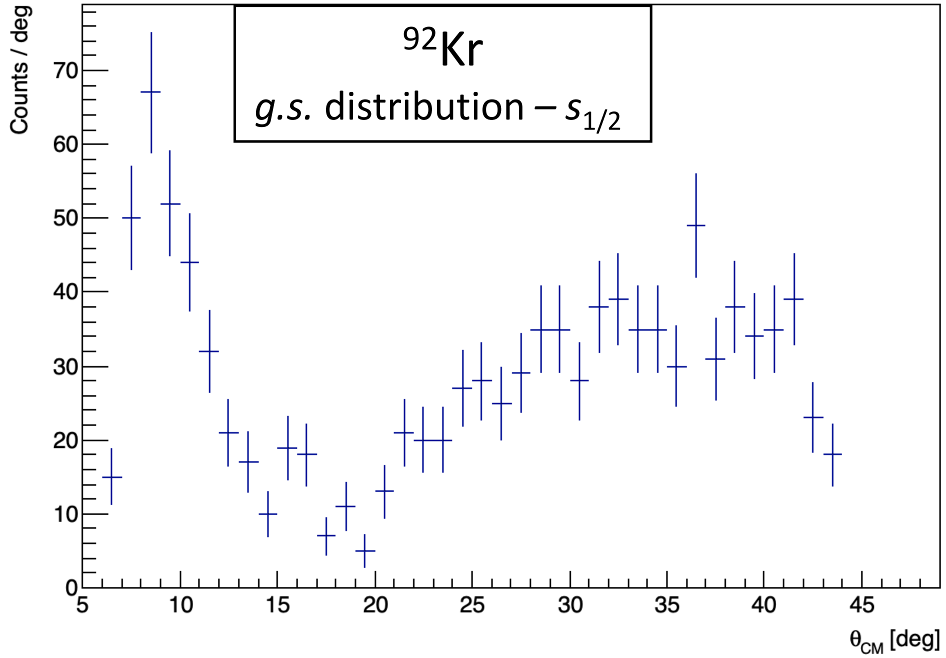
Realistic Simulations - ^{92,94}Kr(d,p)

- Aim to be sensitive to $C^2S > 0.1$ in $g_{7/2}$ state.
- Identification of unobserved $h_{11/2}$ state at $C^2S > 0.1$.
- Fragmentation of strength expected in higher-lying states.

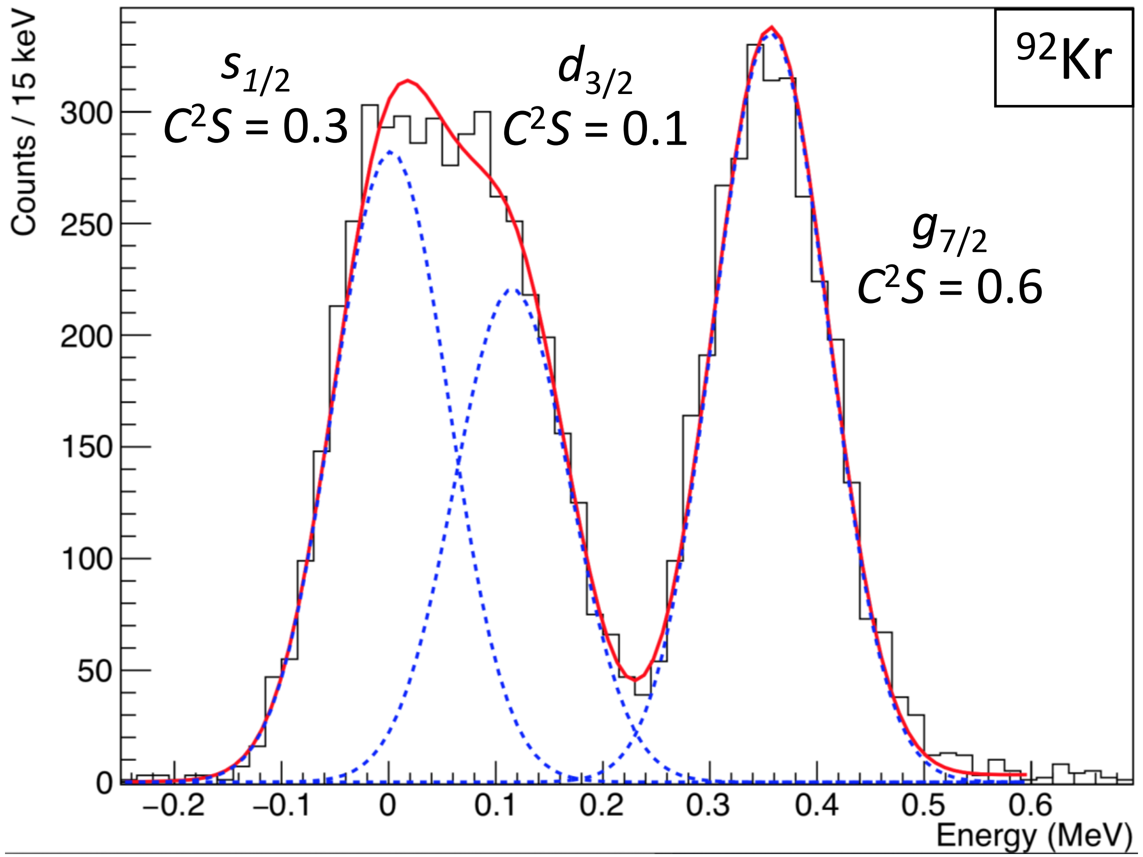


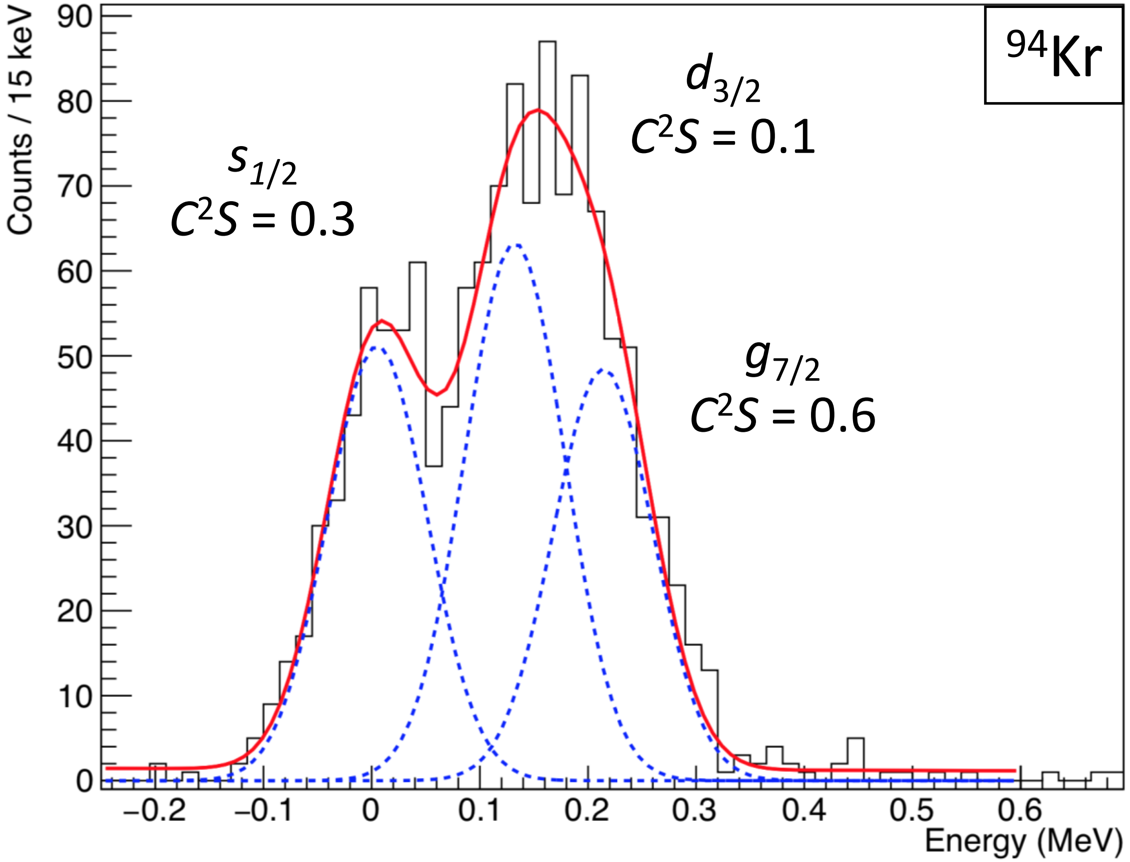
NPTool: A. Matta et al. J. Phys. G **43**, 045113 (2016)
ISS implementation: M. Labiche (STFC Daresbury)





Realistic Simulations – ^{92,94}Kr(d,p)





- Varying C^2S to see effect on doublet fitting.
- Fitted peak width ~120 keV with 0.1 mg/cm^2 CD_2 target.

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Summary and beam time request

ISOLDE Solenoidal Spectrometer

- ^{92,94}Kr(d,p) at ISS to map single-particle strength towards N = 60.
  - Smooth onset of deformation.

	Energy	I^{π}	σ_{DWBA}	Counts per shift ($C^2S = 0.1$)
^{92}Kr(d,p)^{93}Kr (10 shifts)	0 keV	$(1/2^+)$	10.4 mb	124
	117 keV	$(3/2^+)$	15.5 mb	184
	355 keV	$(7/2^+)$	4.6 mb	54
	–	$(11/2^-)$	4.4 mb	52
^{94}Kr(d,p)^{95}Kr (10 shifts)	0 keV	$(1/2^+)$	10.1 mb	21
	114 keV	$(3/2^+)$	16.0 mb	33
	197 keV	$(7/2^+)$	4.8 mb	10
	–	$(11/2^-)$	5.1 mb	10

0.1 mg/cm^2 CD_2 target

~500 counts

~100 counts

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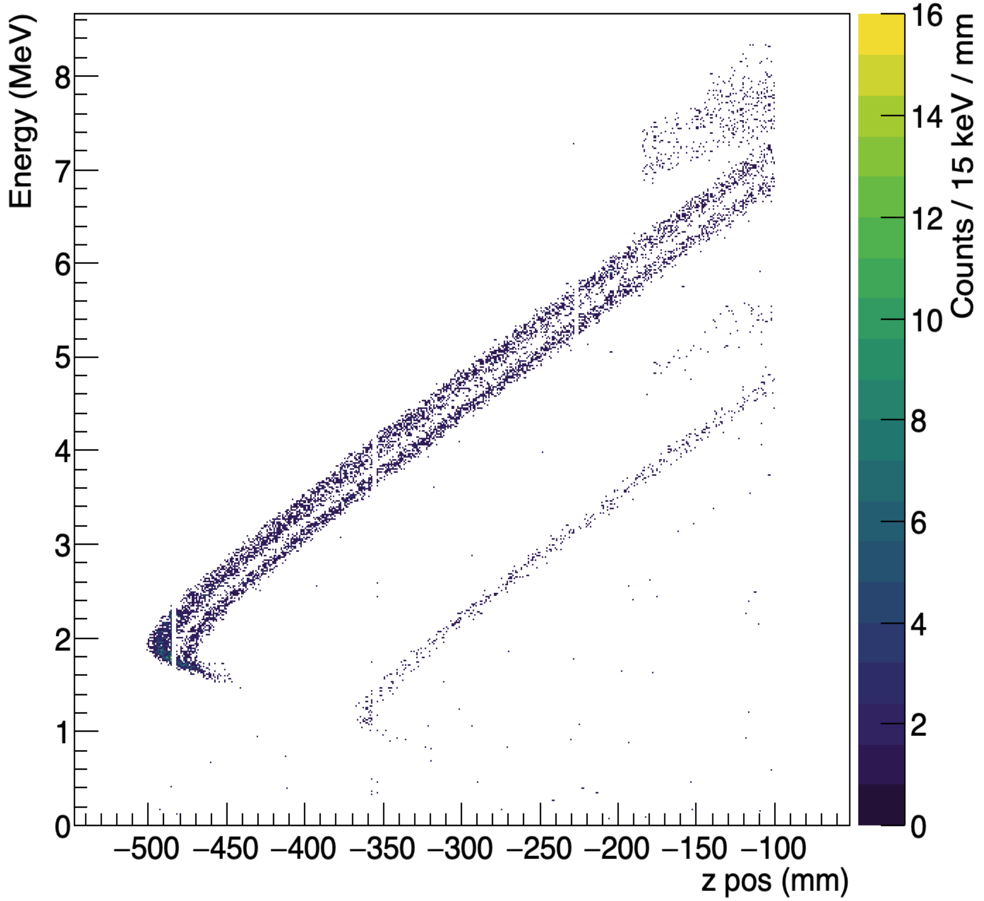
Thank you!



Transfer reactions on the neutron-rich krypton isotopes

January 5, 2022

L. P. Gaffney[1], S. A. Bennett[2], F. Browne[3], P. A. Butler[1], A. Ceulemans[4], D. Clarke[2], A. Dolan[1], F. Flavigny[5], S. J. Freeman[3], K. Garrett[2], D. T. Joss[1], B. Kay[6], M. Labiche[7], I. Lazarus[7], P. T. MacGregor[2], J. Ojala[8], B. Olaizola[3], R. D. Page[1], O. Poleshchuk[4], R. Raabe[4], M.-M. Satrazani[1], D. K. Sharp[2], K. Wimmer[9]

[1] *University of Liverpool, UK*
[2] *The University of Manchester, UK*
[4] *KU Leuven, Belgium*
[5] *LPC Caen, France*
[3] *CERN-ISOLDE, Switzerland*
[6] *Argonne National Laboratory, USA*
[7] *STFC Daresbury Laboratory, UK*
[8] *University of Jyvaskyla, Finland*
[9] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany*

Spokespersons: L. P. Gaffney [liam.gaffney@liverpool.ac.uk]
Contact person: B. Olaizola [bruno.olaizola@cern.ch]

ISOLDE Solenoidal Spectrometer

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Backup slides will follow…

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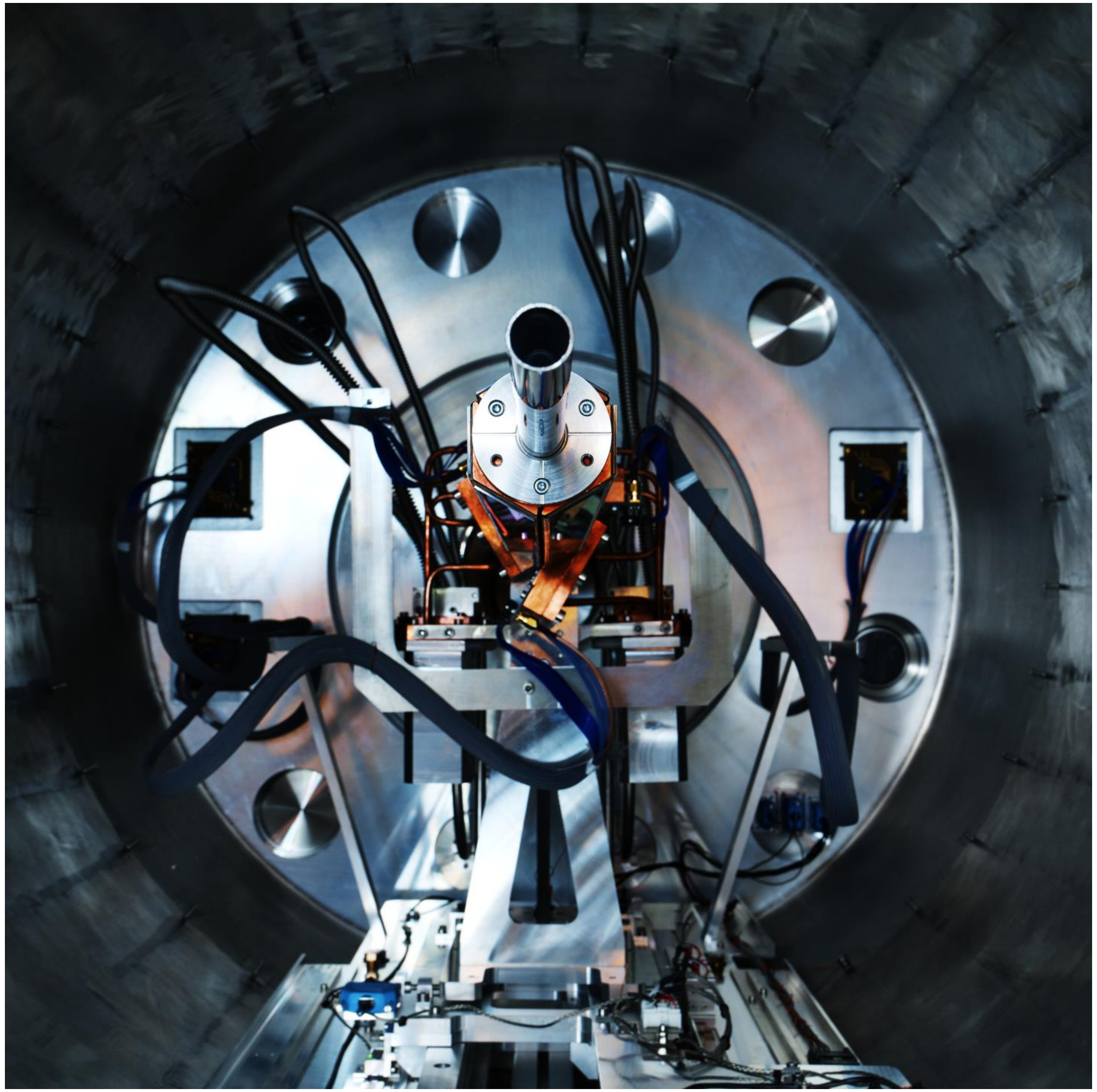
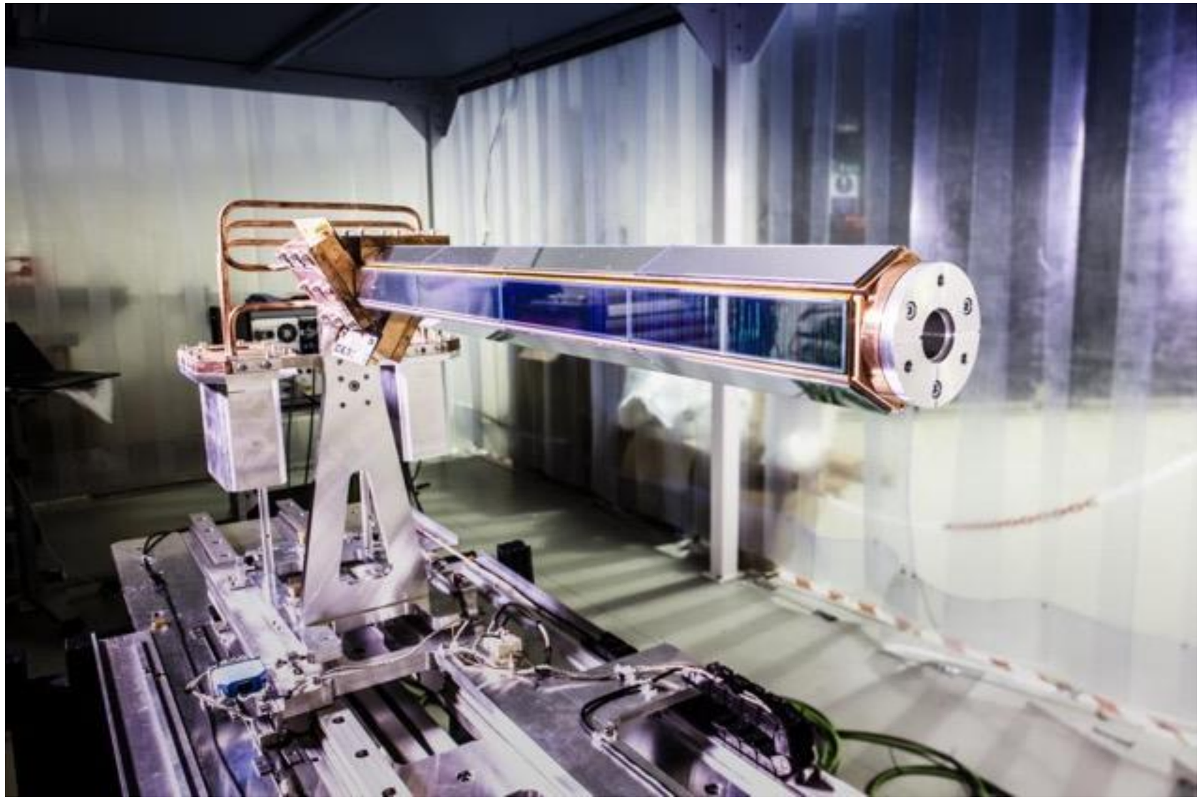
ISS on-axis silicon array





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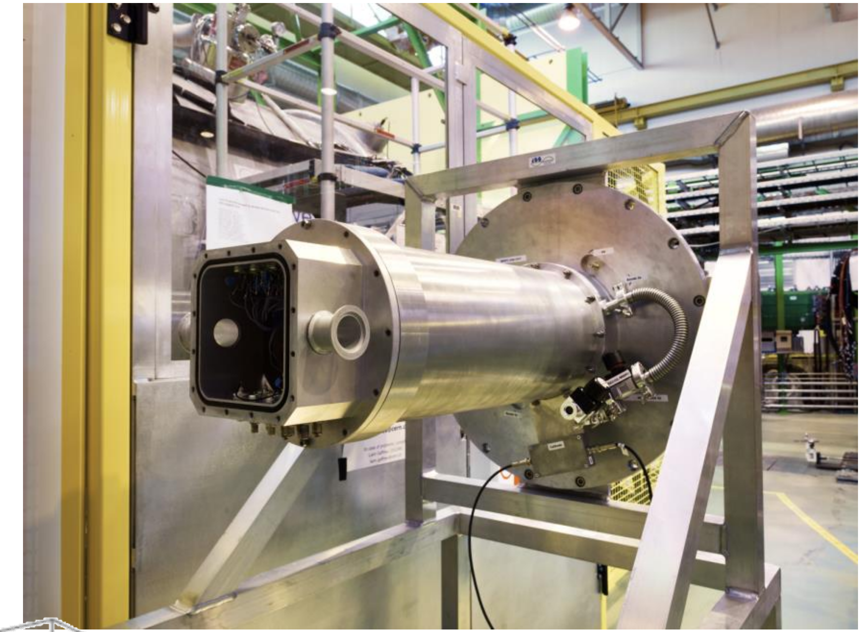
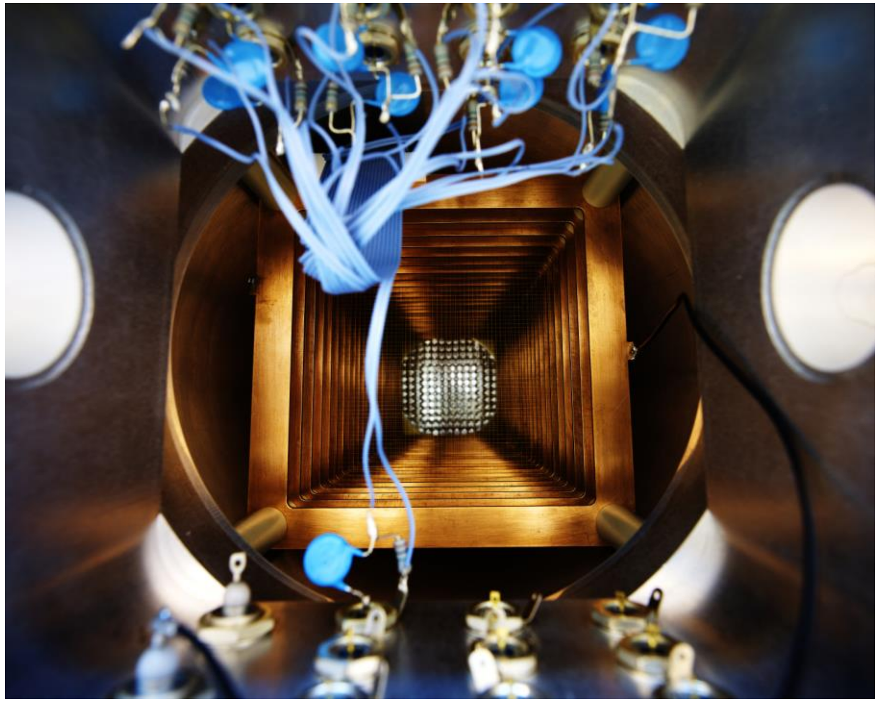
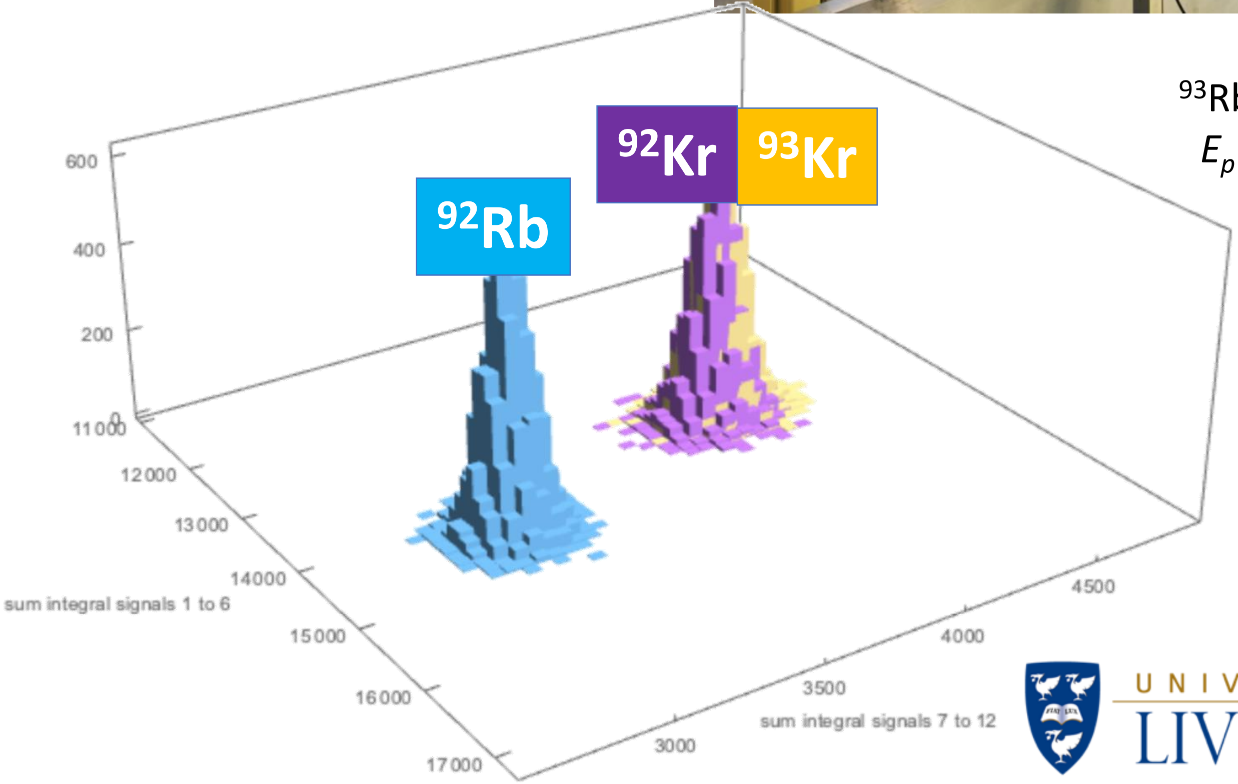
Gas ionisation detector



- Built, delivered and tested with beam in 2021.
- Blocker required to reduce direct/scattered beam.
- Trigger validation from array to reduce data rate, plus fast shapers (upgrades).





^{93}Rb g.s. kinematics:
E_p = ^{93}Kr + 2.5 MeV

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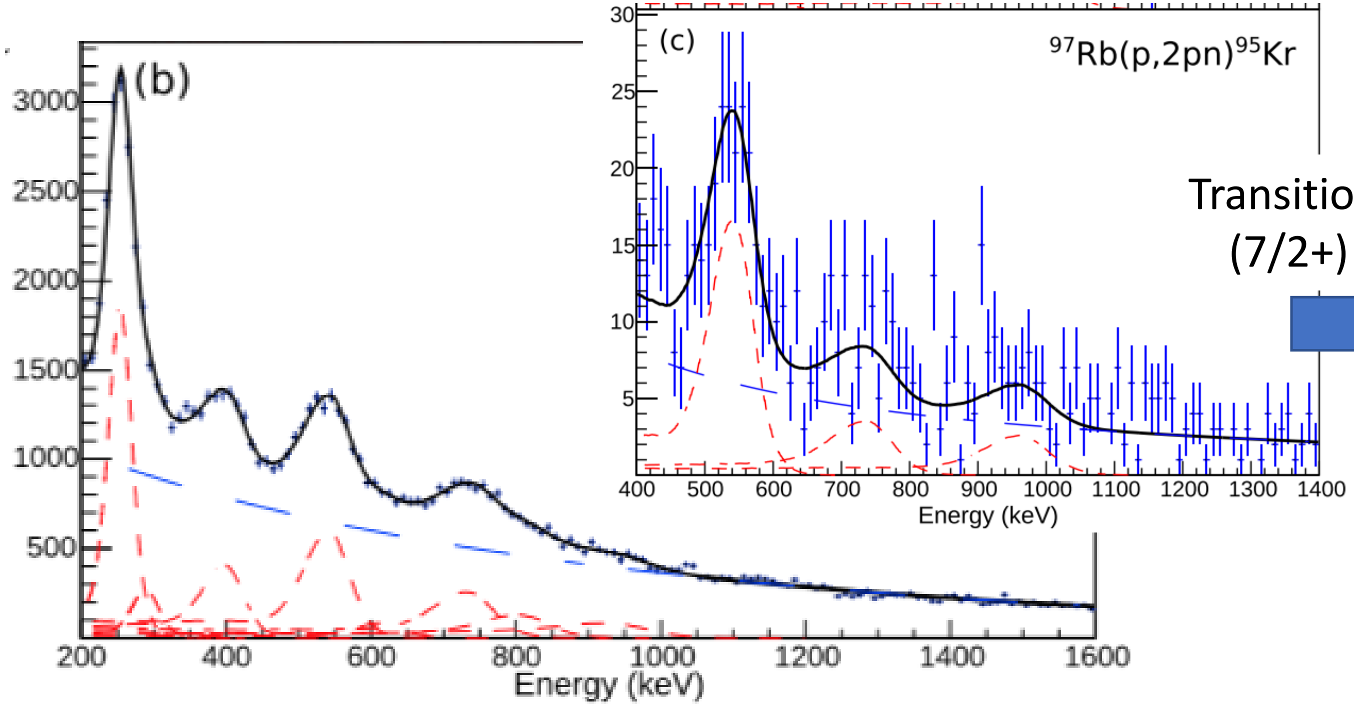
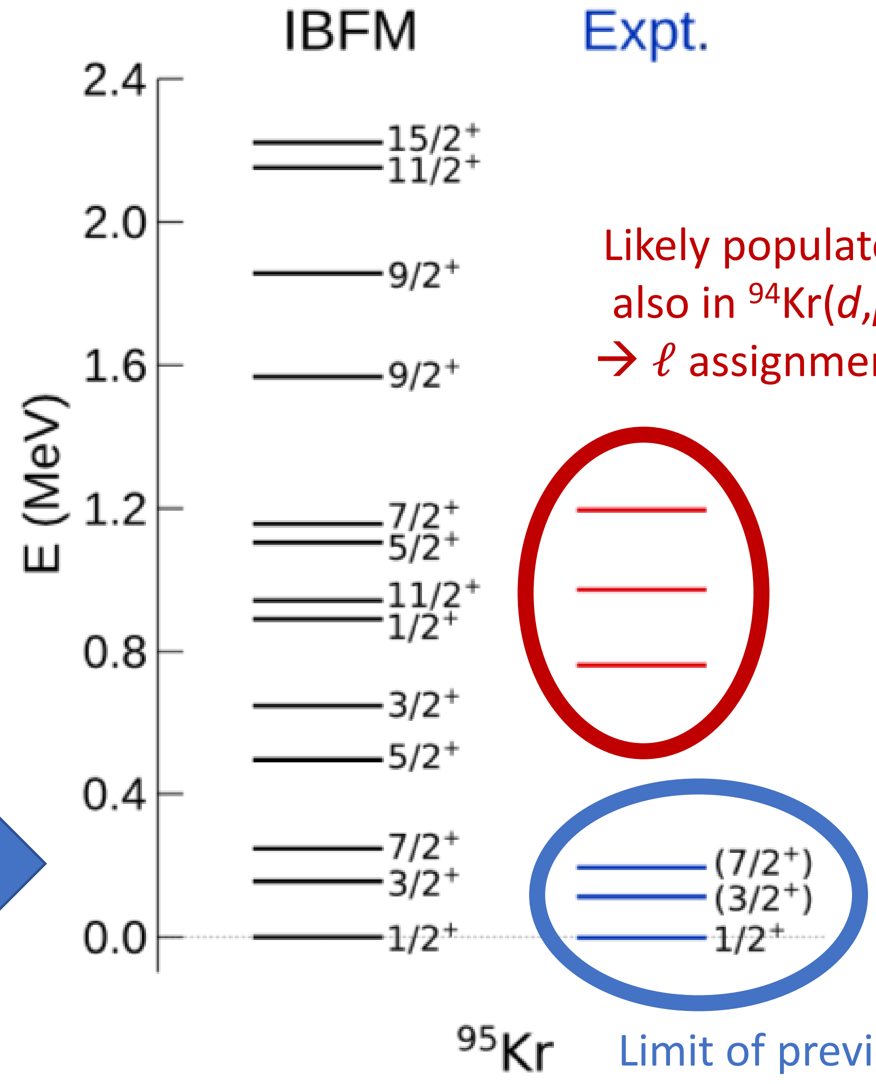
[1] R.-B. Gerst, et al., Phys. Rev. C **105**, 024302 (2022).

Recent results – ^{95}Kr

- Most recent results for ^{95}Kr.
  - γ-ray spectroscopy with DALI2@RIBF[1].
- Isomeric nature of (7/2⁺) state.
  - Prompt-delayed correlations



Transitions feed (7/2+) state



Likely populated also in ^{94}Kr(*d*,*p*) → ℓ assignments

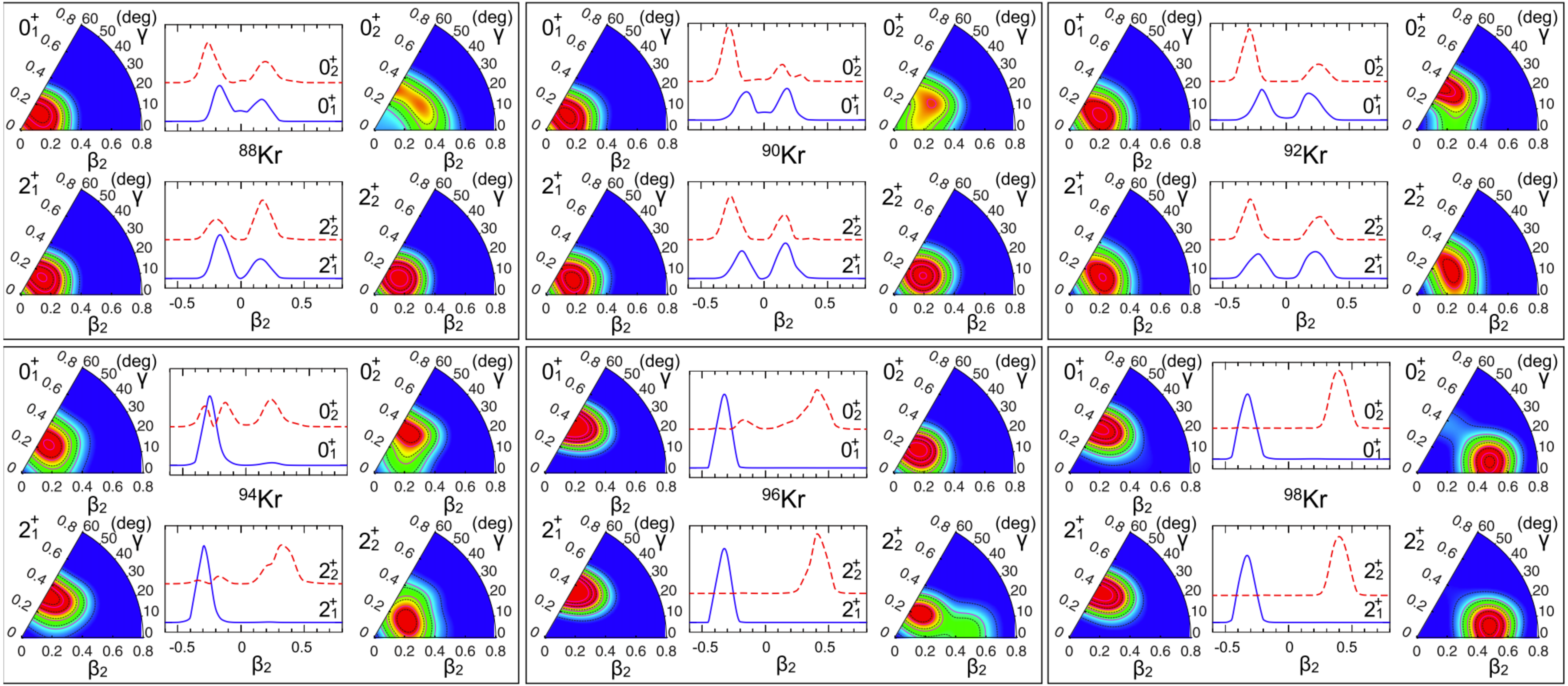
Limit of previous spectroscopy

PHYSICAL REVIEW C **90**, 034306 (2014)

Structure of krypton isotopes calculated with symmetry-conserving configuration-mixing methods

Tomás R. Rodríguez

Departamento de Física Teórica, Universidad Autónoma de Madrid, E-28049 Madrid, Spain



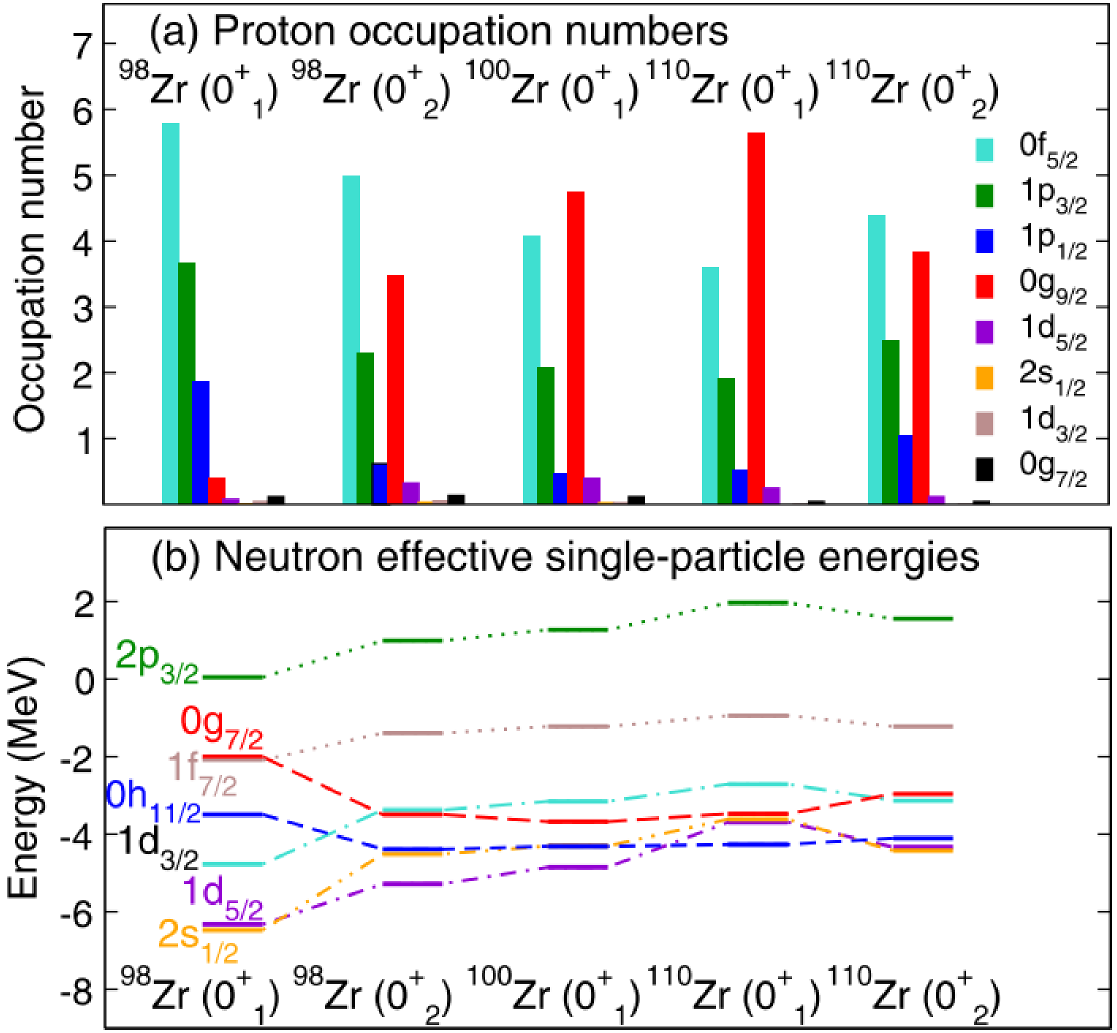
PRL 117, 172502 (2016) PHYSICAL REVIEW LETTERS week ending 21 OCTOBER 2016

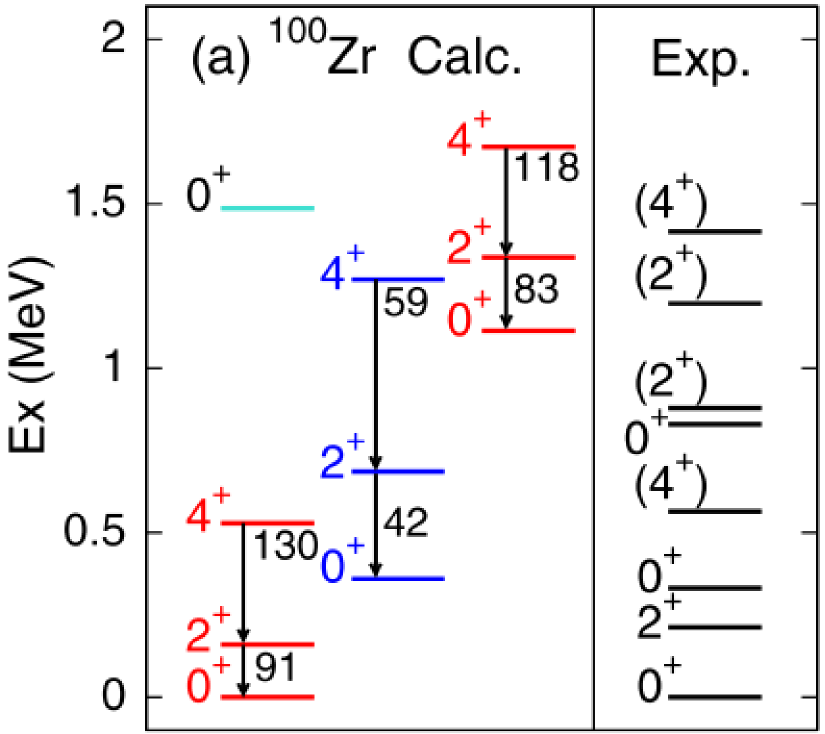
Quantum Phase Transition in the Shape of Zr isotopes

T. Togashi, Y. Tsunoda, T. Otsuka, and N. Shimizu
Phys. Rev. Lett. **117**, 172502 (2016).

Tomoaki Togashi,[1] Yusuke Tsunoda,[1] Takaharu Otsuka,[1,2,3,4] and Noritaka Shimizu[1]
[1]Center for Nuclear Study, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
[2]Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
[3]National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA
[4]Instituut voor Kern- en Stralingsfysica, KU Leuven, B-3001 Leuven, Belgium

(Received 28 June 2016; revised manuscript received 5 August 2016; published 17 October 2016)





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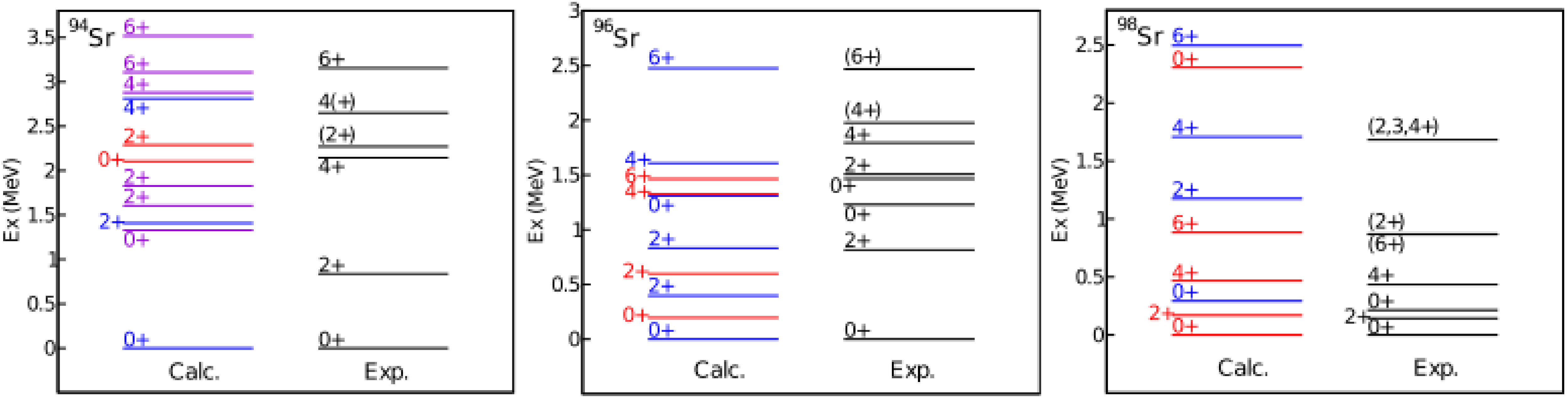
PHYSICAL REVIEW C **95**, 054319 (2017)

Abrupt shape transition at neutron number $N = 60$: $B(E2)$ values in ^{94,96,98}Sr from fast γ-γ timing

J.-M. Régis,[1,*] J. Jolie,[1] N. Saed-Samii,[1] N. Warr,[1] M. Pfeiffer,[1] A. Blanc,[2] M. Jentschel,[2] U. Köster,[2] P. Mutti,[2] T. Soldner,[2] G. S. Simpson,[3,†] F. Drouet,[3] A. Vancraeyenest,[3] G. de France,[4] E. Clément,[4] O. Stezowski,[5] C. A. Ur,[6] W. Urban,[7] P. H. Regan,[8,‡] Zs. Podolyák,[8] C. Larijani,[8,§] C. Townsley,[8] R. Carroll,[8] E. Wilson,[8] L. M. Fraile,[9] H. Mach,[9,‖] V. Paziy,[9] B. Olaizola,[9] V. Vedia,[9] A. M. Bruce,[10] O. J. Roberts,[10] J. F. Smith,[11] M. Scheck,[11] T. Kröll,[12] A.-L. Hartig,[12] A. Ignatov,[12] S. Ilieva,[12] S. Lalkovski,[13,‖] W. Korten,[14] N. Mărginean,[15] T. Otsuka,[16,¶] N. Shimizu,[16] T. Togashi,[16] and Y. Tsunoda[16]



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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Shape transition at $N = 60$: Development of neutron-rich Sr beams

September 28, 2021

K. Wimmer[1], S. Bhattacharjee[2], P. Bender[3], E. Clement[4], K. Chrysalidis[5], S. Freeman[6], L. Gaffney[7], J. Gerl[1], M. Górska[1], T. Hüyük[8], W. Korten[9], S. Rothe[5], D. Sharp[6], S. Stegemann[5], M. Zielińska[9]

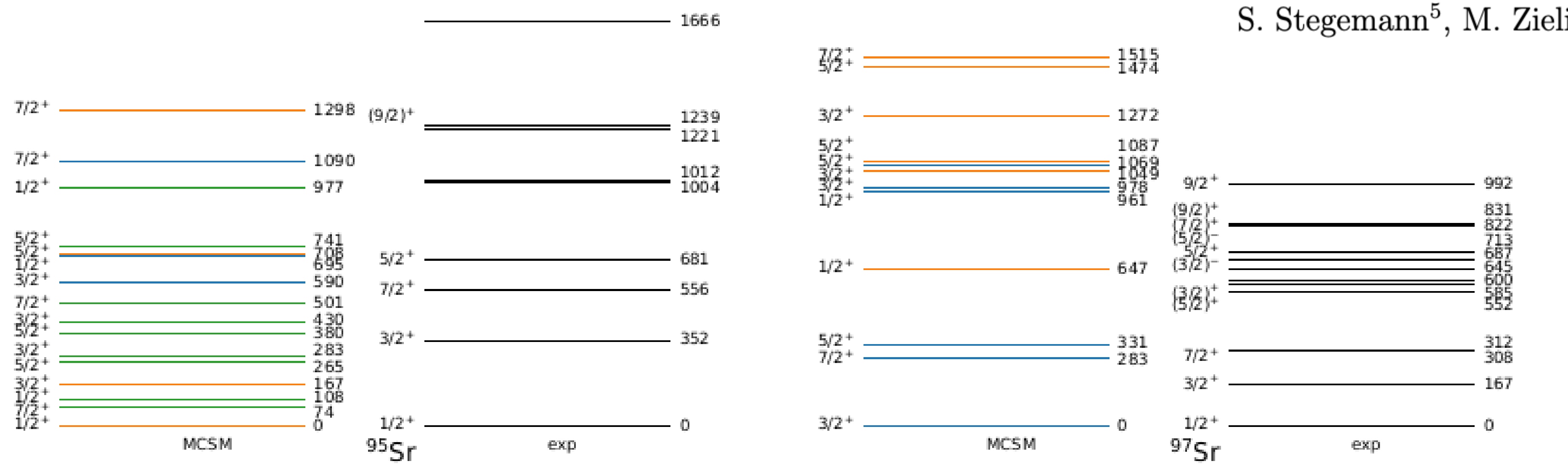
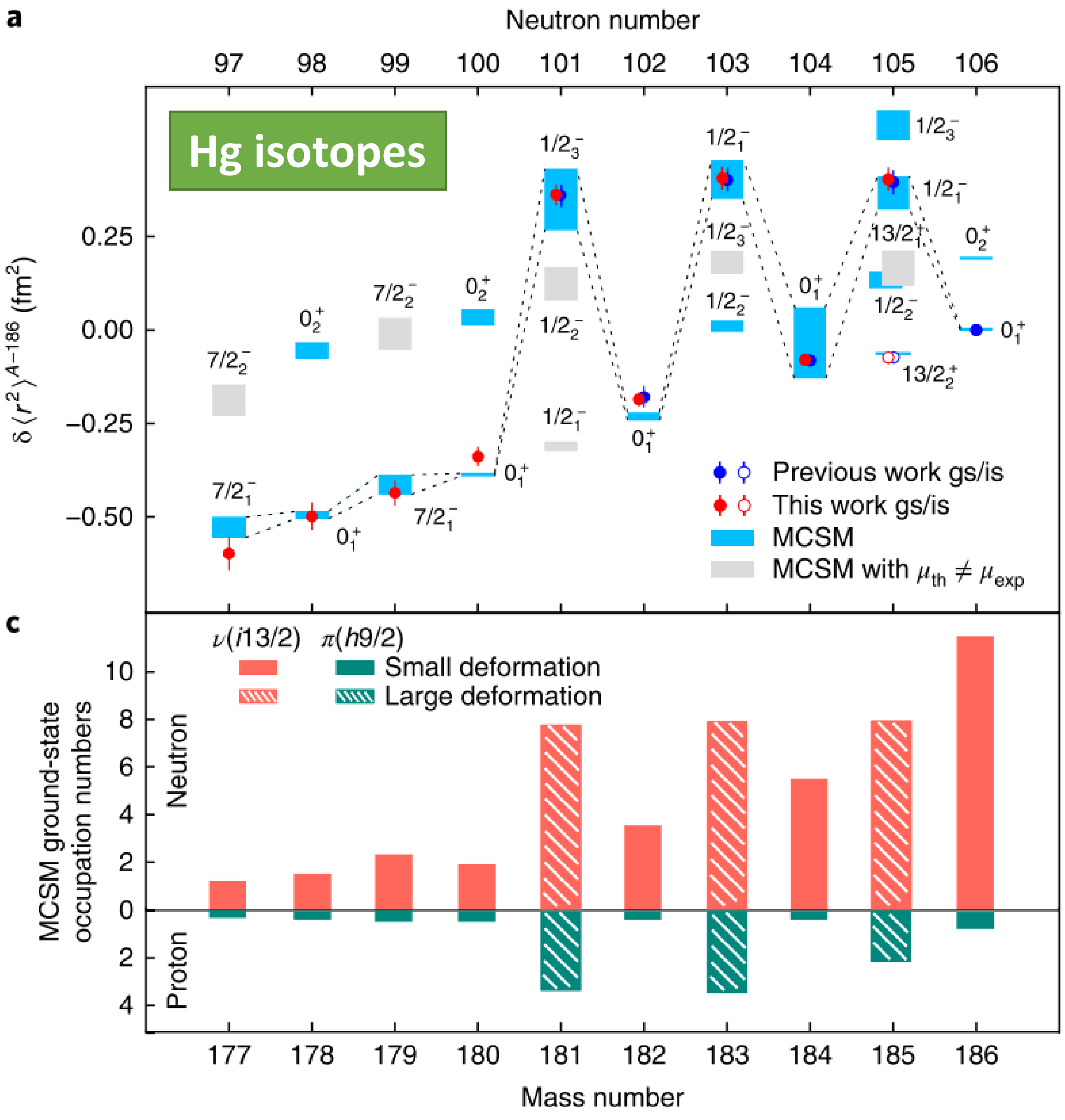


Figure 2: Calculated levels compared to (selected) experimentally known states. Levels are labeled with their energy and, where known, spin and parity. For the MCSM calculations prolate (oblate) states are marked in blue (orange). States with calculated triaxial deformation are shown in green. Note that for ^{97}Sr the triaxial degree of deformation could not yet be assessed in the calculations due to computational limitations.

Analagous mechanism

- Large-scale MCSM calculations in *n*-deficient Hg isotopes.
- Occupancy of $\nu i_{13/2}$ changes along with $\pi h_{9/2}$.
- Fine energy balance of orbitals and odd-neutron shifts energy enough to change configuration of the ground state.
- Can be probed with 1-neutron transfer from even-mass → confirm with small spectroscopic factors for corresponding states.



[1] B.A. Marsh, et al., Nature Physics **14**, 1163 (2018).

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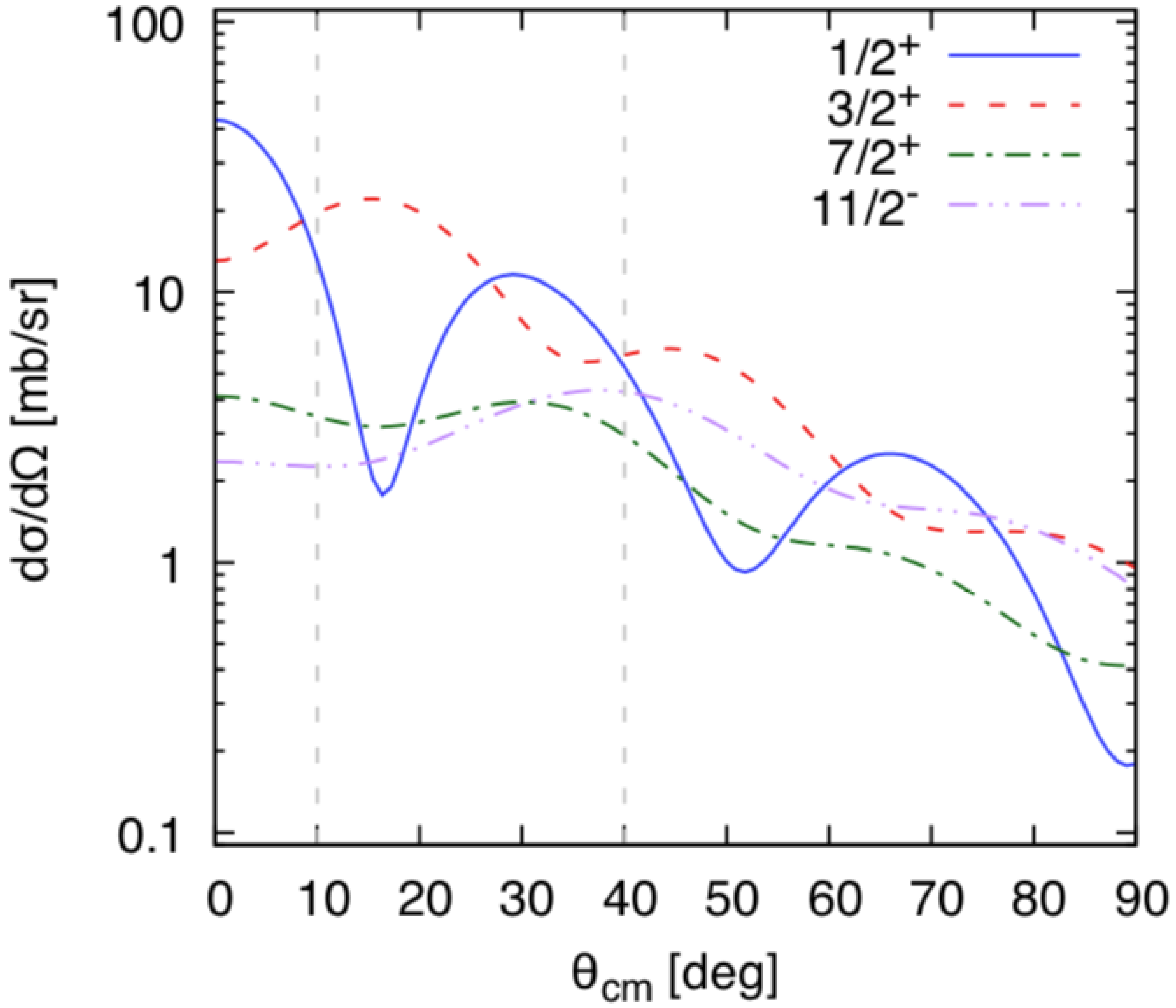
DWBA

- $d_{3/2}$ max. ⇔ $g_{7/2}$ min.
  - And vice versa…
  - Doublet fitting made easier.
- $s_{1/2}$ max. lower than range.
  - No problem as 2nd max. in range.
- $h_{11/2}$ requires max. energy.
  - Difficult to get definitive ℓ.



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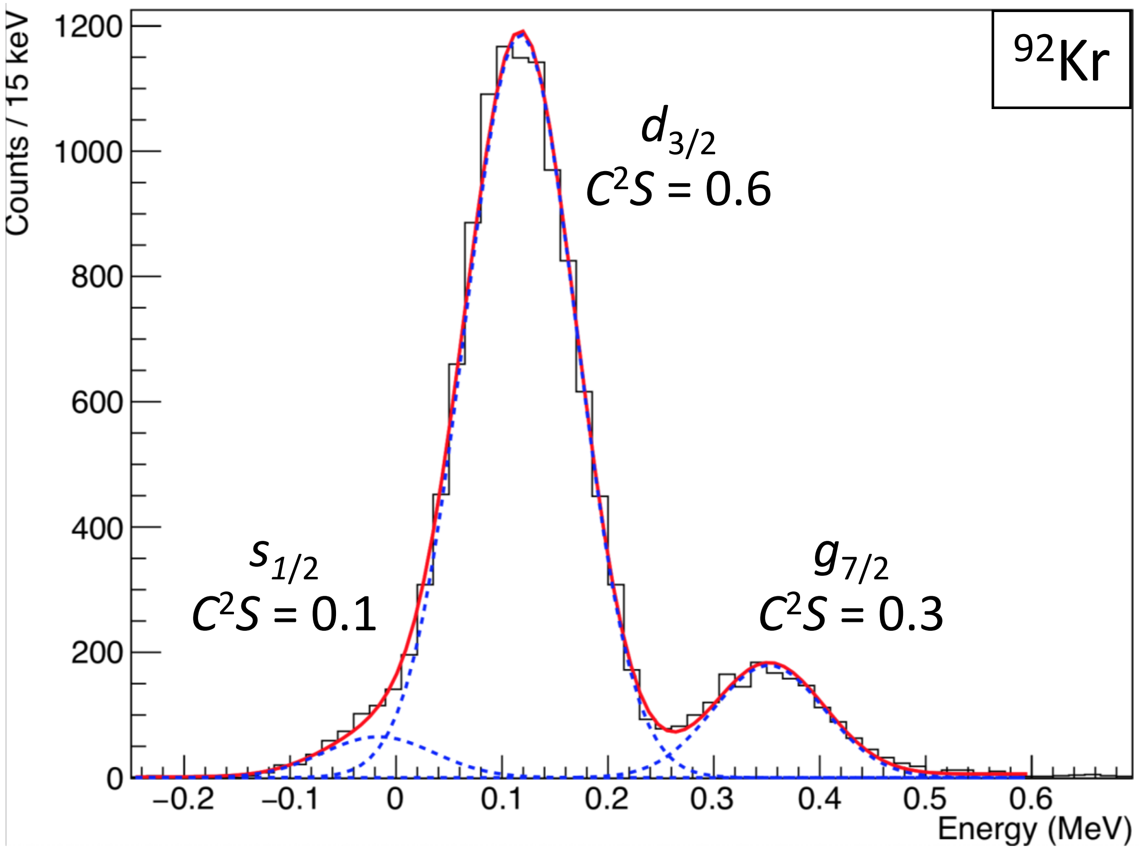
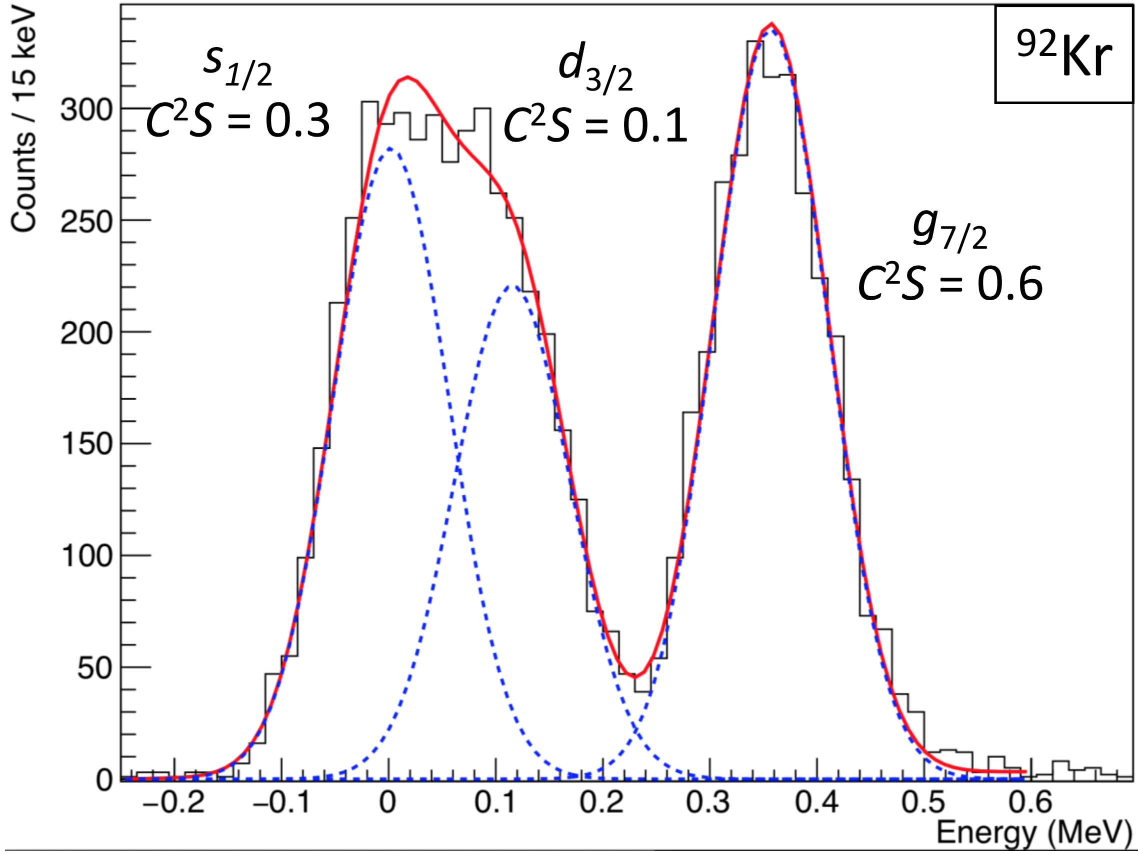
Realistic Simulations - ^{92}Kr(d,p)





- Varying C^2S to see effect on doublet fitting.

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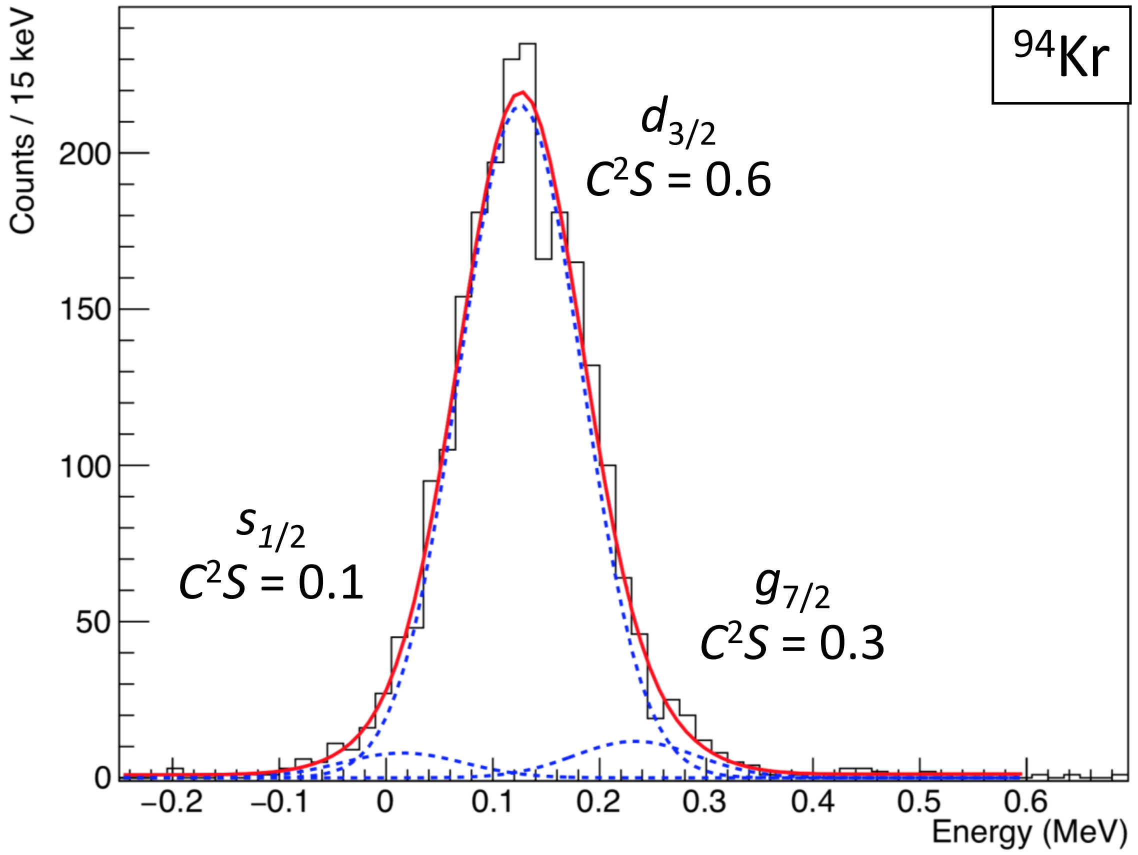
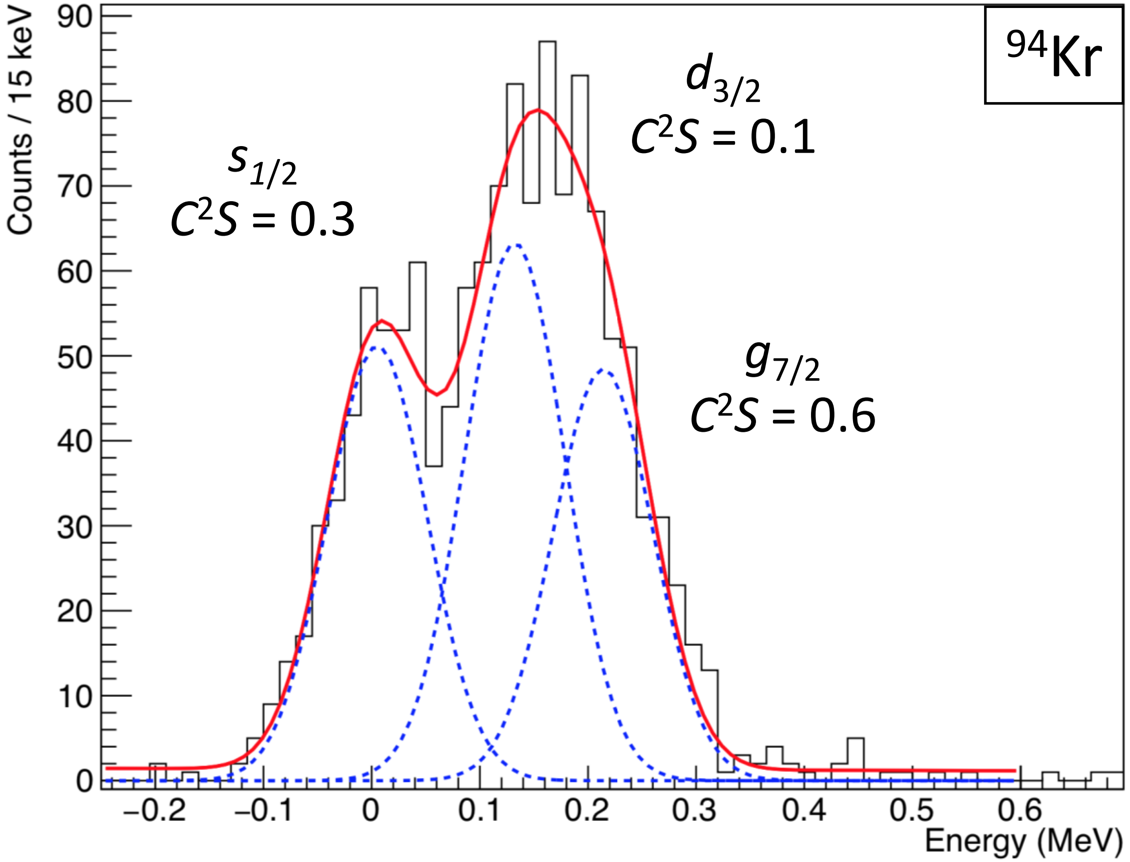
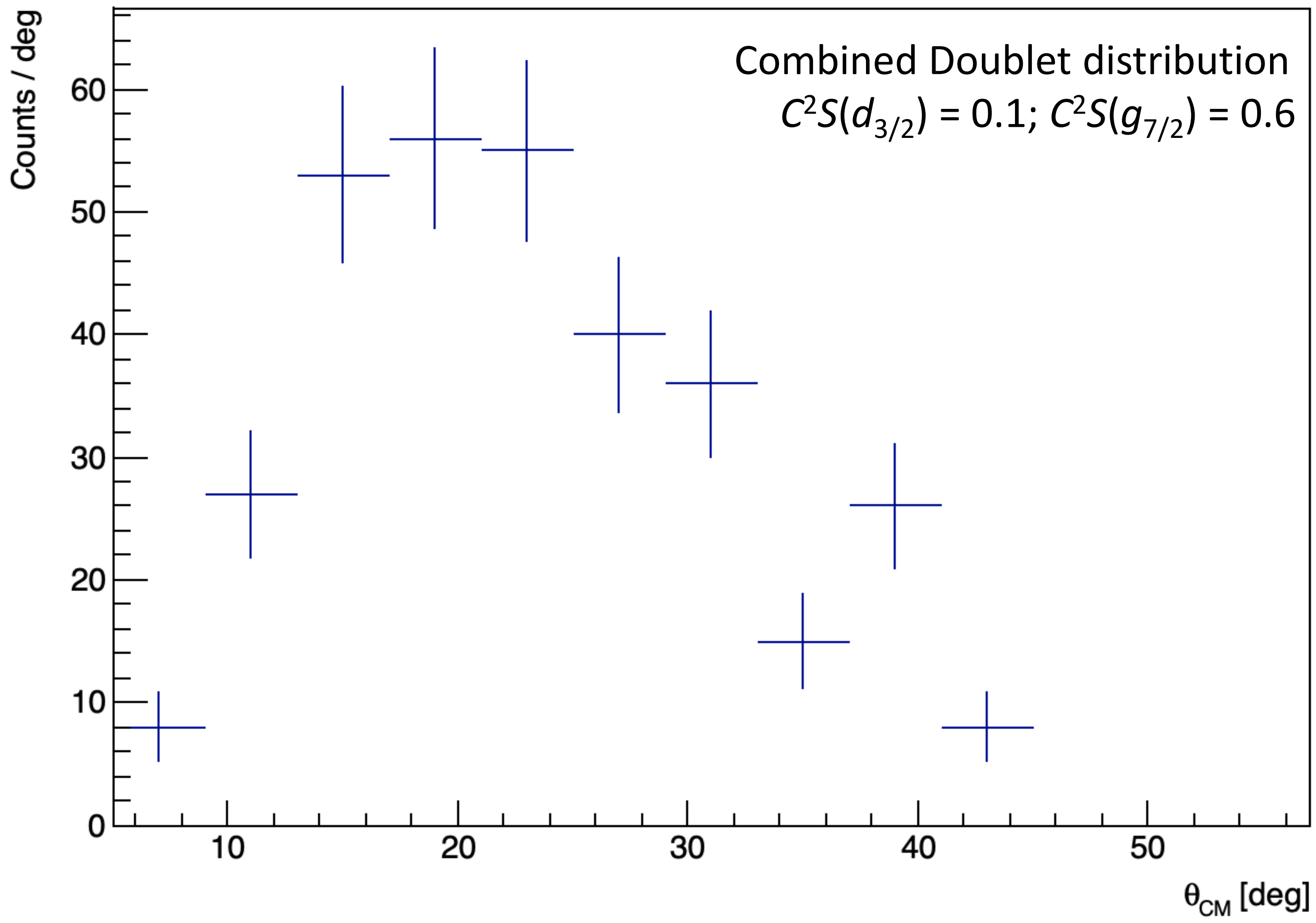
Realistic Simulations - $^{94}Kr(d,p)$





- Varying C^2S to see effect on doublet fitting.

Combined DWBA distributions – ^{94}Kr



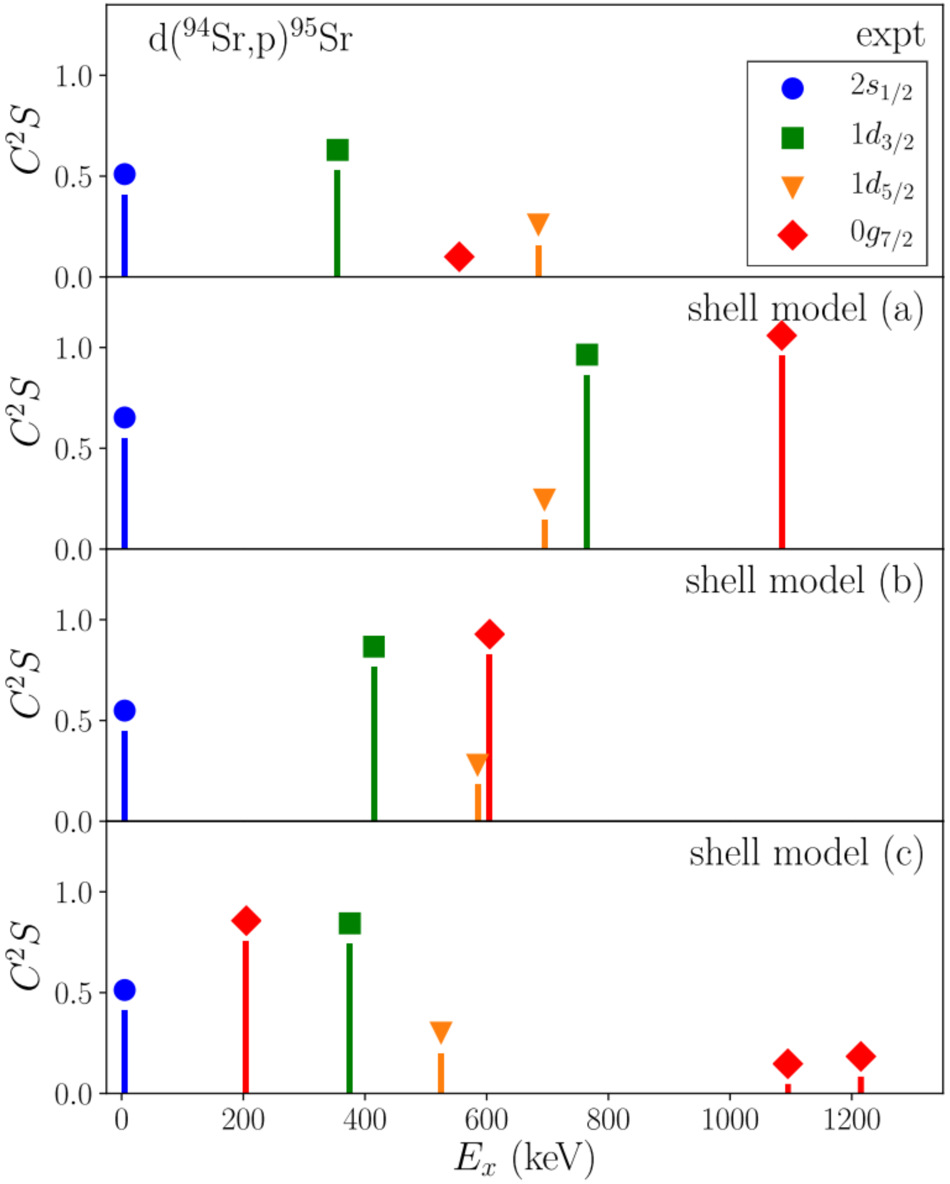


FIG. 16. Comparison of experimental (expt) spectroscopic factors (C^2S) to those from shell model calculations carried out in model spaces (a), (b), and (c), see text. States are labeled by the neutron single-particle orbital populated in the transfer reaction.

^{94}Sr(d,p)^{95}Sr

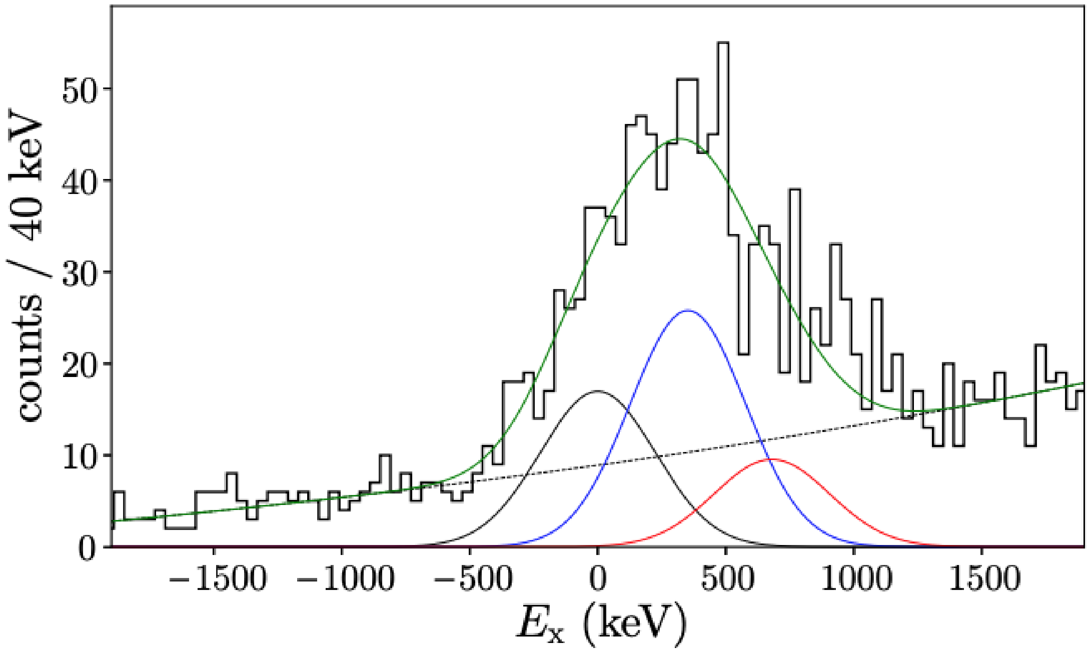


TABLE IV. Comparison of ^{2}H(^{94,96}Sr, p) spectroscopic factors to shell model calculations for low-lying states. The labels SM (a), (b) and (c) denote the three proton model spaces that were investigated (see text).

		exp.		SM (a)		SM (b)		SM (c)	
Nucleus	J^π	E (keV)	C^2S	E (keV)	C^2S	E (keV)	C^2S	E (keV)	C^2S
^{95}Sr	$\frac{1}{2}^+$	0	0.41(9)	0	0.553	0	0.449	0	0.413
	$\frac{3}{2}^+$	352	0.53(8)	766	0.865	412	0.767	375	0.744
	$\frac{5}{2}^+$	681	0.16(3)	691	0.146	585	0.180	523	0.201
	$\frac{7}{2}^+$	556		1086	0.959	602	0.828	205	0.757
^{97}Sr	$\frac{1}{2}^+$	0	0.10(5)	1631	0.013	1279	0.024	417	0.002
	$\frac{3}{2}^+$	167	0.25(5)	0	0.881	0	0.804	117	0.713
	$\frac{7}{2}^+$	308		270	0.979	149	0.931	0	0.819
	$\frac{5}{2}^+$	522	0.13(5)	1714	0.025	1336	0.042	57	0.000

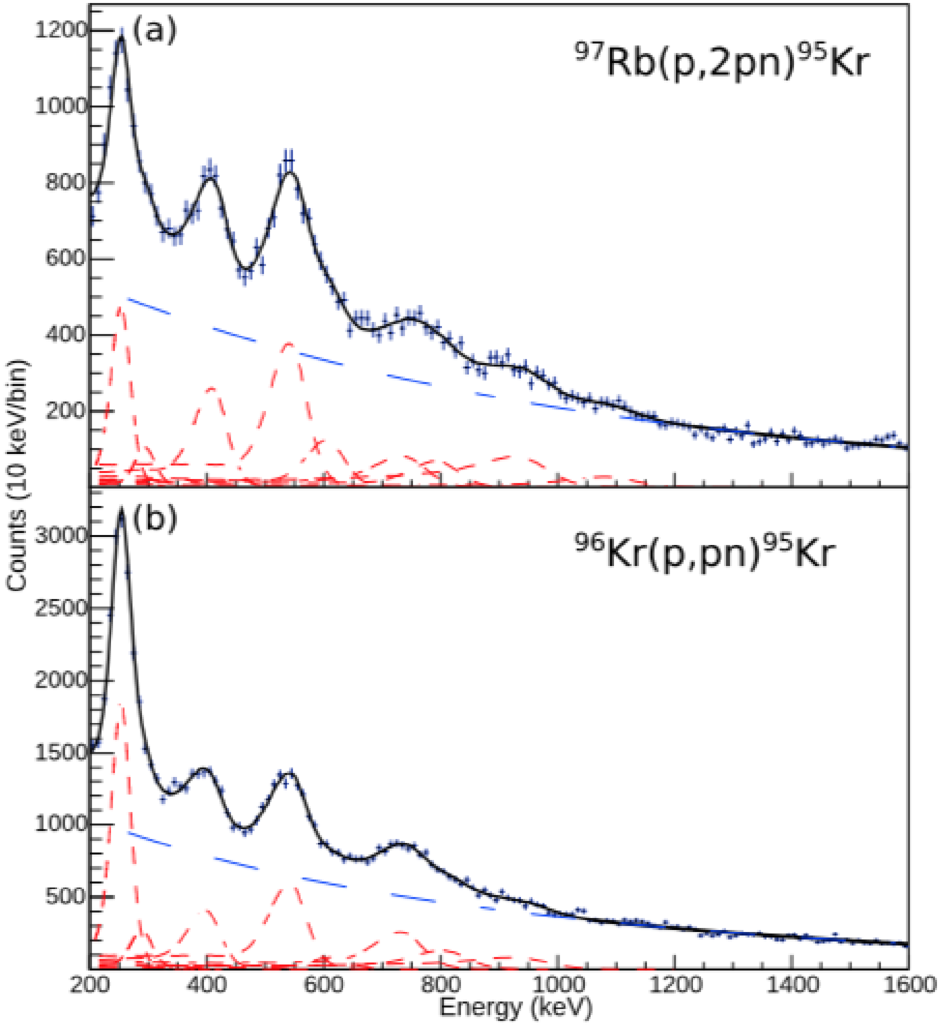


FIG. 10. Doppler-corrected γ-ray energy spectra measured with DALI2 for the two-nucleon removal and one-neutron knockout reaction channels ^{97}Rb$(p,2pn)^{95}$Kr and ^{96}Kr$(p,pn)^{95}$Kr. The spectra were fitted with simulated response functions (red) and a two-component exponential background (blue dashed curve).

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γ-ray spectroscopy of low-lying yrast and non-yrast states in neutron-rich ^{94,95,96}Kr

R.-B. Gerst,[1,*] A. Blazhev,[1] K. Moschner,[1] P. Doornenbal,[2] A. Obertelli,[2,3] K. Nomura,[4] J.-P. Ebran,[5,6] S. Hilaire,[5,6] J. Libert,[5,6] G. Authelet,[3] H. Baba,[2] D. Calvet,[3] F. Château,[3] S. Chen,[7,2] A. Corsi,[3] A. Delbart,[3] J.-M. Gheller,[3] A. Giganon,[3] A. Gillibert,[3] V. Lapoux,[3] T. Motobayashi,[2] M. Niikura,[8] N. Paul,[3,9] J.-Y. Roussé,[3,9] H. Sakurai,[2,8] C. Santamaria,[3] D. Steppenbeck,[2] R. Taniuchi,[2,8] T. Uesaka,[2] T. Ando,[2,8] T. Arici,[10] F. Browne,[11] A. M. Bruce,[11] R. Caroll,[12] L. X. Chung,[13] M. L. Cortés,[10,14] M. Dewald,[1] B. Ding,[15] F. Flavigny,[16,17] S. Franchoo,[16] M. Górska,[10] A. Gottardo,[16] J. Jolie,[1] A. Jungclaus,[18] J. Lee,[19] M. Lettmann,[14] B. D. Linh,[13] J. Liu,[19] Z. Liu,[15,20] C. Lizarazo,[10,14] S. Momiyama,[2,8] S. Nagamine,[2,8] N. Nakatsuka,[2,21] C. R. Nita,[22] C. Nobs,[11] L. Olivier,[16] R. Orlandi,[23] Z. Patel,[12] Zs. Podolyák,[12] M. Rudigier,[12] T. Saito,[2,8] C. Shand,[12] P.-A. Söderström,[2] I. Stefan,[16] V. Vaquero,[18] V. Werner,[14] K. Wimmer,[8] and Z. Xu[19]

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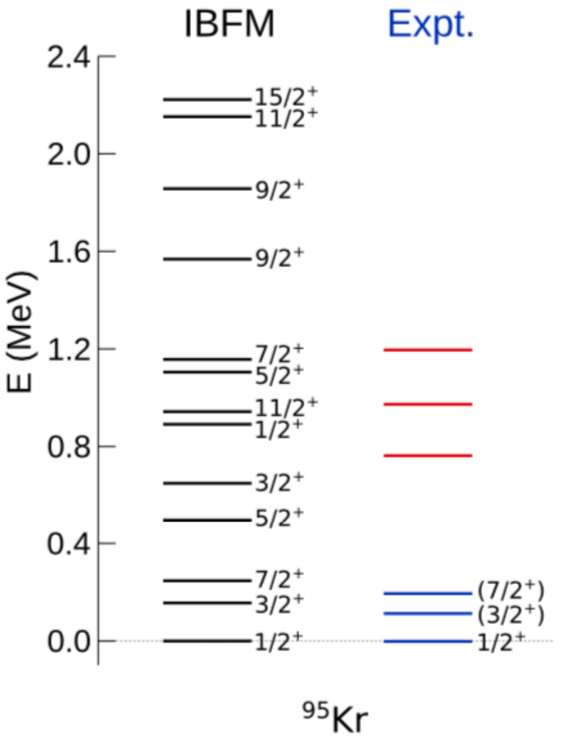

FIG. 16. Low-lying positive-parity excited states for ^{95}Kr on the left, predicted by the IBFM [20] compared with experimental data (on the right) from this work and Refs. [29,40]. The newly suggested excited levels decaying into the $(7/2^+)$ isomer are shown in red.

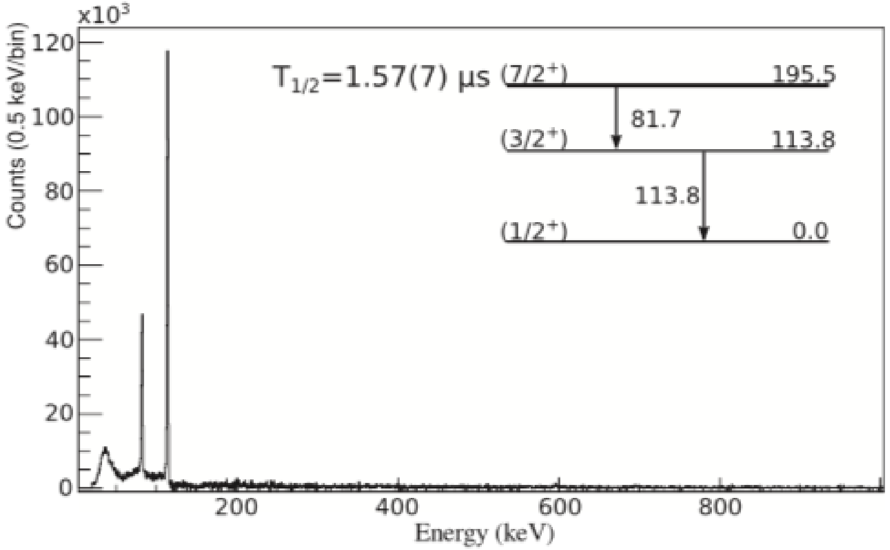

FIG. 9. Background-subtracted EURICA energy spectrum with a gate on ^{95}Kr in the ZeroDegree PID. The two peaks correspond to the two delayed transitions in ^{95}Kr at 81.7(2) and 113.8(2) keV depopulating the known $(7/2)^+$ isomer [29,40] as shown in the inset of the figure (see text for details).