-- "I quibble about this Augusto": John and some aspects of weak binding phenomena in atomic nuclei

Augusto O. Macchiavelli

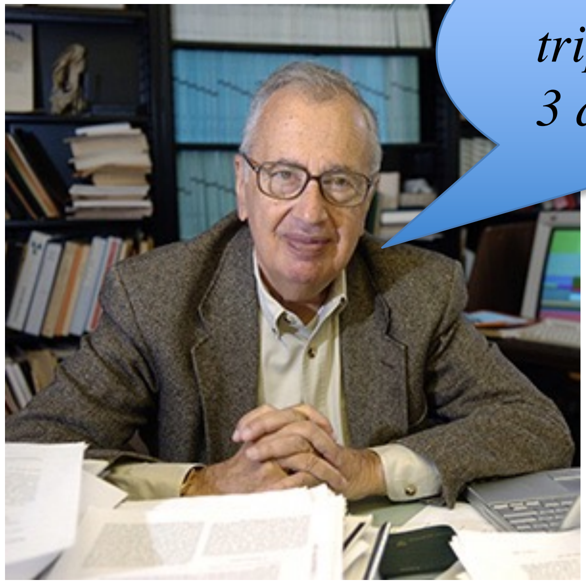
Physics Division

Oak Ridge National Laboratory

Nuclear Physics in the 2020s and Beyond - A Symposium in Honor of John Schiffer
Jul 10 – 11, 2023
Argonne National Laboratory

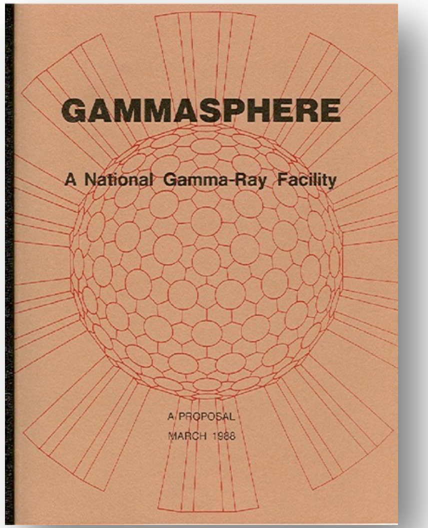
Some introductory remarks

ca 1987

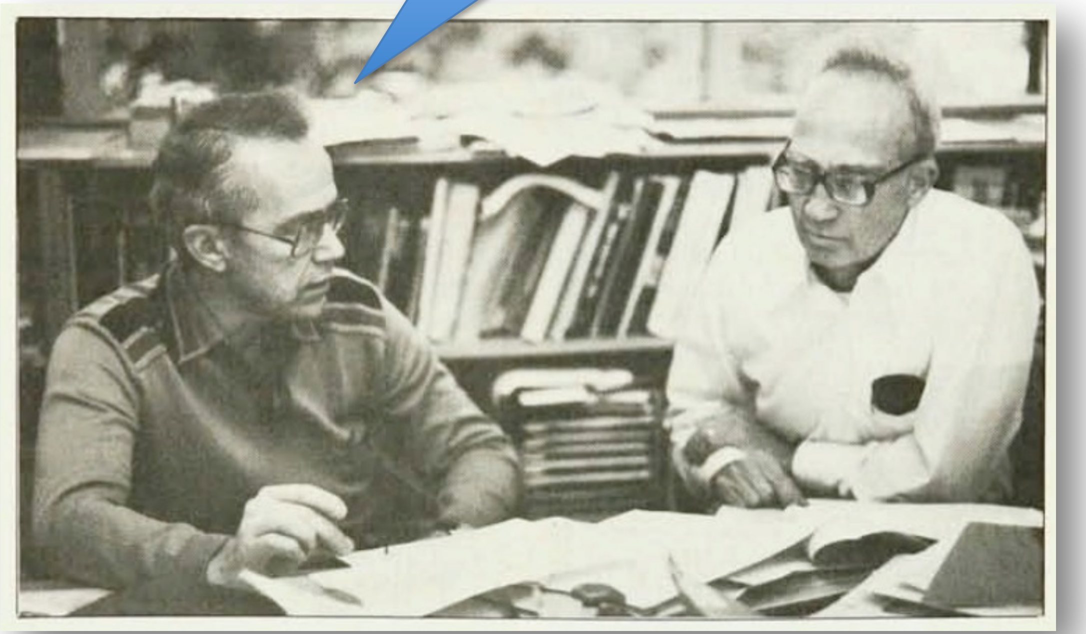


Gentlemen, why is a triple not the same as 3 doubles?

John



Dick, I think we need to introduce a resolving power measure!



Frank Dick

For the non-aficionados

Robert Janssens & Frank Stephens
New Physics Opportunities at Gammasphere,
Nuclear Physics News, 6:4, 9-17 (1996)

New Physics Opportunities at Gammasphere

We have some familiarity with the spectrum of electromagnetic radiation over an energy range of something like thirty orders of magnitude--from radio waves (about 10^{-10} eV) to cosmic rays (up to at least 10^{18} eV). This radiation is enormously important to us in many ways. The light by which we see and the radio and television waves through which we communicate are obvious examples. In science, we also have many examples of this importance: recent ones might be the cosmic microwave background radiation, which constitutes one of the strongest pieces of evidence for the big bang origin of the universe, and the high-energy gamma rays emitted from relativistic heavy ion collisions, which are one of the very few probes that carry information directly from the hottest interaction zones of nuclear matter without subsequent modification in the outlying regions. In addition, much of what we know about atomic, molecular and nuclear energy levels has come from studying the electromagnetic radiation emitted when the system makes a transition from one state to another.

Many types of detectors have been built for electromagnetic radiation which differ widely depending on the energy range of interest—from radio receivers to massive detectors composed of alternating layers of lead and a suitable scintillator. The characteristic energy range for electromagnetic radiation from a system composed of a (charged) particle of a given mass confined to a known volume can be estimated from the uncertainty principle, $(m\Delta v)(\Delta x) \geq \hbar$, which gives a rough value for the zero-point energy of the system and thereby for the separation between energy levels. For a proton in a nucleus the order of magnitude for this energy is 10^6 eV (one MeV). Thus for the study of nuclei, we need to design and build detectors aimed at this energy range.

Generally, the most important properties of a gamma-ray detector are: 1) high efficiency in detecting incident gamma rays; 2) high resolution resulting in very narrow energy peaks for mono-energetic gamma rays; 3) high ratio of full-energy to partial-energy events; and 4) high granularity to localize individual gamma rays. For gamma rays in the one MeV range, by far the best combination of these properties is given by semiconductors made of high purity germanium (Ge) crystals. The largest such crystals that can currently be produced commercially are cylinders about 10 cm in diameter and 10 cm long, which, for about 30% of the incident one MeV mono-energetic gamma rays, produce a full-energy peak with a full width at half its maximum height of about 2 keV.

There are some ways to optimize the performance of such detectors. In order to achieve a better ratio of full-energy to partial-energy events (called the peak-to-total, or P/T, ratio), the Ge detectors are surrounded by a dense scintillator—bismuth germanate (BGO) being the usual one—which detects gamma rays Compton-scattered out of the Ge crystal and then suppresses electronically the partial energy pulse left in the Ge detector. This results in an improvement in the P/T ratio for a 1.3 MeV gamma ray from about 0.3 for the bare crystal to about 0.7 when suppressed. To increase both the efficiency and the granularity, such Compton- suppressed detectors are assembled into arrays. The first such array, called TESSA, was set up in Risø, Denmark, in 1980 and consisted of five detectors; whereas, current arrays like Gammasphere have 110 Ge crystals, 70 of which have two independent elements, for a total of 180 separate detectors. The power of a gamma-ray detector system is not so easy to evaluate. Gammasphere will have about six times higher efficiency for a one MeV gamma ray than its predecessors like HERA at LBL, but that does not mean it is only six times more powerful. Following heavy-ion fusion reactions about 25 gamma rays are typically emitted, of which Gammasphere will often catch a reasonable number, for example five (called a 5-fold event), and its efficiency to do this will be six raised to the fifth power more than HERA's. The power of Gammasphere is not that much higher than HERA, however, because information (though less) is also obtained when only two or three gamma rays from a given reaction are caught and HERA can often do that. To quantify how powerful such detector systems are, a quantity called resolving power (RP) is defined which is given by a deceptively simple relation:

$$RP = \exp[19.5/(1 - \ln\varepsilon/\ln R)],$$

where ε is the efficiency for full-energy gamma rays and R is the gain in peak-to-background ratio when a coincidence gate is set on a weak gamma-ray transition (i.e. the peak-to-total ratio for the gamma rays times the average separation between gamma rays in the spectrum divided by the width of the gamma-ray peaks). The factor, 19.5, comes from several experimental conditions (such as beam current and running time) assumed in the estimate. Using this relation, Gammasphere is about 100 times more powerful than HERA.

Gammasphere

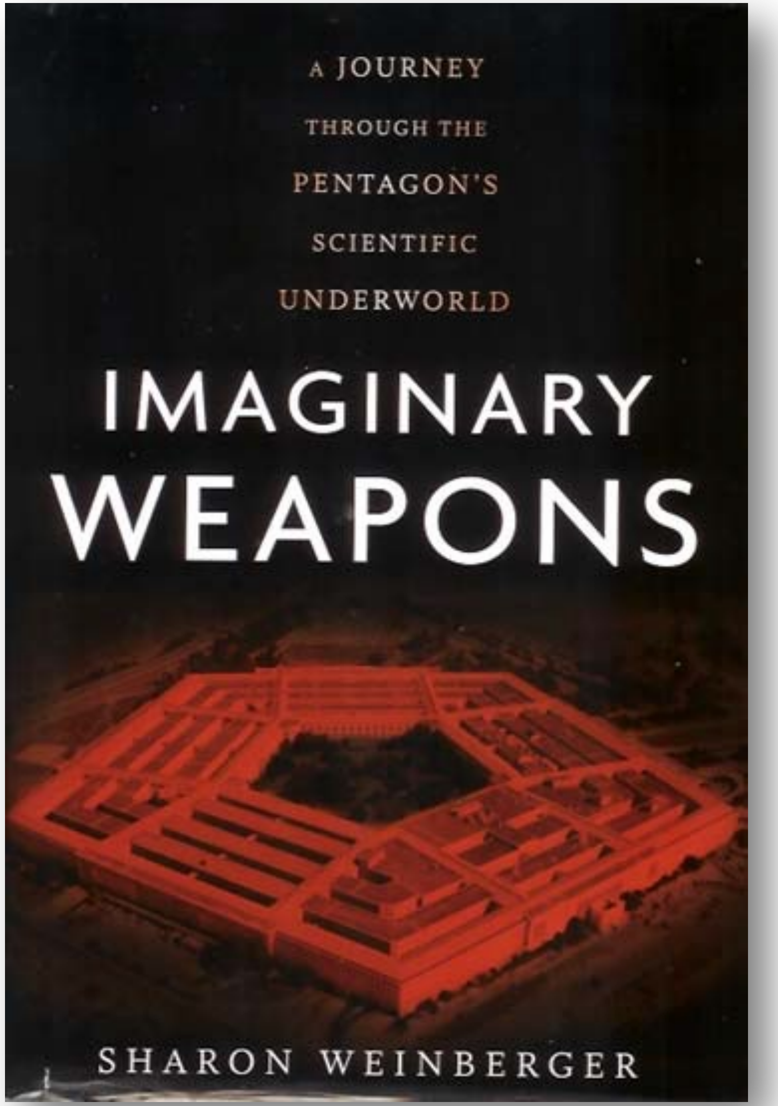
Realizing that considerable

Setting up GAMMASPHERE 1995

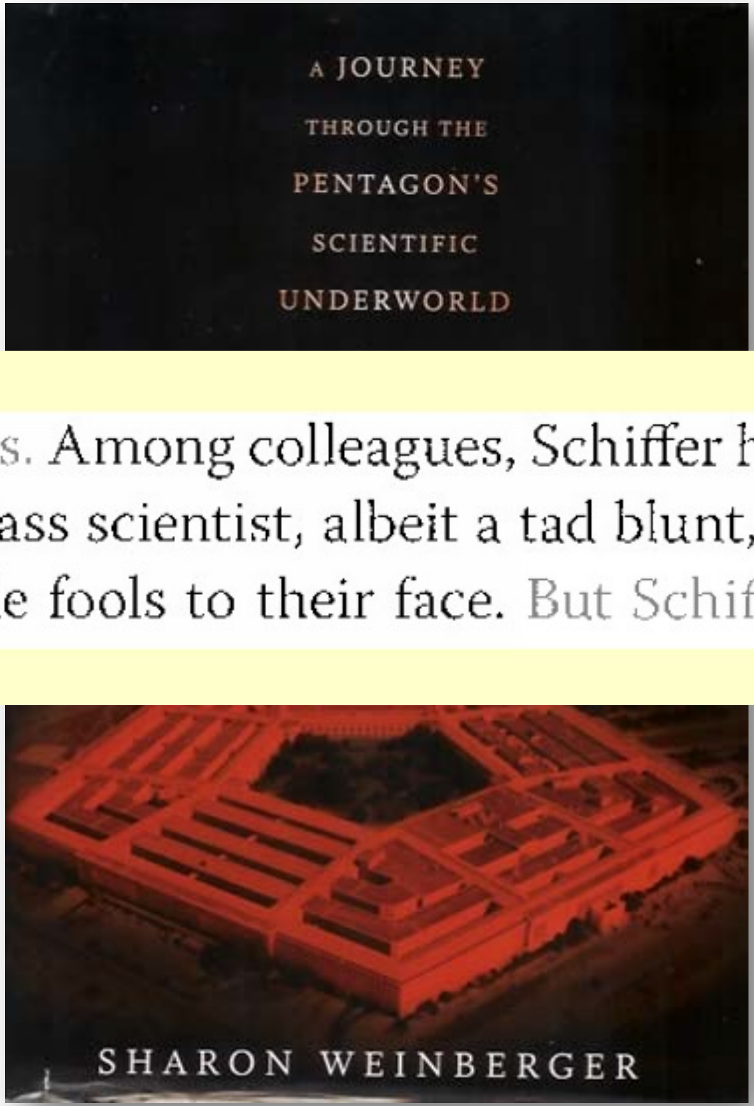
Setting up GAMMASPHERE 1995

At the Gordon Conference 1999

At the Gordon Conference 1999



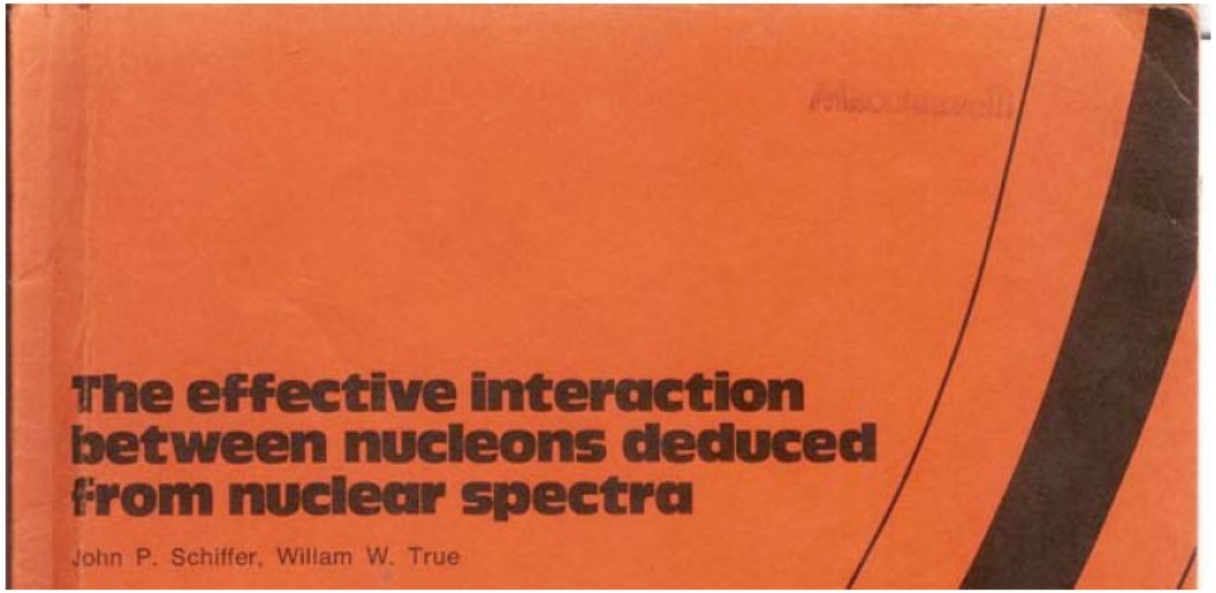
Released in 2006

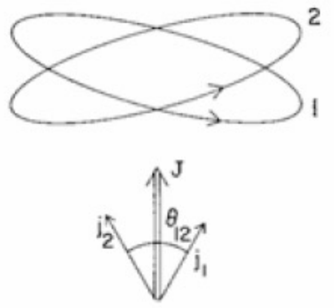


their students. Among colleagues, Schiffer had a reputation as a world-class scientist, albeit a tad blunt, with a habit of calling people fools to their face. But Schiffer was not the

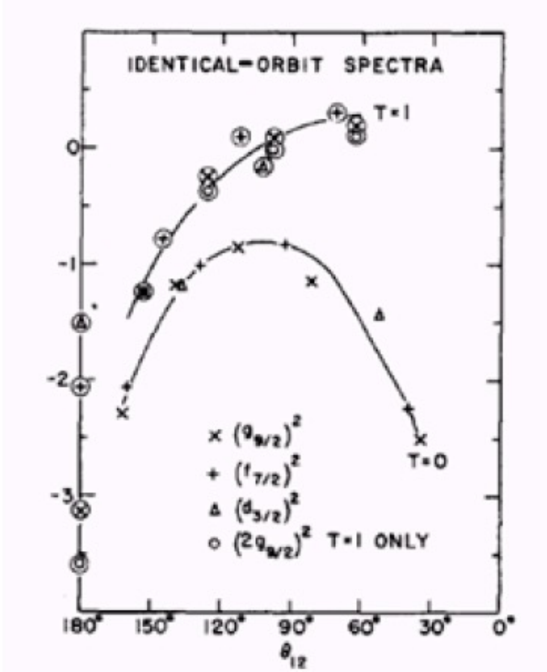
Released in 2006

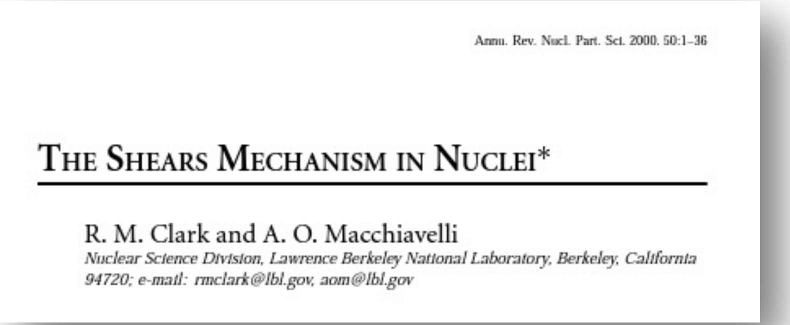
My personal copy of a classic





$$\theta_{12} = \cos^{-1} \frac{j_1(j_1+1) + j_2(j_2+1) - J(J+1)}{\left[2 j_1 j_2 (j_1+1)(j_2+1)\right]^{1/2}}$$



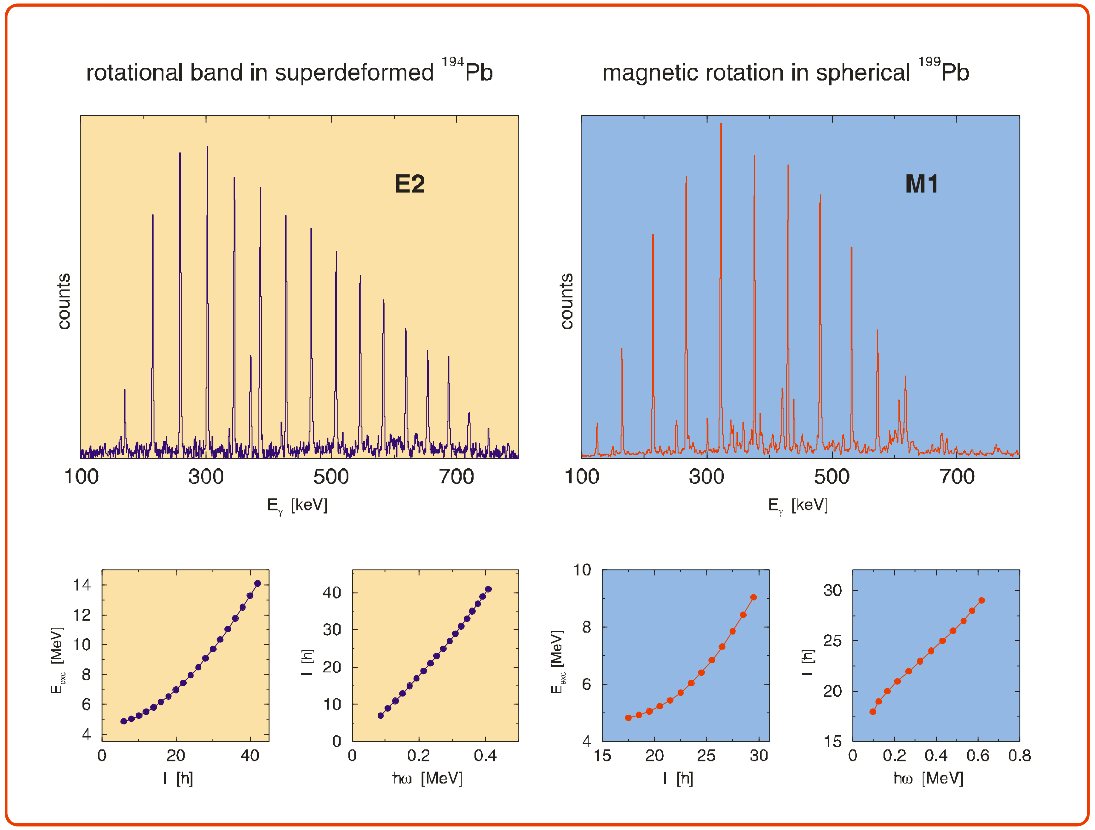

Annu. Rev. Nucl. Part. Sci. 2000. 50:1–36

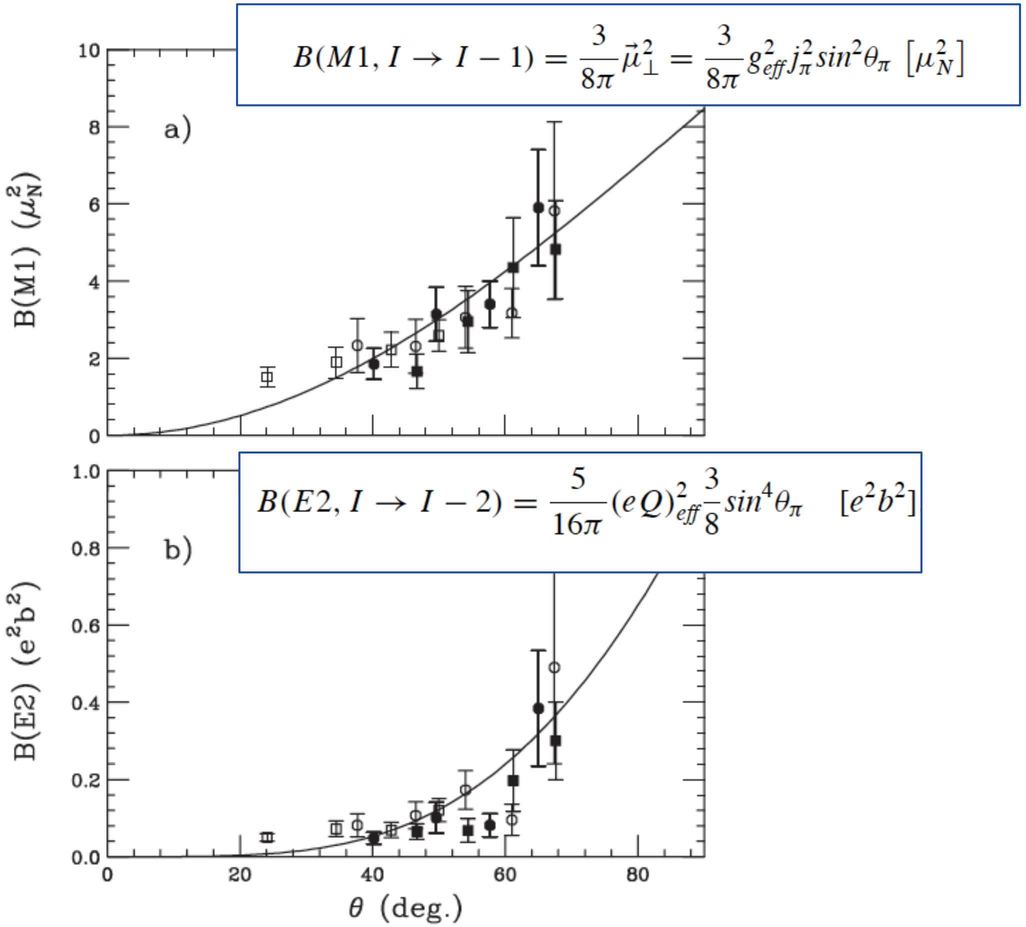
THE SHEARS MECHANISM IN NUCLEI*

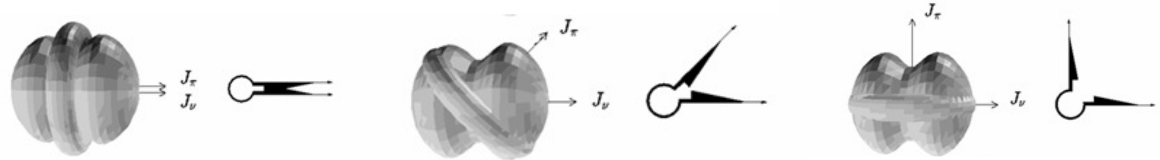
R. M. Clark and A. O. Macchiavelli
Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720; e-mail: rmclark@lbl.gov, aom@lbl.gov

Applied John's concepts to correlate the spectroscopic data with the shears angle → relevant degree of freedom.

and derived effective interaction between the shear's "blades"







Other topics of discussion with John

Neutron-proton pairing and the (3He,p) reaction

Transfer reactions a la Nilsson

Islands of Inversion in the rotational model

Quenching of spectroscopic factors

Effective charges

Halos and weak binding

Pairing correlations and the (t,p) reaction

Other topics of discussion with John

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Pairing correlations and the (t,p) reaction

John and weak binding effects:

VOLUME 92, NUMBER 16 PHYSICAL REVIEW LETTERS week ending 23 APRIL 2004

Is the Nuclear Spin-Orbit Interaction Changing with Neutron Excess?

J. P. Schiffer,[1] S. J. Freeman,[1,2] J. A. Caggiano,[3] C. Deibel,[3] A. Heinz,[3] C.-L. Jiang,[1] R. Lewis,[3] A. Parikh,[3] P. D. Parker,[3] K. E. Rehm,[1] S. Sinha,[1] and J. S. Thomas[4]
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[2]*University of Manchester, Manchester M13 9PL, United Kingdom*
[3]*Yale University, New Haven, Connecticut 06520, USA*
[4]*Rutgers University, Piscataway, New Jersey 08854, USA*

PHYSICAL REVIEW C **94**, 024330 (2016)

Ordering of the $0d_{5/2}$ and $1s_{1/2}$ proton levels in light nuclei

C. R. Hoffman,* B. P. Kay,† and J. P. Schiffer‡
Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA

PRL **119,** 182502 (2017) PHYSICAL REVIEW LETTERS week ending 3 NOVEMBER 2017

Effect of Weak Binding on the Apparent Spin-Orbit Splitting in Nuclei

B. P. Kay,[1,*] C. R. Hoffman,[1] and A. O. Macchiavelli[2]
[1]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[2]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

We thank John Schiffer and Olivier Sorlin for their insightful comments. A. O. M. also acknowledges discussions with the Berkeley nuclear structure group. This material

→ Ben Kay's talk

PHYSICAL REVIEW C **105**, L041302 (2022)

Letter

Single-nucleon energies changing with nucleon number

J. P. Schiffer,* B. P. Kay, and J. Chen
Physics Division, Argonne National Laboratory, Lemont, Illinois 60439, USA

Outline

Short introduction

Part 1

Weak binding effects on the structure of ^{40}Mg

Part 2

Pairing in exotic neutron rich nuclei

OAK RIDGE National Laboratory

From: "Schiffer, John P." <schiffer@anl.gov>
Subject: your arXiv
Date: August 25, 2017 at 1:10:22 PM EDT
To: "Augusto O. Macchiavelli" <aomacchiavelli@lbl.gov>
Cc: "Hoffman, Calem R." <crhoffman@anl.gov>, "Kay, Benjamin P." <kay@anl.gov>

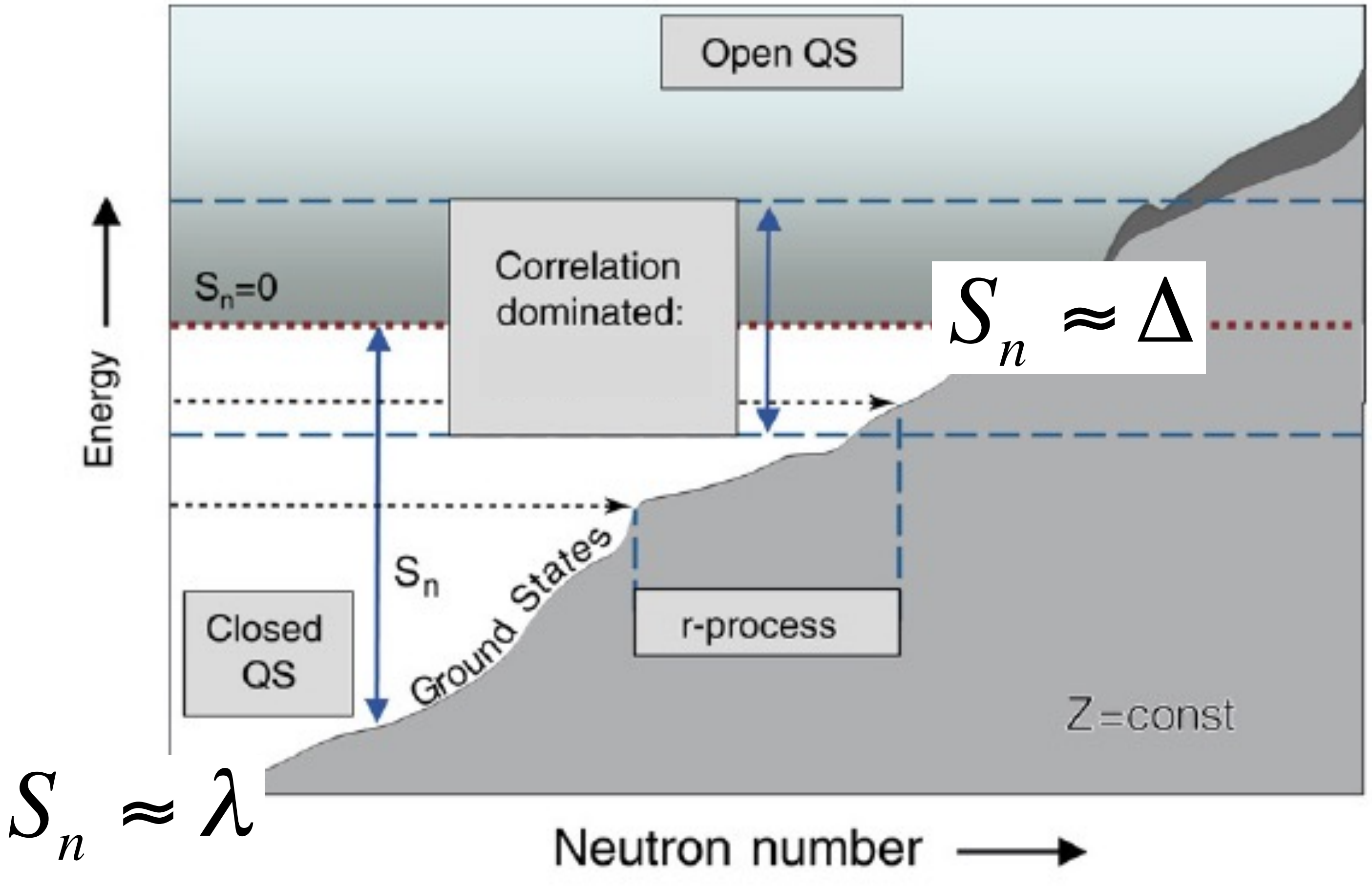
Hi Augusto

I read your 11Be on the ArXiv on 11Be with interest. What you have is nice – but I would quibble with the Introduction.

I am sure John would ask many critical questions and make relevant comments

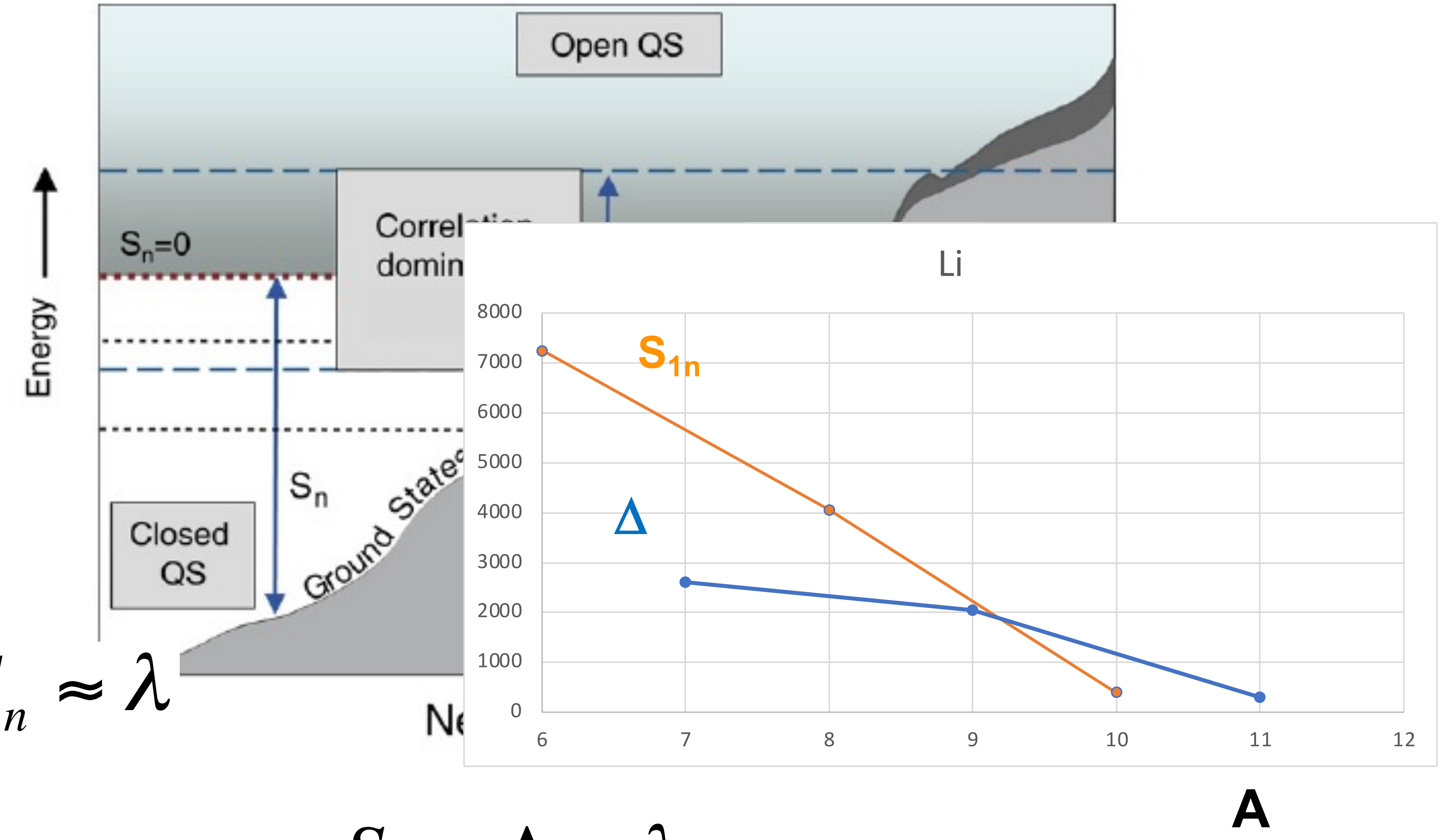
I hope that his spirit will lead you to quibble a few times during the rest of the talk !

J. Dobaczewski et al. / Progress in Particle and Nuclear Physics 59 (2007) 432–445



$$S_n \approx \Delta + \lambda$$

J. Dobaczewski et al. / Progress in Particle and Nuclear Physics 59 (2007) 432–445



$$S_n \approx \lambda$$

$$S_n \approx \Delta + \lambda$$

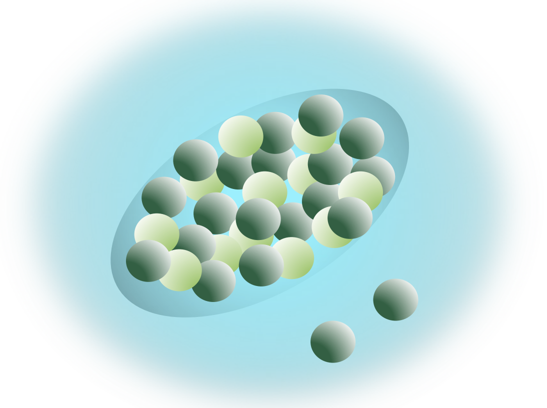
Motivation

Rotational Motion

Islands of Inversion → deformation

Weak binding

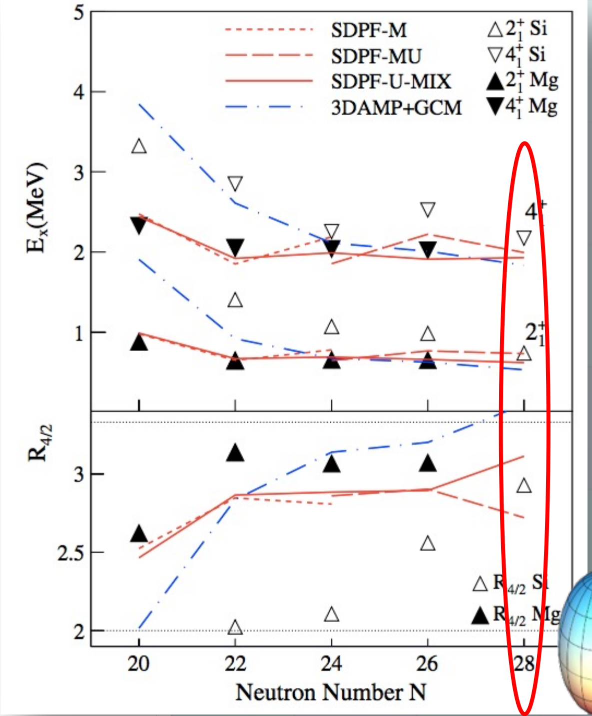
Neutron-rich nuclei → drip-line

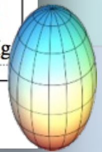


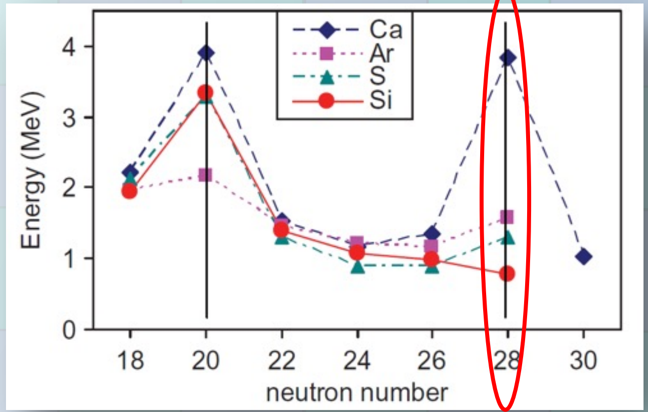
Courtesy of Ben Kay

^{40}Mg – Shell Evolution, Deformation and Weak Binding

The neutron-rich Mg isotopes from *N*=20 to *N*=28 are deformed.

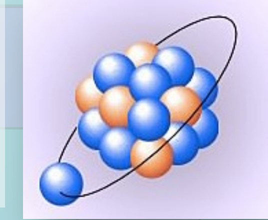




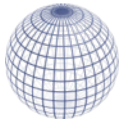


^{40}Mg is a (near)drip-line nucleus, at the intersection of *N*=28, where shapes are believed to be rapidly changing.

Low-ℓ orbitals near the Fermi surface bring the possibility of nuclear halos.

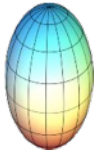


^{48}Ca



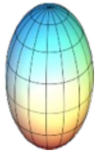
^{47}K

^{46}Ar



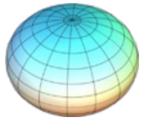
^{45}Cl

^{44}S



^{43}P

^{42}Si



^{41}Al

^{29}Mg ^{30}Mg ^{31}Mg ^{32}Mg ^{33}Mg ^{34}Mg ^{35}Mg ^{36}Mg ^{37}Mg ^{38}Mg ^{39}Mg ^{40}Mg

N=28

Tensor Driven Jahn-Teller Effect

Otsuka et al.

Gaudefroy and Grevy, Nucl. Phys. News **20**, 13 (2010); Li *et al.*, PRC **84**, 054304 (2011).
Nowacki and Poves, PRC **79**, 014310 (2009); Doornenbal *et al.*, PRL 111, **212502 (2013)**

The third is the charm

PHYSICAL REVIEW LETTERS **122,** 052501 (2019)

Editors' Suggestion

First Spectroscopy of the Near Drip-line Nucleus ^{40}Mg

H. L. Crawford,[1,*] P. Fallon,[1] A. O. Macchiavelli,[1] P. Doornenbal,[2] N. Aoi,[3] F. Browne,[2] C. M. Campbell,[1] S. Chen,[2] R. M. Clark,[1] M. L. Cortés,[2] M. Cromaz,[1] E. Ideguchi,[3] M. D. Jones,[1,†] R. Kanungo,[4,5] M. MacCormick,[6] S. Momiyama,[7] I. Murray,[6] M. Niikura,[7] S. Paschalis,[8] M. Petri,[8] H. Sakurai,[2,7] M. Salathe,[1] P. Schrock,[9] D. Steppenbeck,[9] S. Takeuchi,[2,10] Y. K. Tanaka,[11] R. Taniuchi,[7] H. Wang,[2] and K. Wimmer[7]

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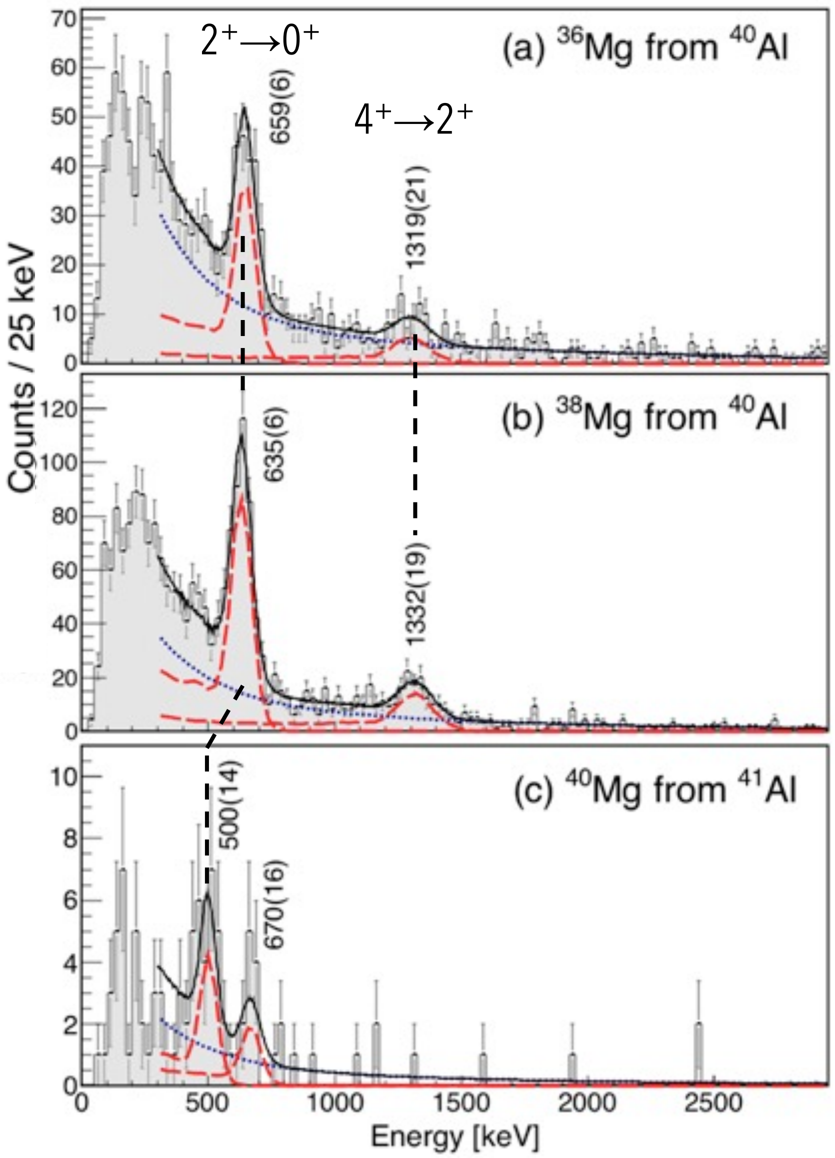
Two Measurements at RIKEN/RIBF - high energy ^{48}Ca beam 345 MeV/u

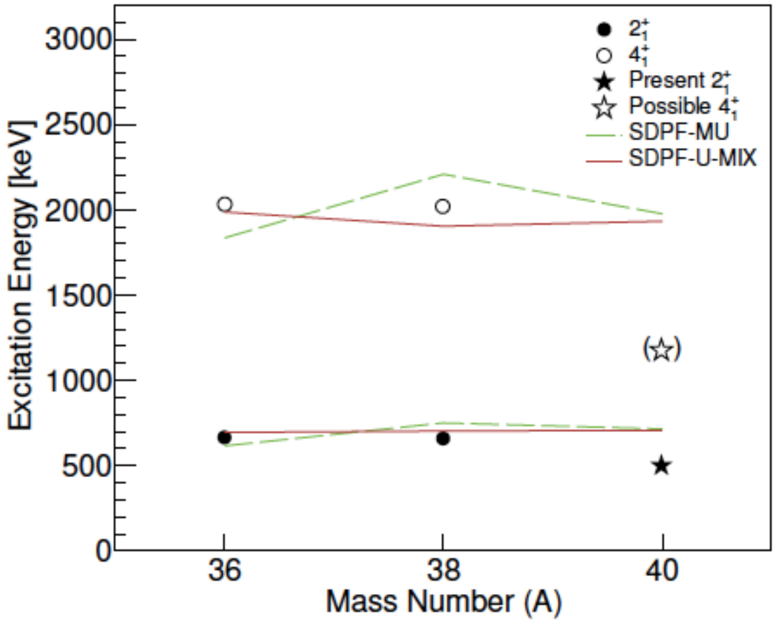
^{48}Ca → ^{42}Si (200 MeV/u), 2p Knockout: ^{42}Si -2p → ^{40}Mg (v/c ~ 60%)

^{48}Ca → ^{41}Al (240 MeV/u), 1p Knockout: ^{41}Al -1p → ^{40}Mg (v/c ~ 60%)

OAK RIDGE National Laboratory

^{40}Mg Gamma-ray Spectrum DALI 2

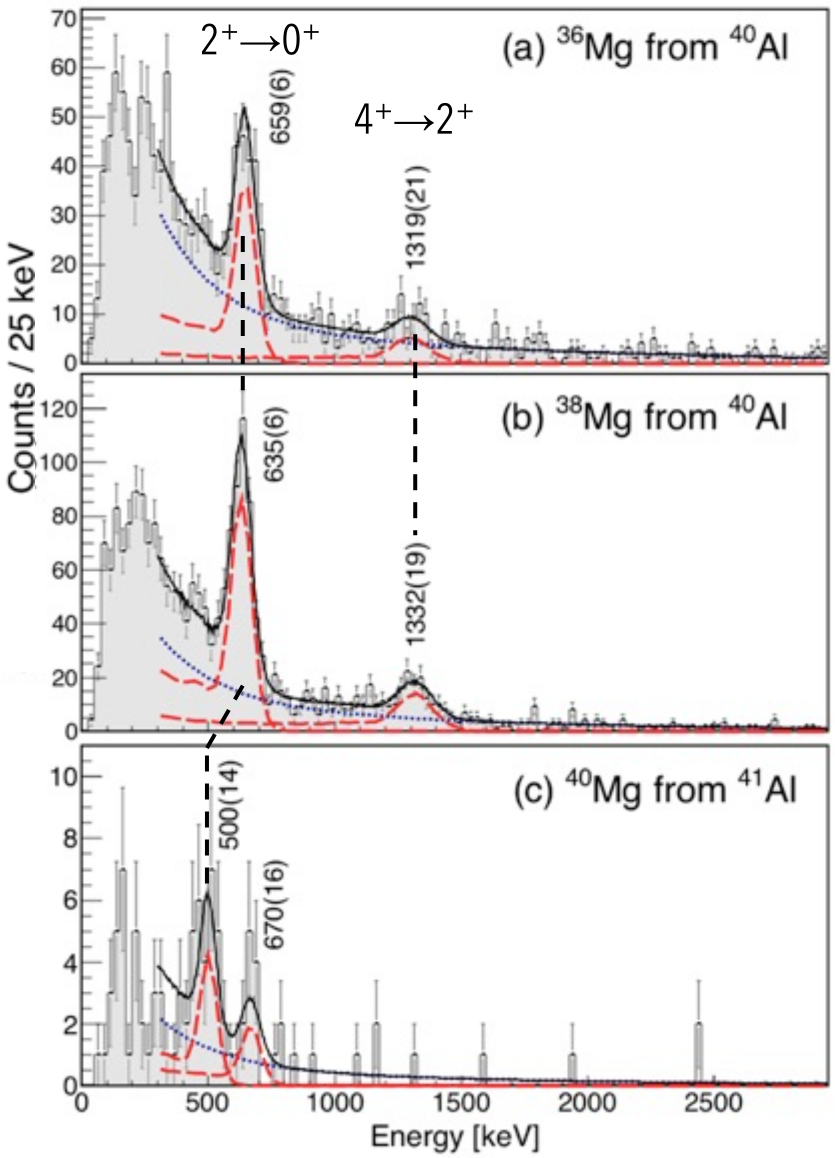


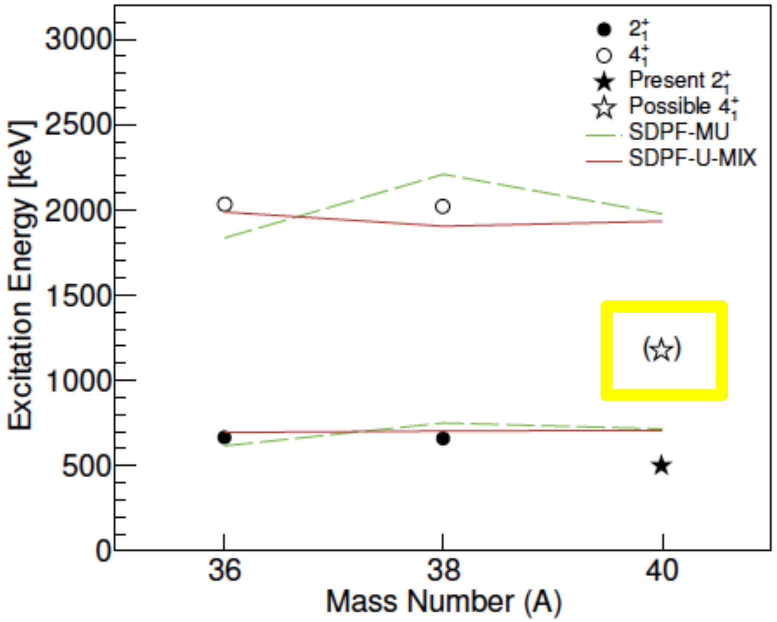


- **500 keV transition assigned to 2⁺→0⁺**
- Observe a 20% decrease in ^{40}Mg 2⁺ energy relative to ^{38}Mg.
- Relative change in 2⁺ (more robust prediction than absolute value) is not captured in calculations

Oak Ridge National Laboratory

^{40}Mg Gamma-ray Spectrum DALI 2





- **670 keV transition ?**

$4_1^+ \rightarrow 2_1^+$ $2_2^+ \rightarrow 0_1^+$ * $2_2^+ \rightarrow 2_1^+$ $0_2^+ \rightarrow 2_1^+$ + …

- No scenario fits with existing expectations (systematics) nor predictions from calculation
- Breakdown of systematics and theory predictions may suggest something is happening at the dripline ??

* **adopted, cf.** Crawford *et al.*, PRC 89, 041303(R) (2014).

Weak binding effects

Eur. Phys. J. A (2022) 58:66
https://doi.org/10.1140/epja/s10050-022-00719-5

THE EUROPEAN PHYSICAL JOURNAL A

Check for updates

Regular Article - Theoretical Physics

Weak binding effects on the structure of ^{40}Mg

A. O. Macchiavelli[1,a], H. L. Crawford[1], P. Fallon[1], R. M. Clark[1], A. Poves[2]

[1] Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
[2] Departamento de Física Teórica and IFT-UAM/CSIC, Universidad Autónoma de Madrid, 28049 Madrid, Spain

As discussed by Hansen an Jonson and subsequent works the extended matter radius exhibited by a two-neutron halo nucleus can be expressed in terms of the separation energy of the weakly bound neutrons (S_{2n}) through the tunneling parameter

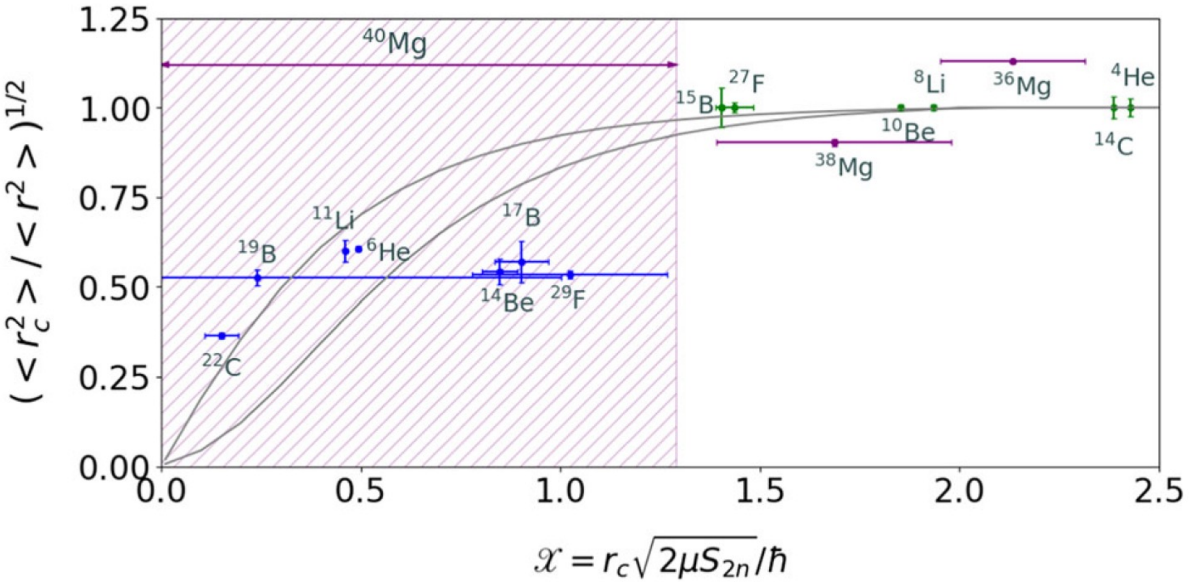
$$\mathscr{X} = r_c\sqrt{2\mu S_{2n}}/\hbar$$

derived from the exponential nature of the asymptotic wavefunction. Following these authors, we consider a plot of

$$(< r_c^2 > / < r_m^2 >)^{1/2} \text{ vs. } \mathscr{X}$$

to capture the universal features of the *2n* halo systems. Their root-mean-square (RMS) ratio represents the volume overlap between the valence nucleons and the core.

S_{2n} of 667±706 keV.



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Particle-core coupling

The strength of the interaction between the core and the *2n* system in terms of particle surface (phonon) coupling could serve as a metric to establish whether the halo can be considered "weakly" or "strongly" coupled.

As discussed in detail by Bohr and Mottelson, the strength of the particle-vibration (surface) coupling for quadrupole modes is given by:

$$f_{\lambda=2} = \left(\frac{5}{16\pi}\right)^{1/2} \left(\frac{\hbar\omega_2}{2C_2}\right)^{1/2} \frac{\langle k_2 \rangle}{\hbar\omega_2}$$

where C_2 is the quadrupole restoring force parameter, $h\omega_2$ is the vibration frequency, and $k_2(r) = R\,\partial V/\partial R$ the single-particle form factor, where we take R as the core radius r_c

In turn we have:

$$B(E2, 0^+ \rightarrow 2^+) = 5\left(\frac{3}{4\pi} ZeR^2\right)^2 \frac{\hbar\omega_2}{2C_2}$$

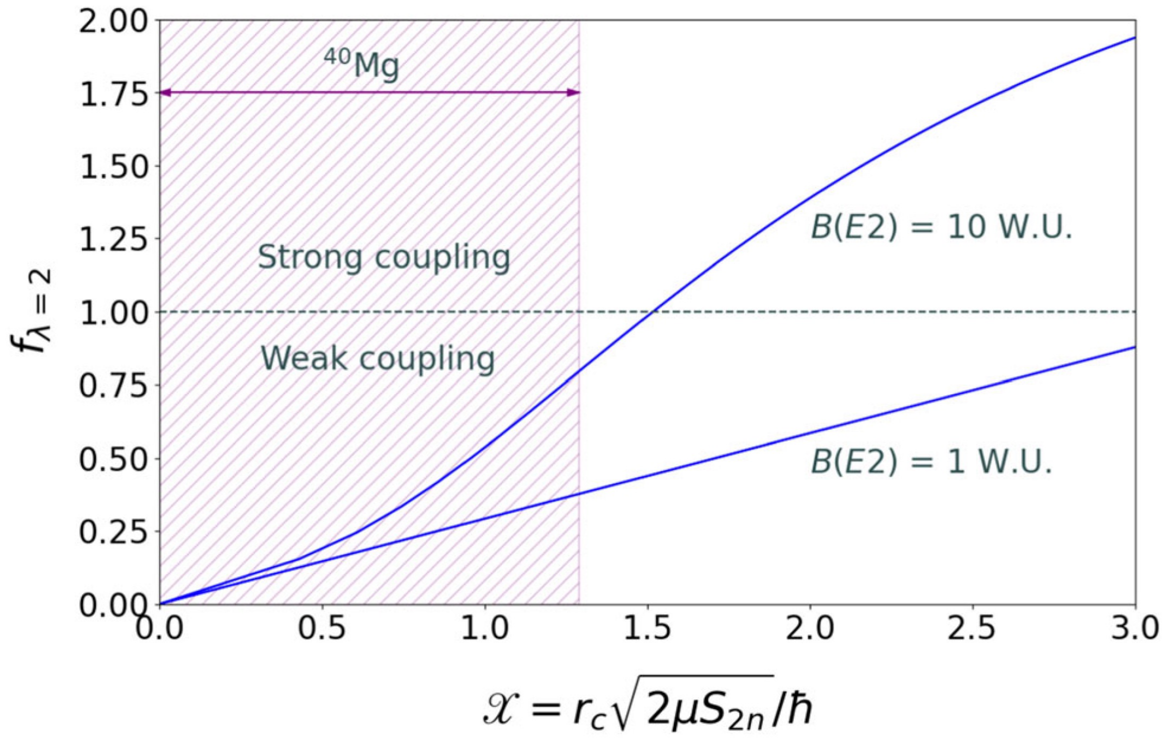
The softness of the surface quadrupole vibration/phonon mode is related to the C_2 coefficient, or the $B(E2)$ and the frequency $h\omega_2$

Particle-core coupling

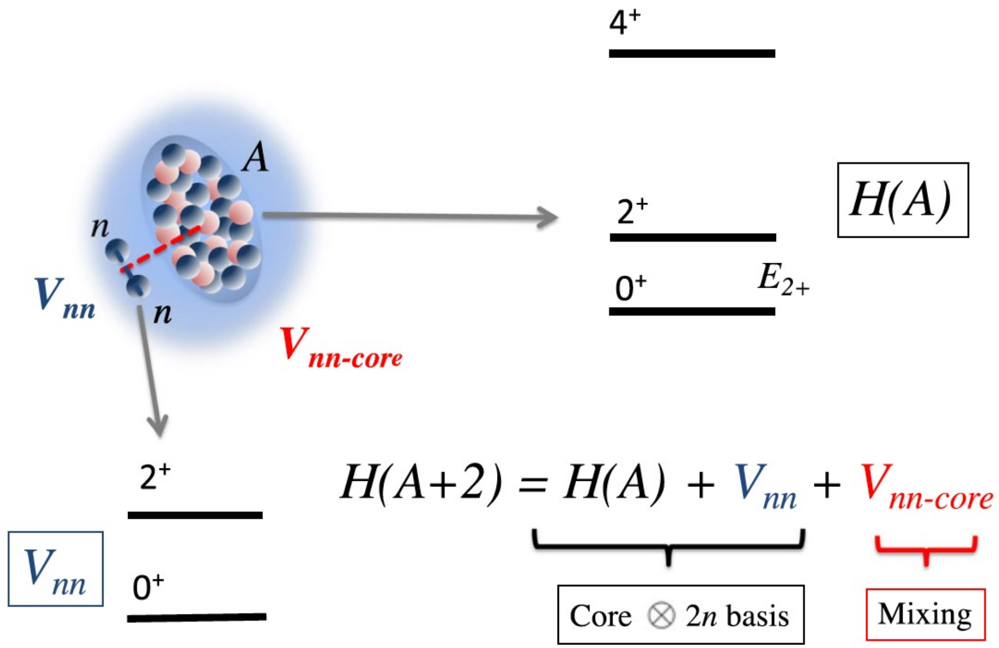
The curves represent two cases that can be associated with a soft- and a hard- core as indicated by the $B(E2)$ strengths in W.U.

For the range of binding energies expected for ^{40}Mg, $f_{\lambda=2}$ is below unity for a $B(E2)$ of 10W.U., signaling a regime where weak particle-surface coupling dominates, in contrast to the strong coupling expected in the lighter (more bound) even-A magnesium isotopes from ^{32}Mg to ^{38}Mg.

A consequence of the weak coupling between the deformed core and the neutron halo is that the latter can be considered spherical to all practical purposes.



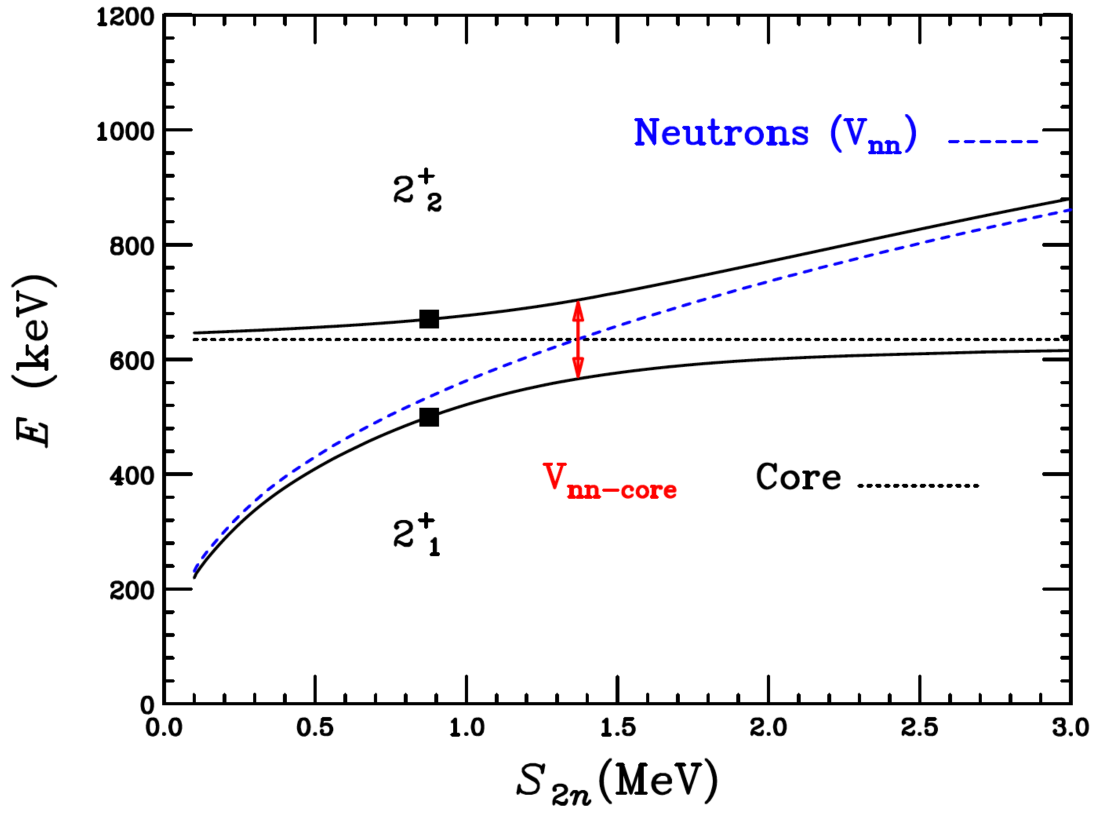
Weak coupling phenomenological model



It is natural to expect that effects of weak binding on excited states will show when the energy scales of the two degrees of freedom become comparable:

$$E_{core}(2^+) \approx E_{2n}(2^+)$$

State energies and wavefunctions



It is interesting to see that the unperturbed lines cross for binding energies in the range expected for ^{40}Mg and even a small mixing matrix element *Vnn−core* will give rise to largely mixed states in the laboratory frame.

A minimization procedure on the experimental energies of the two potential states populated gives a solution with

Vnn−core = 69keV S_{2n} = 877 keV

and wavefunctions:

$$|2_1^+\rangle = \quad 0.45|2_{core}^+\rangle + 0.89|2_{2n}^+\rangle$$
$$|2_2^+\rangle = -0.89|2_{core}^+\rangle + 0.45|2_{2n}^+\rangle$$

The fact that *Vnn−core* << E_{core} (V_{nn}) supports the weak coupling assumption.

Reaction cross sections

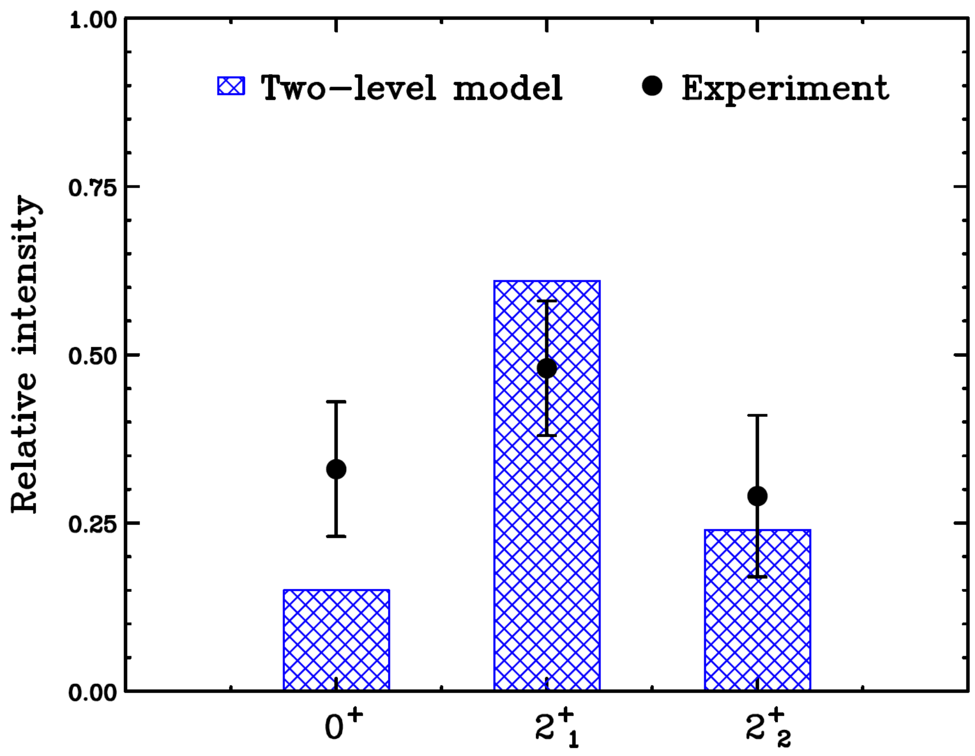
The wavefunctions of the two 2^+ states can readily be used to determine their relative intensities populated in a direct knockout reaction

To calculate the population of the final states in ^{40}Mg produced from the ^{41}Al(-1p) reaction we assume that the ground state of ^{41}Al is $K = 5/2^+$, from the $\pi[202]5/2$ Nilsson level originating from the $d_{5/2}$ spherical level.

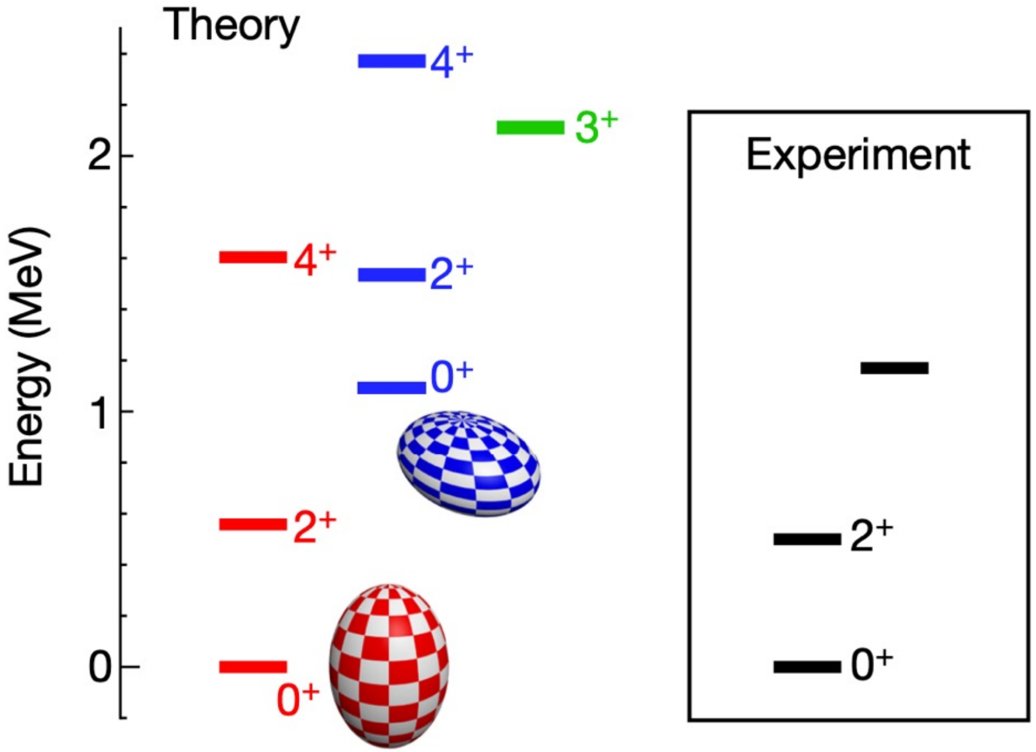
In the single-j approximation the collective spectroscopic factors follow the values of the Clebsch-Gordan coefficients:

$$\langle \frac{5}{2} \frac{5}{2} \frac{5}{2} - \frac{5}{2} | I_f 0 \rangle$$

In the minimization procedure we also include a single-particle spectroscopic factor $S_{sp}(5/2+ \rightarrow 2^+_{2n})$ with a fitted value of 0.14. This gives a measure of the component of the $|2^+_{2n}\rangle$ state in the ground state of ^{41}Al.



MCSM results



- The recent Nature publication shows MCSM results which reproduce well the observed levels, assuming transitions in cascade

N. Tsunoda, T. Otsuka *et al*., Nature **587**, 66 (2020).

Summary

Observed spectrum of ^{40}Mg does not fit with expectations and existing calculations. Breakdown of experimental systematics and theory may suggest something is happening at the neutron dripline

Qualitative arguments indicate that weak binding effects could reproduce the spectrum seen in ^{40}Mg

We have studied the coupling of weakly bound (halo) valence neutrons to a deformed core using a Weak-Coupling and Particle-Rotor models. Despite its simplicity, our phenomenological approach captures the main physical ingredients and provides a framework that allows us to to examine possible coupling schemes involving a core and halo

MCSM results differ in the nature of the second experimental γ transition

It is clear that further experimental and theoretical works will be required to elucidate its intriguing structure

FRIB Experiments

Beta-decay. Approved FDSi proposal

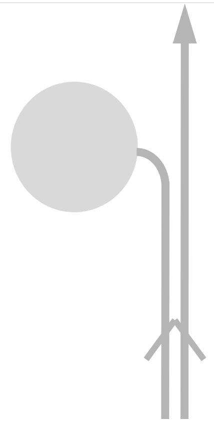
Total Reaction Cross Section. Approved proposal

Mass Measurement. NOT approved

Pairing in Exotic Nuclei

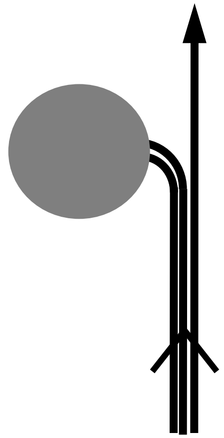
The evolution of pairing correlations in exotic nuclei is a topic of great interest in nuclear structure, in particular pairing in neutron-rich isotopes and the role of weak binding.

Direct Reactions



$$< A+1 \mid a^{+} \mid A >$$

Spectroscopic (*u*, *v*) Factors



$$< A+2 \mid a^{+}a^{+} \mid A >$$

Constructive interference

Two particle transfer reactions like (t,p) or (p,t), where 2 nucleons are deposited or picked up at the same point in space provide an specific tool to probe the amplitude of this collective motion.

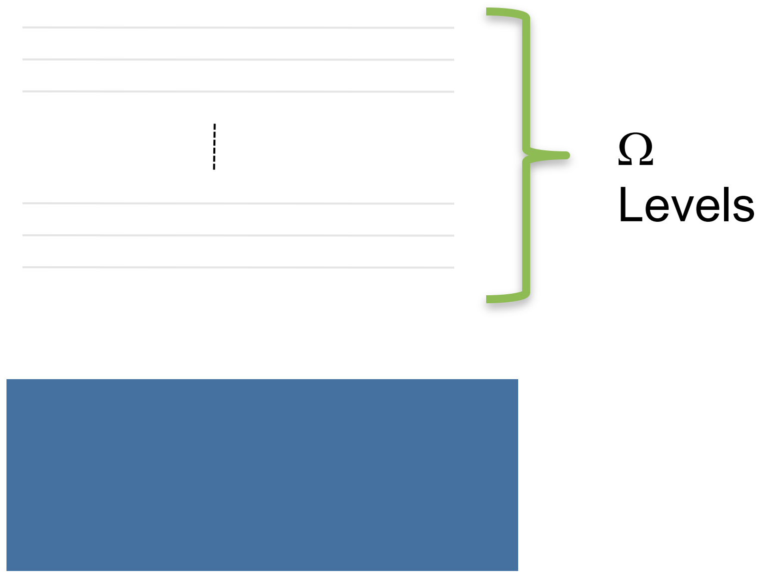
The transition operators $<f|a^{+}a^{+}|i>$, $<f|aa|i>$ are the analogous to the transition probabilities BE2's on the quadrupole case.

R.A. Broglia, O. Hansen and C. Riedel, Adv. Nucl. Phys. Vol 6 (1973) 287

D. M. Brink and R.A. Broglia, Nuclear Superfluidity, Cambridge Monographs.

Pairing vibration and the (t,p) reaction

$$\sigma \propto < A_o + 2 | T | A_o >^2$$

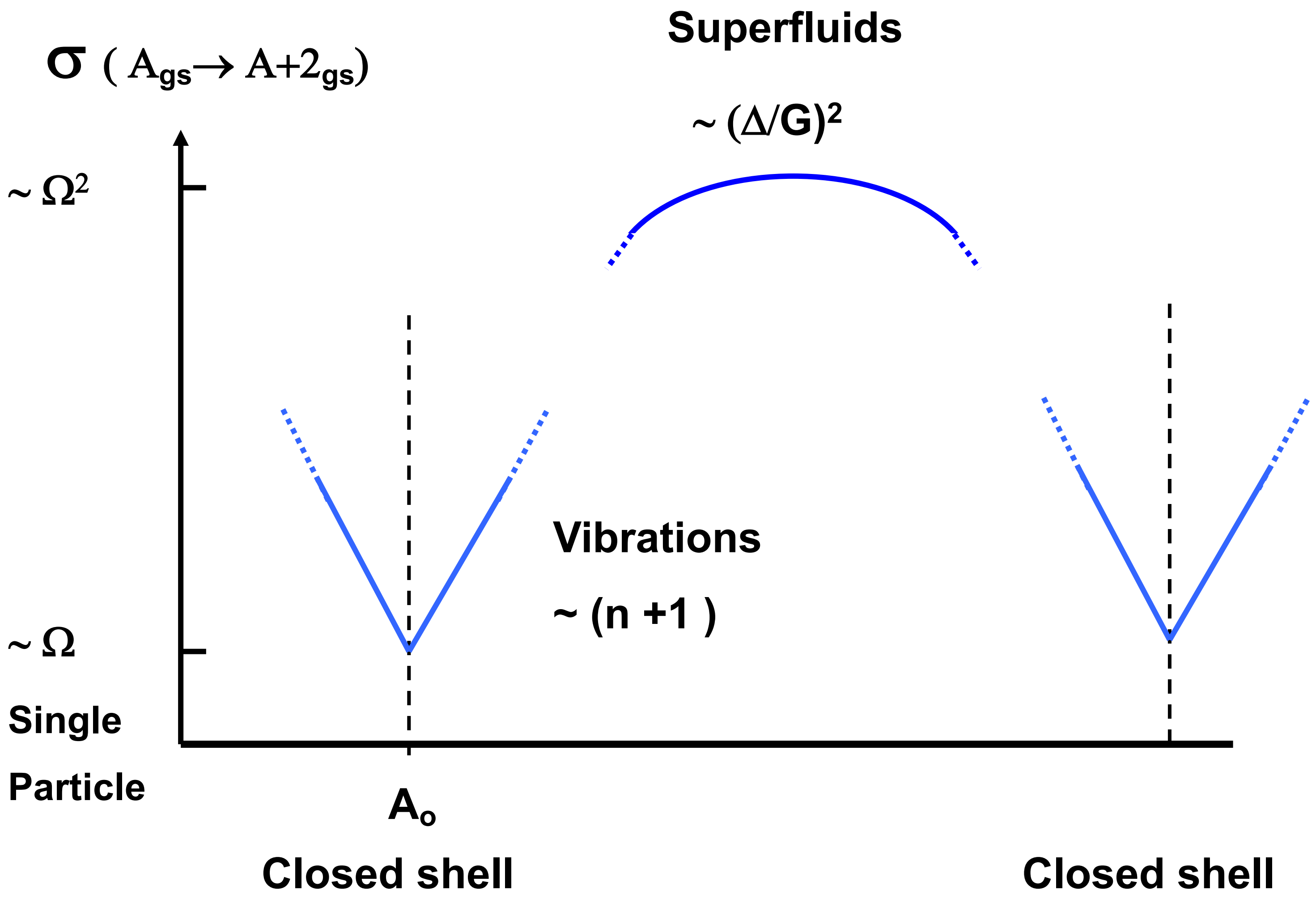


Closed shell nucleus, A_0

$$| A_o + 2 > = \sum_i \frac{1}{\sqrt{\Omega}} | i >$$

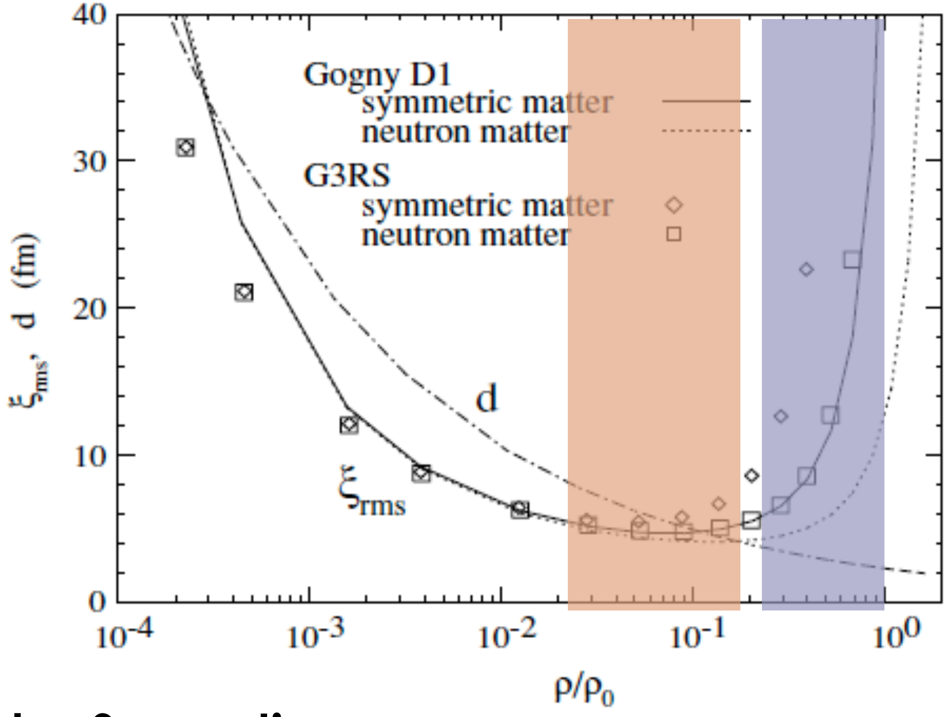
$$\sigma \propto \left(\sum_i \frac{1}{\sqrt{\Omega}} < i | T | o > \right)^2$$

$$\sigma \approx \Omega \sigma_{sp}$$



Systematic relative measurements and within a given nucleus.

Motivation

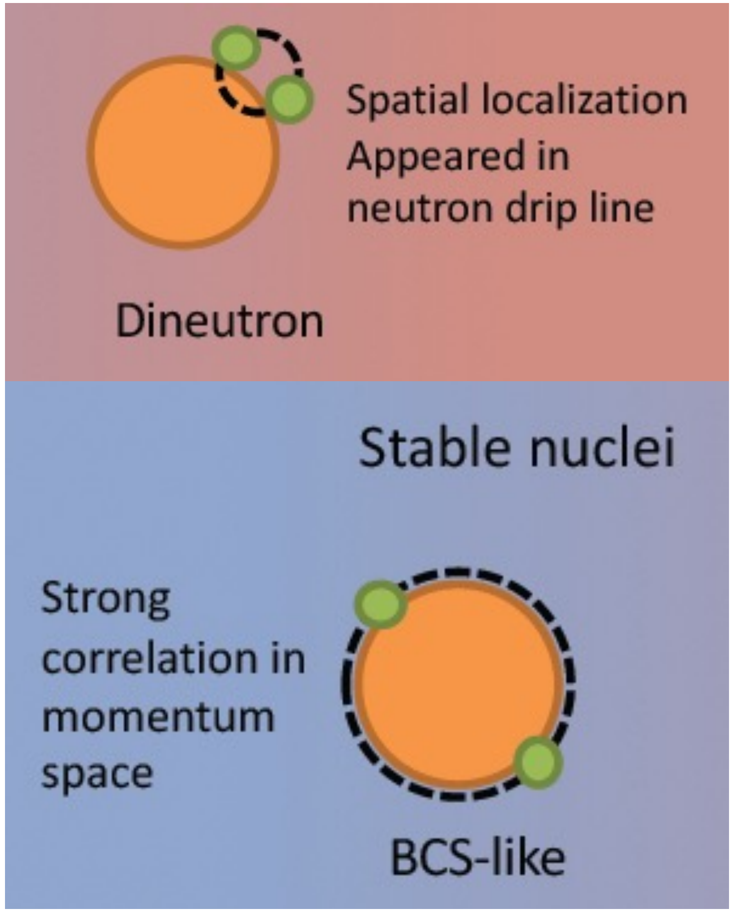


d **Separation**

ζ_{rms} **Correlation Length**

Key observable
→ (t,p) two-neutron transfer reactions

Matsuo *et al*. PRC 73 (2006) 044309
Pillet *et al*. PRC 76 (2007) 024310

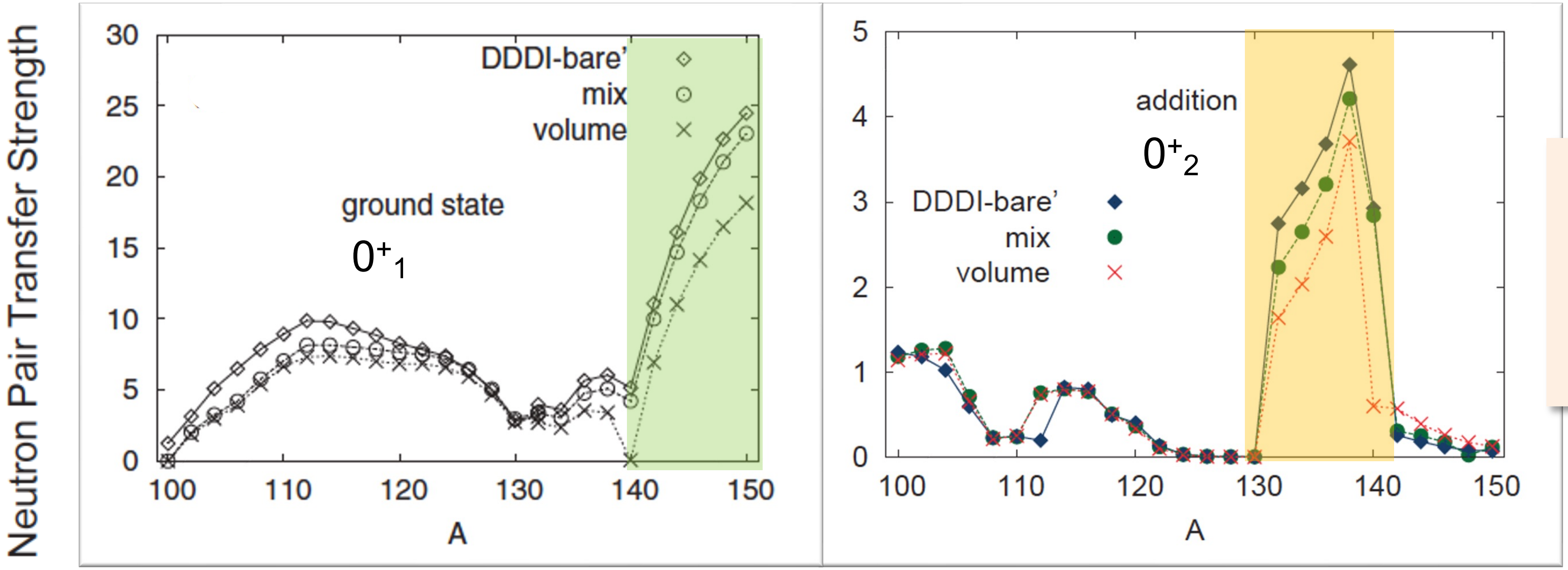


Motivation

PHYSICAL REVIEW C **84**, 044317 (2011)

Anomalous pairing vibration in neutron-rich Sn isotopes beyond the $N = 82$ magic number

Hirotaka Shimoyama and Masayuki Matsuo



Currently it is not possible to study Sn nuclei with A > 140.
However, the region 132 < A < 140 where strong transitions to an excited pairing vibrational 0^+_2 state are predicted is within reach of present accelerator facilities.

ISS Experiment at ISOLDE coming soon

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Pairing vibrations beyond $N = 82$

May 12, 2021

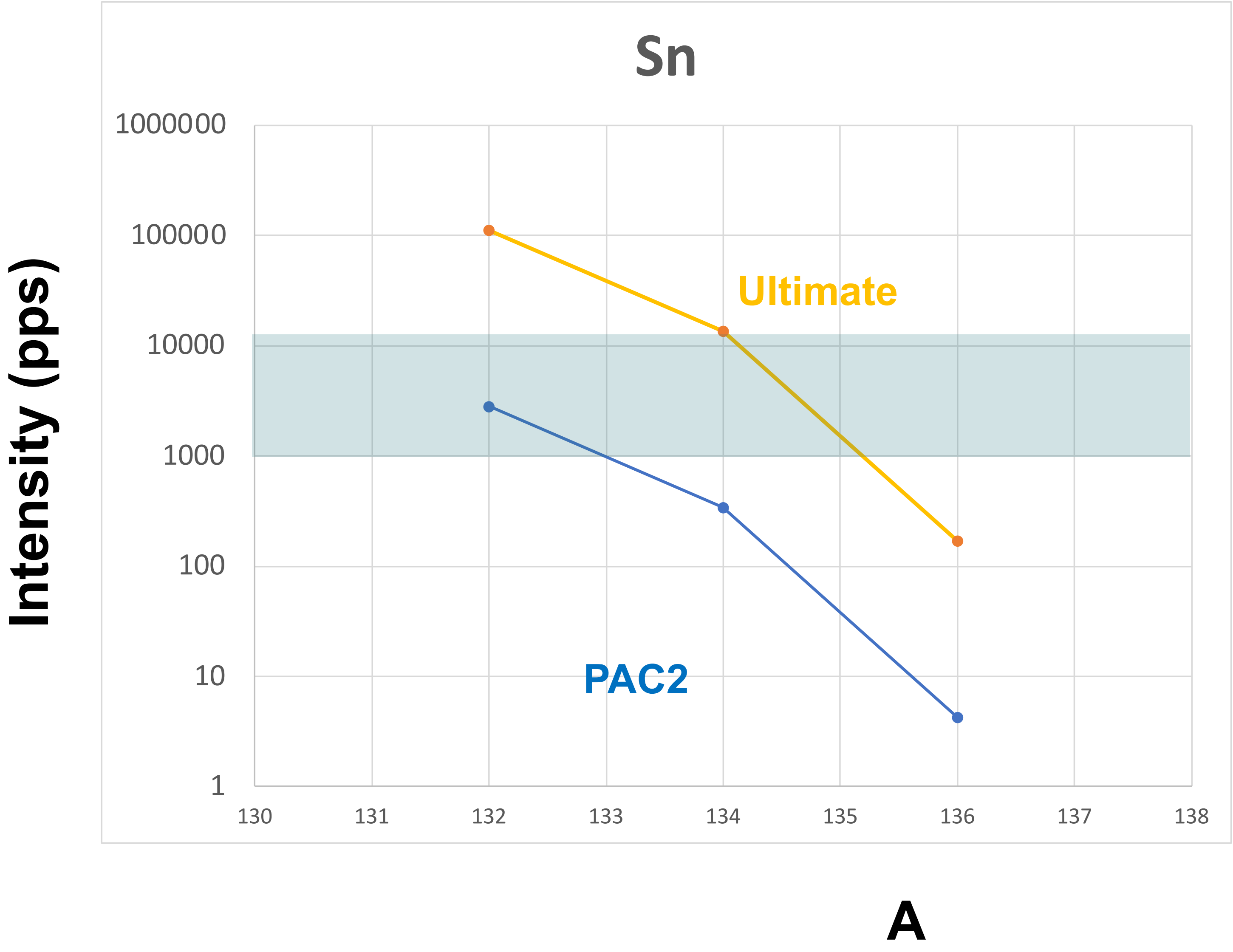
A. O. Macchiavelli[1], K. Wimmer[2], M. J. Borge[2], P. Butler[3], C. M. Campbell[1], J. Chen[4], R. M. Clark[1], H. L. Crawford[1], M. Cromaz[1], P. Fallon[1], S. Freeman[5], L. Gaffney[3], C. Henrich[6] C. Hoffman[4], B. P. Kay[4], A. Jungclaus[2], N. Kitamura[7], T. Kröll[6], M. Labiche[8], I. Lazarus[8], P. Papadakis[8], R. Page[3], R. Raabe[9], D. Sharp[5], T. L. Tang[4], O. Tengblad[2]

Similar effects are expected in the PV mode in ^{138}Xe
[S. Tamaki. Master thesis, Niigata University, 2016]

^{134,136,138,140}Xe(t,p)^{140}Xe at 7 AMeV

Cf. W. Henning talk

FRIB Experiments



Superradiance and two-neutron transfer reactions

Quasi-bound quantum system with a common set of decay channels.

Increasing coupling to continuum leads to segregation long-lived (compound) and short-lived (superradiant) resonance states.

Applications in nuclear physics (e.g. giant & pygmy resonances…), particle physics (baryon resonances) biophysics (photosynthesis), …

P. von Brentano, Physics Report 264**,** 57 (1996) 57
A. Volya, V. Zelevinsky, AIP Conf.Proc. 777, 229 (2004)
N. Auerbach, V. Zelevinsky, Rep. Prog. Phys. 74, 106301 (2011)
I. Rotter, J.P. Bird, Rep. Prog. Phys. 78, 114001 (2015)

communications
physics

ARTICLE

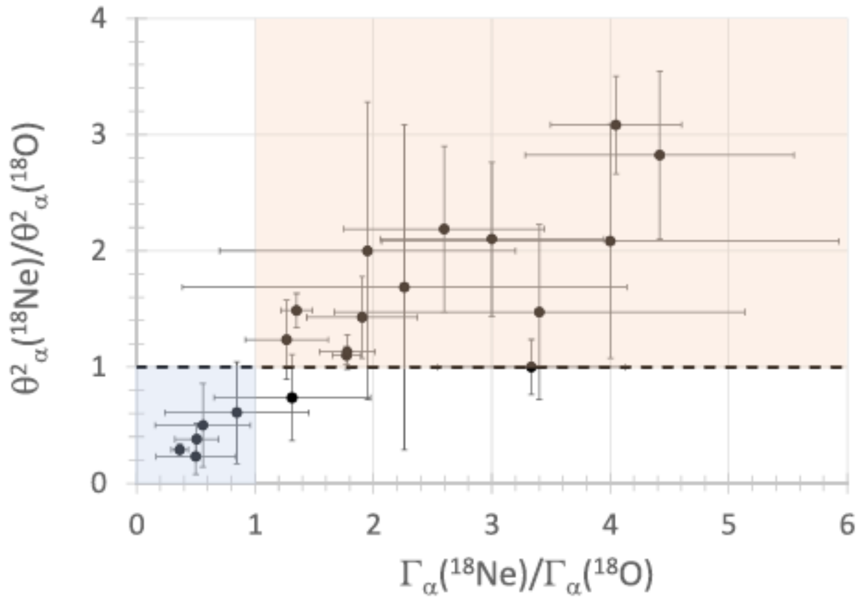
Check for updates

https://doi.org/10.1038/s42005-022-01105-9 OPEN

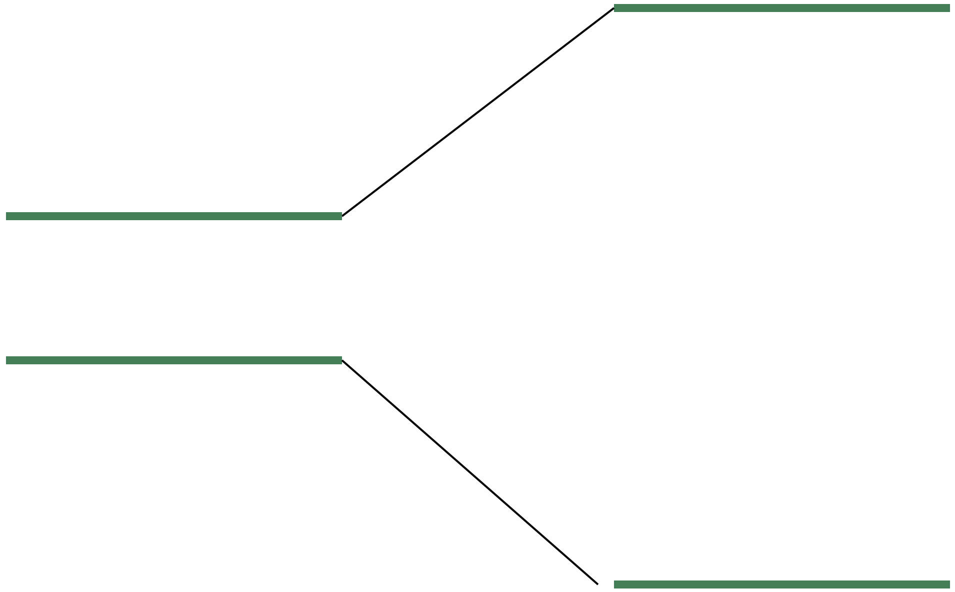
Superradiance in alpha clustered mirror nuclei

Alexander Volya[1,2✉], Marina Barbui[2], Vladilen Z. Goldberg[2] & Grigory V. Rogachev[2,3,4]

includes other decay channels are necessary. It would also be interesting to use different reactions, such as alpha-transfer, to populate the cluster states and provide an independent measure of the total width and branching ratios in mirror nuclei to verify and benchmark current findings. Yet, our findings here may be the clearest manifestation of the superradiance phenomenon in nuclear physics to date.

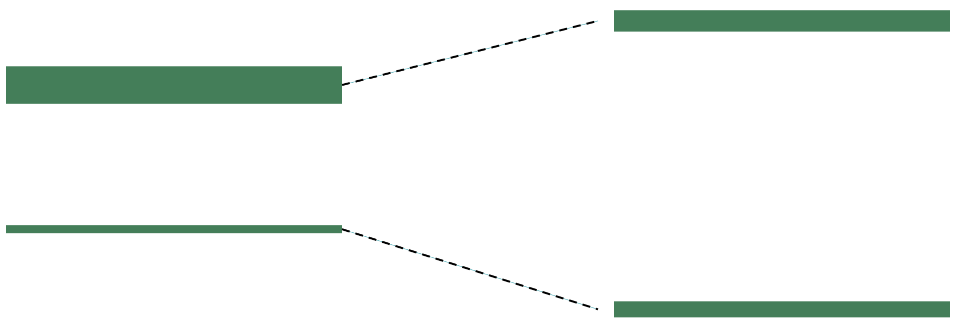


What is superradiance anyway?



Normal mixing of bound levels

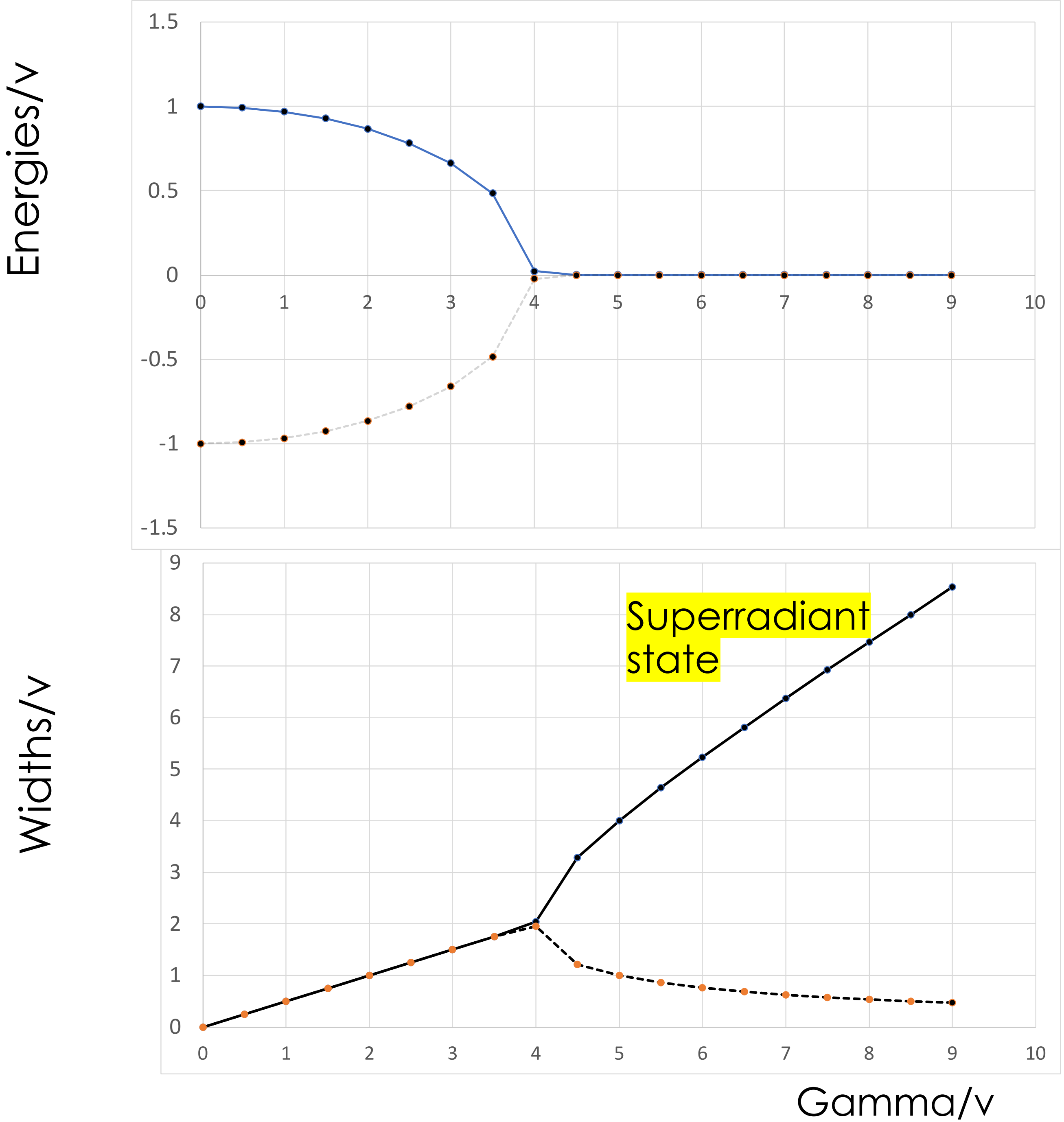
What is superradiance anyway?



Mixing of unbound levels

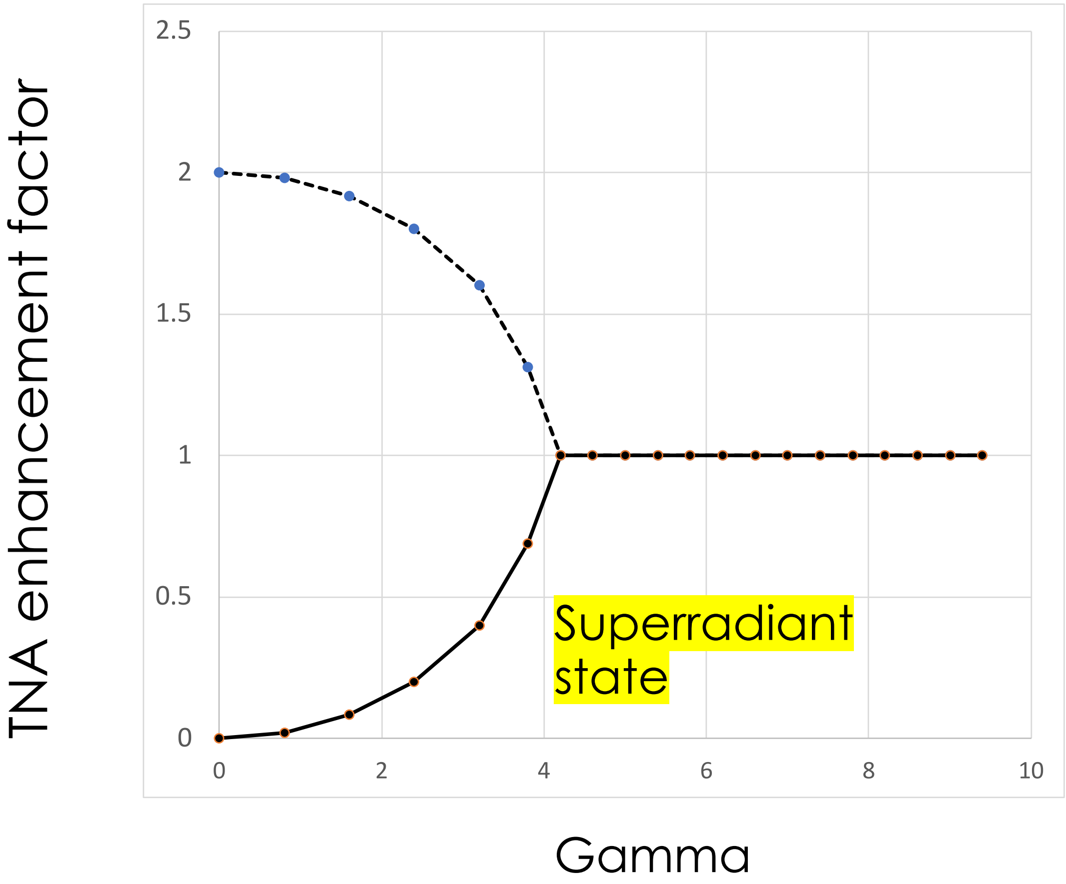
$$H = \begin{pmatrix} \epsilon - \frac{i}{2}\Gamma & v \\ v & 0 \end{pmatrix}$$

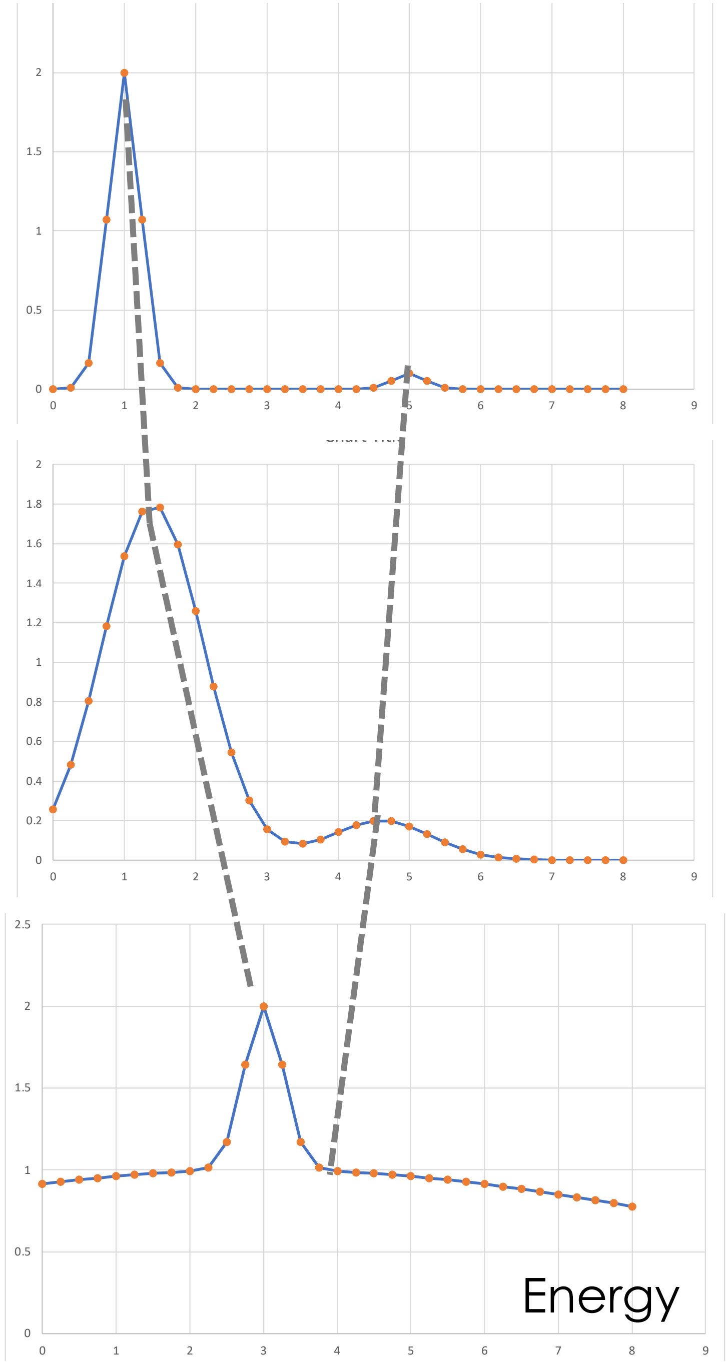
$$\mathcal{E}_{1,2} = \frac{1}{2}\left(\epsilon - \frac{i}{2}\Gamma \pm \sqrt{\left(\epsilon - \frac{i}{2}\Gamma\right)^2 + 4v^2}\right)$$



Simplest case

ε =0


TNA enhancement factor
Superradiant state
Gamma
0
2
4
6
8
10
0.5
1
1.5
2
2.5


Energy

An Active Target Tritium TPC

Y. Ayyad, IGFAE, Universidade de Santiago de Compostela
A.O. Macchiavelli, Physics Division – ORNL

Maximize physics reach on N/Z

↓

Large efficiency and resolving power

↓

Target and detector in one device

BIG QUIBBLE

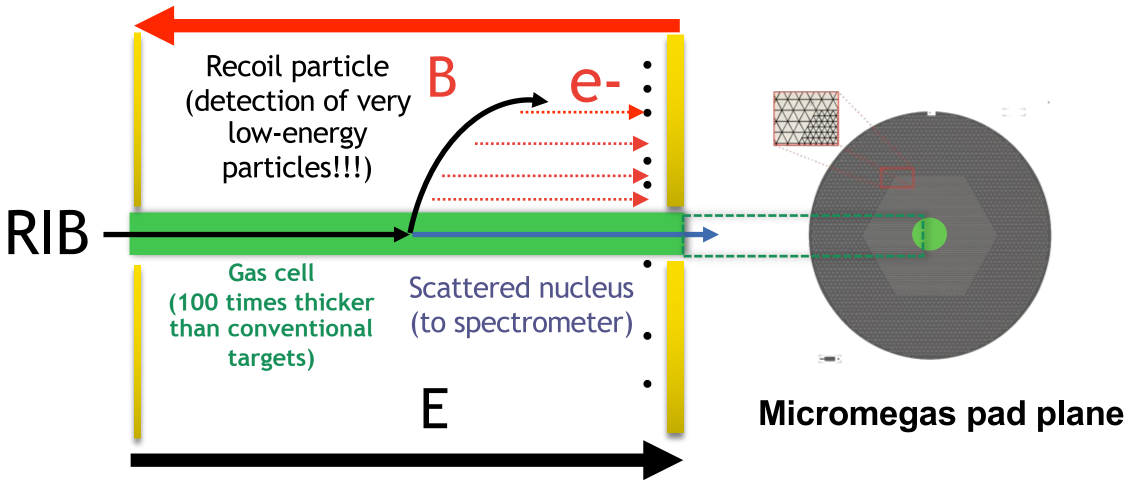
While one could consider reactions such as (^{18}O,^{16}O), **(t,p) reactions clearly stand as the best tool to study pairing correlations in nuclei**

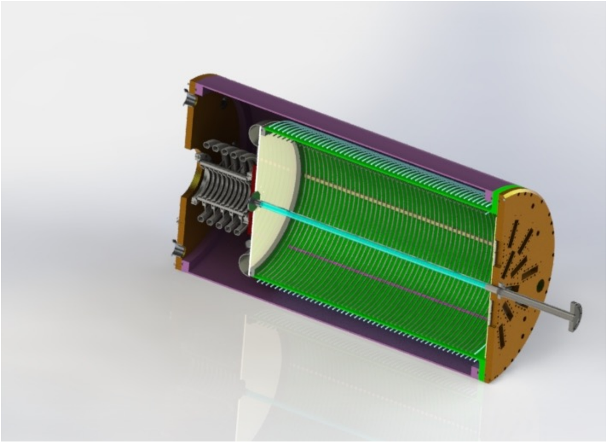
↓

A dedicated
Active Tritium Target TPC (AT^{3}PC)

D. Bazin, T. Ahn, Y. Ayyad, S. Beceiro-Novo, A.O.Macchiavelli, W. Mittig, J.S. Randhawa
Low energy nuclear physics with active targets and time projection chambers,
Progress in Particle and Nuclear Physics, Volume 114 (2020)

Conceptual design of the AT^{3}PC





Mylar cell 1 cm diameter

200 torr of **pure** tritium ~ 20Ci

Equivalent to 3.2 mg/cm^2

(~ 100 times thicker than current foils)

Advantages

- Also for rare gases: ^{3}He → **(^{3}He,p) for *np* pairing at N=Z**
- Improved rate capabilities with two isolated regions: gas cell and drift volume.
- Confinement of beta particles inside the cell due to the magnetic field.

Challenges

- **Tritium poses a hazard. Several safety layers will be required. Double/Triple enclosing volumes**
- Preserve the homogeneity of the electric field along the beam axis
- Proper material for the cell (mylar, boron nitride, kevlar, graphene…)
- Reconstruction of vertex. Energy and angular resolution
- Design of pad plane: Granularity and geometry

Work is on-going …. Stay tuned

Thank you John

We miss you !

Thank you !