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# Looking for emergent phenomena induced by near-threshold physics





#### U.S. DEPARTMENT OF ENERGY Office of Science



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## The exploration of the drip lines

Established at N = 9 and Z = 13. Many new isotopes to discover on the neutron-rich side.



Neutron number, N

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#### Some opportunities:

- Test of nuclear forces in extreme N/Z conditions.
- Strong constraints: an isotope exists or it does not.
- Finding new phenomena induced by near-threshold effects.

Where should we look first and why?



## Theoretical challenges in near-threshold physics

Drip lines, higher excitation energies.

Exotic decay modes



## Theoretical approaches for near-threshold physics

Many methods developed over time, but in practice, only a few methods can go beyond 2 nucleons in the continuum.

Feshback projection formalism:

CSM, SMEC

**Complex-scaling techniques:** 

Faddeev-Yakubowsky, lattice

Limited to 5 particles (need further development to go beyond)

The (current) G-DMRG code can handle Hamiltonians of theoretical dimension up to dim =  $10^{11}$ .

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#### Berggren basis:

GSM, NCGSM, G-DMRG, CCT, IM-SRG, GCC, PRM

**Resonating group method** (reactions with structure):

In theory, the GSM can have all nucleons in the continuum, but in practice it needs truncations beyond ~4-5 nucleons.

#### NCSM+RGM, NCSMC, (NC)GSM-CC, Symplectic-NCSM And more...

So far up to 9 particles in the continuum.



#### Gamow density matrix renormalization group Configuration interaction + renormalization group. $|\Psi^{A,J^{\pi}}\rangle_{1} = \sum C^{a}_{b,i=1} \{ |\mathsf{SD}^{f_{\mathscr{A}}}\rangle_{0}^{\mathscr{A}} \otimes |\mathsf{SD}^{f_{\mathscr{B}}}\rangle_{1}^{\mathscr{B}} \}^{A,J^{\pi}}$ S. R. White, Phys. Rev. Lett. 69, 2863 (1992) *a*,*b* Reference space Medium

$$\sum_{i=(b,r)} |k_i\rangle \langle \tilde{k}_i| + \int_{L^+} dk \, |k\rangle \langle \tilde{k}| = \hat{1}$$

T. Berggren, Nucl. Phys. A **109** 265 (1968)



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J. Rotureau et al., Phys. Rev. Lett. 97, 110603 (2006)



space

## Studying drip line nuclei in practice

We want to have **predictive power** and to make **usable predictions (= precise enough)**.



Even if we had exact ab initio solutions including 1-, 2-, ..., A-body continua, our representation of nuclear forces will always have some error that will be magnified in the many-body problem  $\rightarrow$  Emergent phenomena.

Current ab initio methods precise within ~ 1.0 MeV at best on binding energies  $\rightarrow$  We need EFTs.

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Small change in the input Large change in the output

### Nuclei are complex systems

Small change in the input  $\rightarrow$  large change in the output.





## Studying drip line nuclei in practice

Building an EFT for the shell model appears to be the best compromise to deal with drip line nuclei. Still working on the details, but adjusting a phenomenological contact interaction in the EFT spirit promising.

Core-nucleon interaction must reproduce core-nucleon phase shifts.



 $E_{4}_{He} (MeV)$  $\square$ 

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Then, nucleon-nucleon interaction adjusted on A+2,3 systems only.





## Studying drip line nuclei in practice

Similar results form an effective core of 160 in sd space with continuum (very preliminary):



Far from USDB but approaching current ab initio precision.

All nucleons can couple to the continuum (s1/2, d5/2, d3/2).

Extension to a core of 40Ca possible.

> (The emergence of universality might make it possible to reach 60Ca.)

## An (old?) idea for future high-impact FRIB experiments

Find the systems or areas of the nuclear chart where new/unique/sensitive emergent phenomena magnify less known aspects of nuclear forces.

Where should we look first (and why)?

Universal behaviors, complex interplays between decay and clustering, deformation, rotational motion, new forms of radioactivity...

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**Drip line systems** provide excellent opportunities thanks to near-threshold physics modifying nuclear structure in sometimes new and various ways.







Known examples



#### Halo structures

I. Tanihata et al., Phys. Rev. Lett. 55, 2676 (1985)

A. S. Jensen et al., Rev. Mod. Phys. 76, 215 (2004)



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Many-body dynamic in the 6n-continuum: toward universal behaviors.



K. Fossez et al., Phys. Rev. C 98, 061302(R) (2018)







## Continuum inducing deformation?

#### Continuum couplings decrease the $\nu 1 p_{3/2} - \nu 0 f_{7/2}$ gap.

	Na 25	Na 26	Na 27	Na 28	Na 29	Na 30	Na 31	Na 32	Na 33	Na 34			
	59.1 s	59.1 s 1.0713 s 301 ms 30.5 ms		30.5 ms	44.1 ms	48.4 ms	<sup>17.</sup> de	5.5 ms					
	Ne 2 <sup>4</sup>	nell e	Voluti	on 7	Ne 28	Ne 29	Ne 30	Ne 31	Ne 32	Ne 33			
	3.38 m	602 ms	197 ms	31.5 ms	18.9 ms	14.7 ms	7.3 ms	3.4 ms	3.5 ms	< 260 1e-			
	F 23	F 24	F 25	F 26	F 27	F 28	F 29	F 30	F 31				
	2.23 s	384 ms	80 ms	9.7 ms	4.9 ms	< 40 1e-09	2.5 ms	< 260 1e-09		(			
	O 22	O 23	O 24	O 25	O 26	O 27	O 28		22				
	2.25 s	97 ms	65 ms	2.8 zs	90 zs	< 260 1e-09	< 100 1e-09						
	N 21	N 22	N 23	N 24	1	500 F		, 	<mark>                                     </mark>				
	83 ms	ms 24 ms 13.9 ms < 52 1e-09 < 2											
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"island of nversion"











## Suggestion for finding interesting mechanisms

**Continuum-induced deformation:** Look for areas where s/p-waves come down (neutron).

- $\rightarrow$  38Ne, 39Na (N=20) fill the 0f7/2, the 1p3/2 might go down as in 28-31F. D. S. Ahn et al., Phys. Rev. Lett. **123**, 212501 (2019)

**Universality:** Look for situations with a well-bound spherical core + many neutrons like in neutron-rich He and O, and compare with their mirrors.

- $\rightarrow$  systematic of masses in neutron-rich C (Z=6), Ca (Z=20), and proton-rich N=6, 8, 20 chains.
- $\rightarrow$  correlations between the valence nucleons.
- $\rightarrow$  multi-neutron/proton decay (neutron-rich Be, O).

#### Interplays between week binding/decay and clustering:

- $\rightarrow$  radii/moments = f(N/Z) in deformed/clustered + weakly bound/unbound n/p (neutron-rich Li, Be).
- $\rightarrow$  look for systems with nearby proton, neutron, and cluster decay channels and search for new states.
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See H. Iwasaki's talk

 $\rightarrow$  22Si (Z=14, N=8), should fill the 0d5/2 but the 1s1/2 might go down. Similar in neutron-rich N isotopes.

See D. Lee's talk

See A. Volya's talk







## Suggestion for finding similar mechanisms

													20	Ca 34 < 35 1e-09	Ca 35 25.7 ms	Ca 36
													K 32 ?	K 33 < 25 1e-09	K 34 < 40 1e-09	K 35
											18	Ar 30 < 20 1e-09	Ar 31 14.4 ms	Ar 32 98 ms	Ar 33 173.0 ms	Ar 34 843.8 m
											Cl 28 ?	Cl 29 < 20 1e-09	Cl 30 < 30 1e-09	Cl 31 150 ms	Cl 32 298 ms	Cl 33 2.511 s
									16	S 26	S 27	S 28 125 ms	S 29 188 ms	S 30	S 31 2.572 s	S 32 94.99
									P 24	P 25	P 26	P 27	P 28	P 29	P 30	P 31
								Si 22	Si 23	Si 24	43.7 ms	Si 26	270.3 ms	4.142 s Si 28	2.498 m Si 29	Si 30
								29 ms	42.3 ms	140 ms	220 ms Al 24	2.2283 s Al 25	4.15 s Al 26	92.223 Al 27	4.685 Al 28	3.092 Al 29
							N 10	< 35 1e-0	91.5 .hs	470 ms	2.053 s	7.183 s	717 ky	100.	2.2414 m	6.56 m
						T2	Mg 19 5 ps	Mg 20 90 ms	Mg 21 122 ms	Mg 22 3.8755 s	Mg 23 11.317 s	Mg 24 78.99	Mg 25 10.00	Mg 26 11.01	Mg 27 9.458 m	Mg 28 20.9151
							Na 18 1.3 zs	Na 19 >1 as	Na 20 447.9 ms	Na 21 22.49 s	Na 22 2.6027 y	Na 23 100.	Na 24 14.997 h	Na 25 59.1 s	Na 26 1.0713 s	Na 27 301 ms
					10	Ne 16 9 zs	Ne 17 109.2 ms	Ne 18 1.6656 s	Ne 19 17.262 s	Ne 20 90.48	Ne 21 0.27	Ne 22 9.25	Ne 23 37.14 s	Ne 24 3.38 m	Ne 25 602 ms	Ne 26
					F 14 500 ys	F 15 410 ys	F 16	F 17 64.49 s	F 18 109.771 m	F 19 100.	F 20 11.163 s	F 21 4.158 s	F 22 4.23 s	F 23 2.23 s	F 24 384 ms	F 25 80 ms
			8	O 12 >6.3 zs	O 13 8.58 ms	011 r 70.621 s	O 15 122.24 s	O 16 99.757	O 17 0.038	O 18 0.205	O 19 26.464 s	O 20 13.51 s	O 21 3.42 s	O 22 2.25 s	O 23 97 ms	O 24 65 ms
			N 10 200 ys	N 11 550 ys	N 12 11.000 ms	N 13 9.965 m	N 14 99.636	N 15 0.364	N 16 7.13 s	N 17 4.173 s	N 18 619.2 ms	N 19 336 ms	N 20 136 ms	N 21 83 ms	N 22 24 ms	N 23 13.9 ms
	6	C 8 3.5 zs	C 9 126.5 ms	C 10 19.306 s	C 11 20.364 m	C 12 98.93	C 13	C 14 5.70 ky	C 15 2.449 s	C 16 747 ms	C 17 193 ms	C 18 92 ms	C 19 46.2 ms	C 20 16 ms	C 21 < 30 1e-09	6.2 ms
		B 7 570 ys	B 8 770 ms	B 9 800 zs	B 10 19.9	B 11 80.1	B 12 20.20 ms	B 13 17.33 ms	B 14 12.5 ms	B 15 9.93 ms	B 16	B 17 5.08 ms	B 18 <26 ns	B 19 2.92 ms	B 20	B 21
4	Be 5 ?	Be 6 5.0 zs	Be 7 53.22 d	Be 8 81.9 as	Be 9	Be 10	Be 1	ве 12 21.50 ms	Be 13	Be 14 4.35 ms	Be 15 < 200 1e-09	Be 16 650 ys	Contractions			16
	Li 4 91 ys	Li 5 370 ys	Li 6 7.59	Li 7 92.41	Li 8 839.40 ms	Li 9 178.3 ms	Li	Li 11 8.75 ms	Li 12 <10 ns	Li 13 ?		12				
2	He 3	He 4	He 5	He 6	He 7	He 8	He 9	He 10		10						
H 1	Н 2	Н 3	H 4	H 5	H 6	Н 7		8	י ר <b>א</b> ו	.l+i	nc	<b></b> +	ror	•		
99.9885	n 1	2	139 ys	->910 ys	290 ys	6										
	613.9 s						decay									



### Thank you for your attention!

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