

Group Meeting 10.04

Reading Phys. Rev. Lett 124 (2020) 222504

Two-neutron halo is unveiled in ^{29}F

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Borromean nuclei

Borromean two-neutron halo consists of a bound state between a core nucleus and two neutrons, where any of the two-body subsystems are unbound.

The figure shows a table of nuclides with three rows and nine columns. The nuclides are arranged in a triangular pattern. The top row contains 3Li, 4Li, 5Li, 6Li, 7Li, 8Li, 9Li, 10Li, and 11Li. The second row contains 3He, 4He, 5He, 6He, 7He, 8He, 9He, and 10He. The third row contains 1H, 2H, 3H, 4H, 5H, 6H, and 7H. A cyan box labeled 'Neutron' is positioned below the 2H and 3H boxes. Two green boxes highlight the 6He and 8He nuclides, with two pink arrows pointing to them from the bottom right.

3Li	4Li	5Li	6Li	7Li	8Li	9Li	10Li	11Li
	3He	4He	5He	6He	7He	8He	9He	10He
1H	2H	3H	4H	5H	6H	7H		
	Neutron							

FIG 1: Table of nuclides. [1]

A new Borromean halo nuclei

$N = 20$, we discover the heaviest Borromean halo to date, and the first of its kind in the proton sd shell.

The measured total reaction cross section of the $N = 20$ nucleus ^{29}F is much larger than that of ^{27}F . This fact shows a two-neutron halo structure in ^{29}F .

The information of ^{29}F

- $S_{2n} = 1.4(6)\text{MeV}$
- The excited states of ^{27}F and ^{29}F are $915(12)\text{keV}$, $1080(18)\text{keV}$.
- Carbon is the last known element to exhibit a Borromean two-neutron halo, and we do not know about any neutron halos in fluorine.

Cross section of the ^{29}F

- The Cross section of ^{29}F is larger than others.
- ^{29}F is far away from the linear relationship, increasing by about 12%.

This shows the presence of a two-neutron halo.

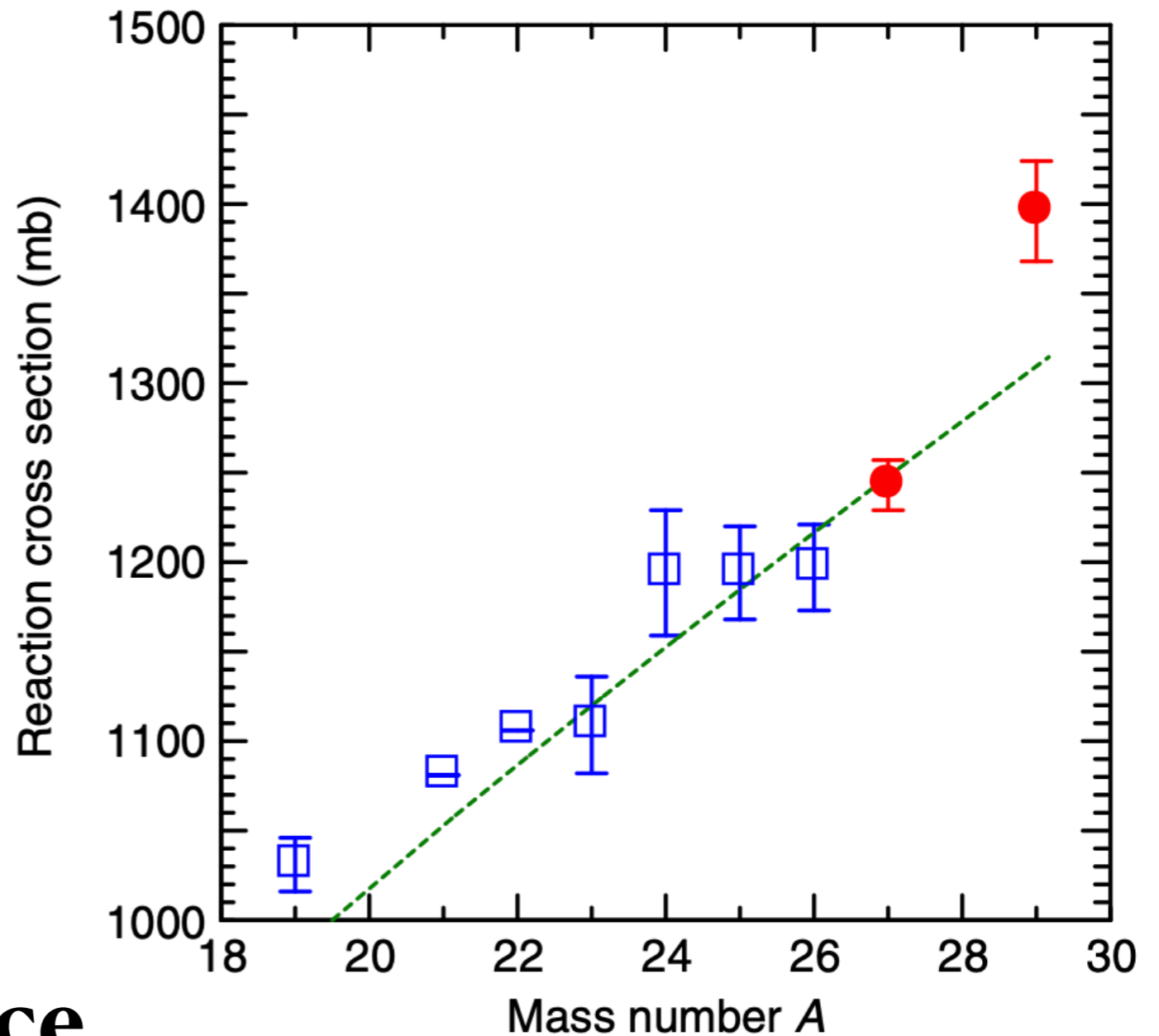


FIG 2: Cross section of Fluorine isotopes, $A = 19 \sim 29$

Cross section of the ^{29}F

Meanwhile, we get the experimental radius of $3.15 \pm 0.04\text{fm}$ and $3.50 \pm 0.07\text{fm}$, increasing by 11%. And consider the ^{29}F 's proton radius as ^{27}F 's, we will get a large rms halo radius of 6.6fm for ^{29}F .

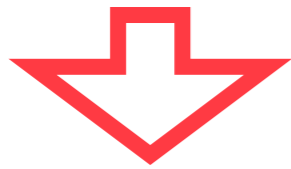
The difference between ^{27}F and ^{29}F 's radius is about 0.35fm, which is similar to other 2-halo nuclei.

Shell calculation



There is a strong component of $2p_{3/2}$.

$$\sigma_R = \alpha\sigma_R(2p_{3/2}) + (1 - \alpha)\sigma_R(1d_{3/2})$$



$$\alpha = 0.54 - 1$$

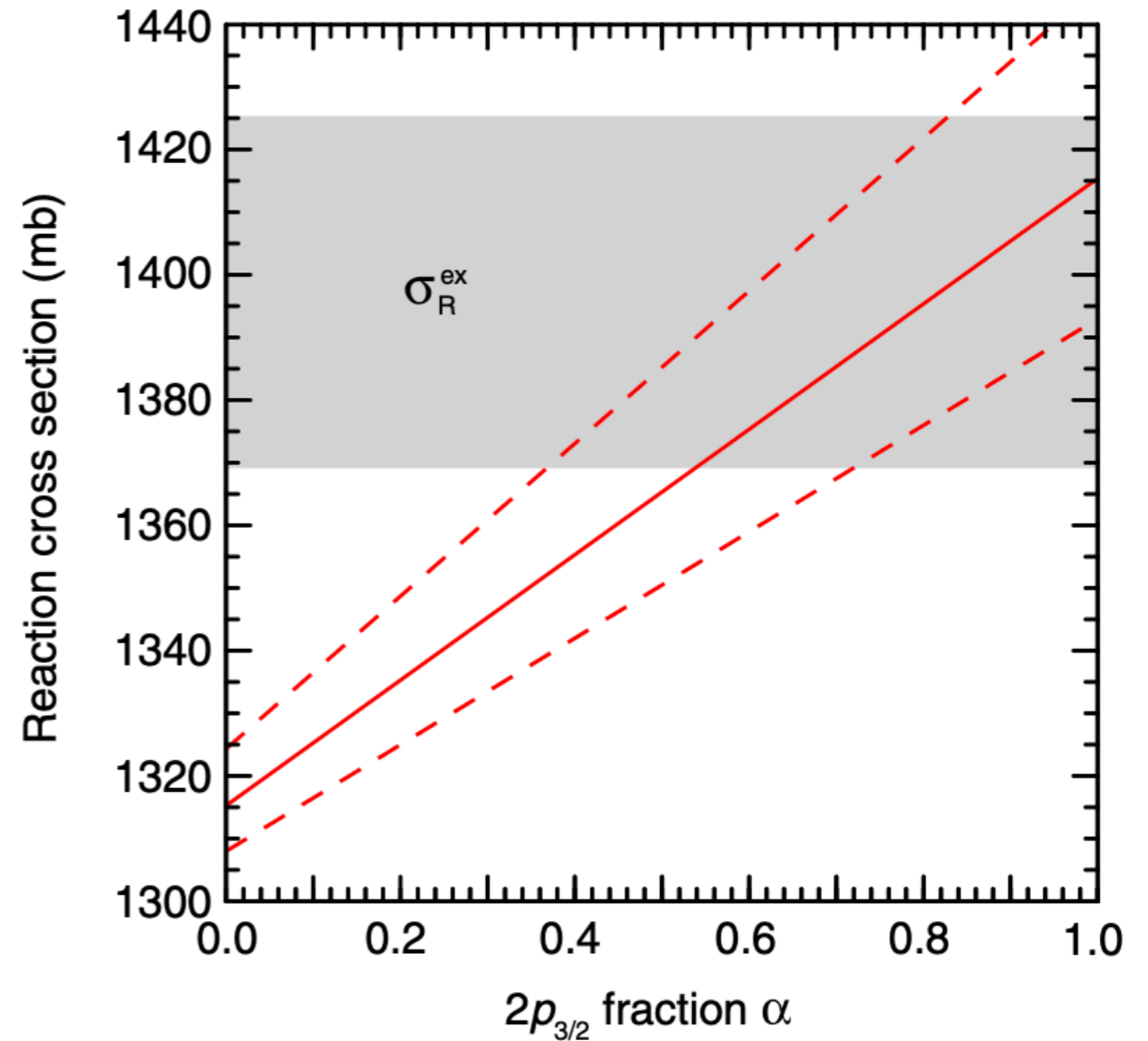


FIG 3: Mixing up $1d_{3/2}$ and $2p_{3/2}$

Shell calculation

- SDPF-MU hamiltonian
- EE_{df1} interaction (including N₃LO interaction and Fujita-Miyazawa three-body force)

Model	Isotope	1d _{3/2}	1f _{7/2}	2p _{3/2}
SDPF-MU	²⁷ F	1.67	0.48	0.24
	²⁹ F	2.68	0.90	0.56
EE _{df1}	²⁷ F	0.84	2.19	1.26
	²⁹ F	0.80	1.08	0.67

FIG 4: The neutron occupying number of ²⁷F and ²⁹F, calculated by different shell models.

Other models and result

- Ab initio coupled-cluster

Δ -NNLO_{GO}

NNLO_{SAT}

In the deformed reference state, the neutrons are dominantly associated with the 1d_{3/2} orbital. These states were self-consistently selected by the Hartree-Fock method. But halo is more related to the neutron in 2p_{3/2}.

- Particle rotor

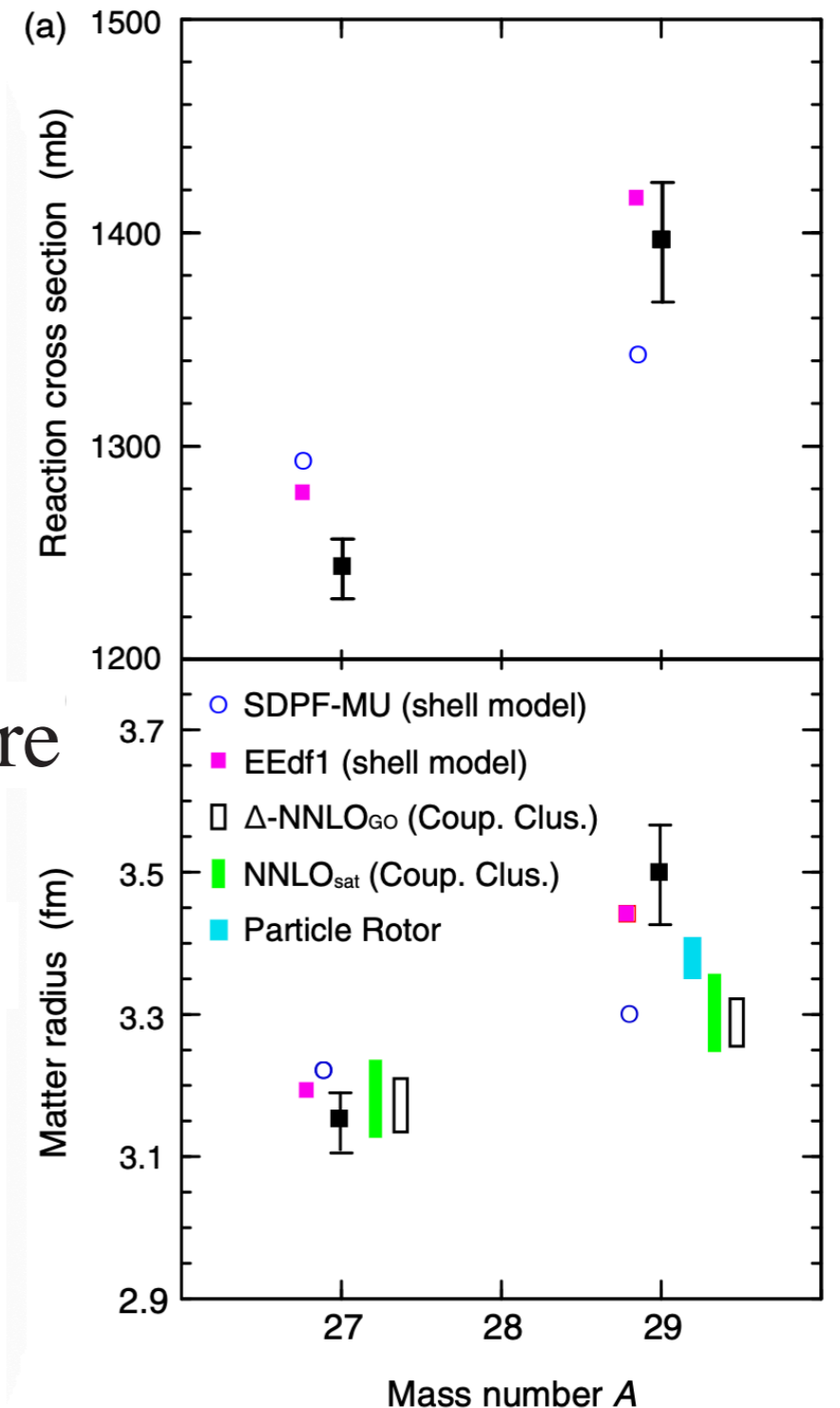


FIG 5: Cross section predicted by different models

Conclusion

This work shows that a small neutron separation energy (~ 1 MeV) and tensor force effects lead to a p-wave halo in ^{29}F , one proton above conventional doubly closed shell $Z = 8$ and $N = 20$, just like ^{11}Li .

^{27}F 5.0 ms $\beta^- = 100.00\%$ $\beta n = 90.00\%$ $\beta 2n ?$	^{28}F ≈ 0.046 as N	^{29}F 2.67 ms $\beta^- = 100.00\%$ $\beta n \approx 20.00\%$ $\beta 2n ?$	^{30}F N
^{26}O 4.5 ps $2N = 100.00\%$ N?	^{27}O < 260 ns N?	^{28}O < 100 ns N?	

^9Li 178.3 ms $\beta^- = 100.00\%$ $\beta n ? 50.00\%$	^{10}Li N = 100.00%	^{11}Li 8.75 ms $\beta^- = 100.00\%$ $\beta n = 86.60\%$ $\beta 2n = 4.20\%$	^{12}Li < 10 ns N?
^8He 119.1 ms $\beta^- = 100.0\%$ $\beta n = 16.0\%$	^9He N = 100.00%	^{10}He 300 keV N = 100.00%	

To get further, we want to know whether or not similar nuclei exist on $N=50, 82, 126$.