Heavy B isotopes as multineutron Halos

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MENU

n-^{17}B scattering and the ^{18}B virtual state

^{19}B as ^{17}B core + **nn**

^{20}B and ^{21}B as ^{17}B+ x **n**   x=3,4

INTRODUCTION

The neutron-Nucleus (nA) **low-energy** scattering is a privileged tool to learn **about** the nuclear force

- Free from Coulomb interactions

- Not disturbed by the kinetic energy

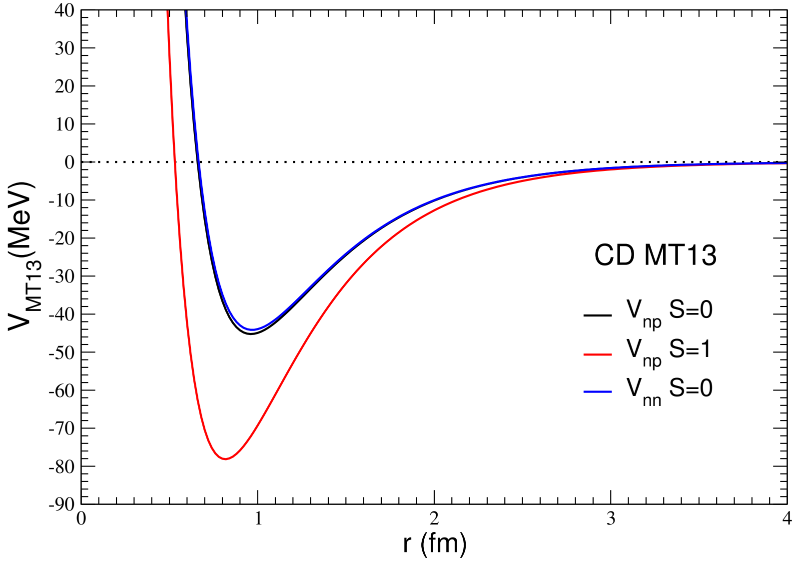
$$H = H_0 \ll V + V$$

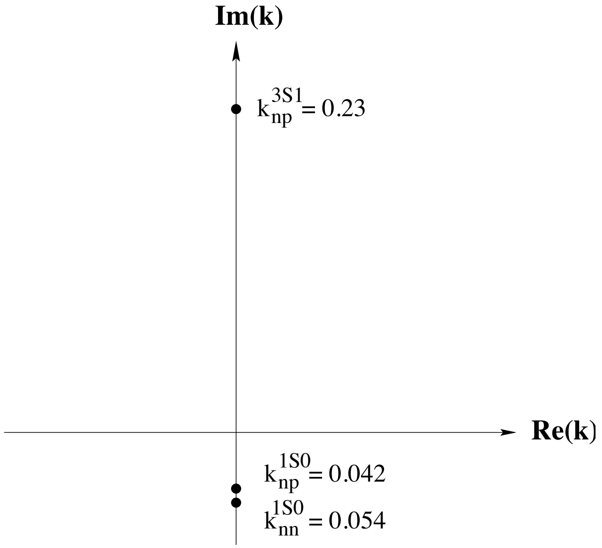
It is very sensible to any detail of **V**, the non trivial part of **H**

By doing a systematic study of **nA**, i.e. by increasing A=1,2,3,… some interesting trends governing the nuclear processes are manifested

INTRODUCTION

The S-wave neutron-Nucleon (**n**,**p**) interaction is **attractive in all spin and isospin channels**





The **np** S=1 state is the more attractive one, enough to **bind** the deuteron by B=2.22 MeV

The **np** and **nn** S=0 states are not bound… but almost: have a “virtual state” close to threshold

This spin-dependence accounts for a 20% difference in the attractive strength of NN interaction

However, and despite all V_{nN} are attractive, the **low-energy n scattering on light nuclei,** starting as soon as n-^{2}H, behave **as if V_{nA} was repulsive**…

A **n** approaching a nucleus **”feels”** others **n’s** in the target and **it doesn’t like them !** **(Pauli)**

INTRODUCTION

A dramatic consequence happens in 3n and 4n systems :

H_{3n} has a (ground) bound state at about 1 MeV (5 MeV for **H_{4n}**)

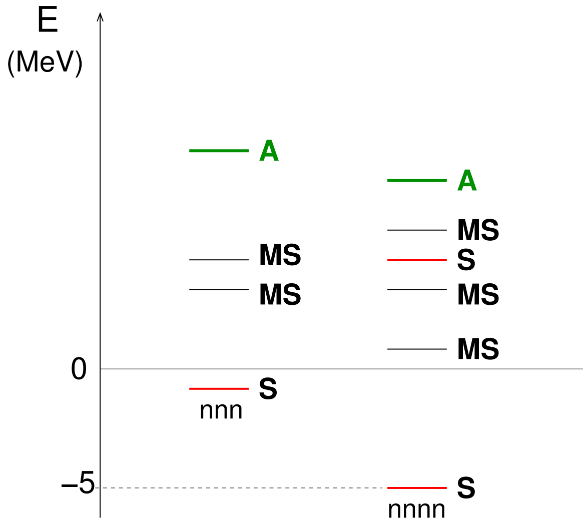
… but in nature neither **3n** nor **4n** are bound

The lowest state of **H_{3n}** and **H_{4n}** is symmetric

The first antisymmetric state is much higher in spectrum

Everything happens as if **there was a repulsion among n**'s:

the "Pauli repulsion"

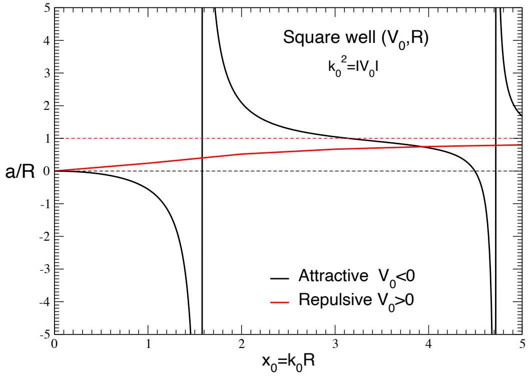


An interesting quantity to measure the repulsive/attractive character of V_{nA} **is the scatt length**

$$a_{nA} = - f_{nA}(E=0)$$

For purely repulsive V, $a>0$

For purely attractive V, $a<0$…until a bound state appears

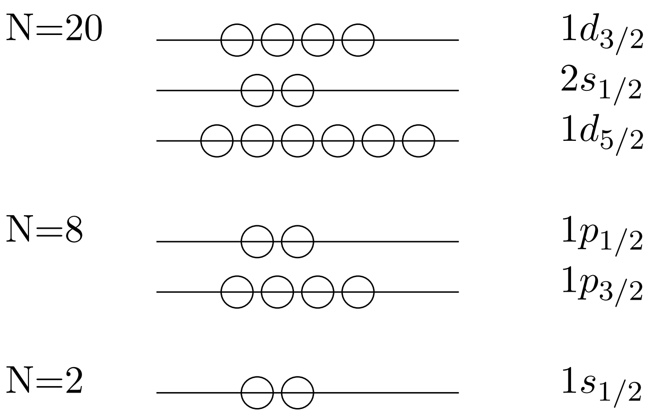


For a realistic interaction – mixing repulsive core with attractive parts – the result is the net balance of both tendences

INTRODUCTION

The evolution of a_{nA} when increasing N is summarized below

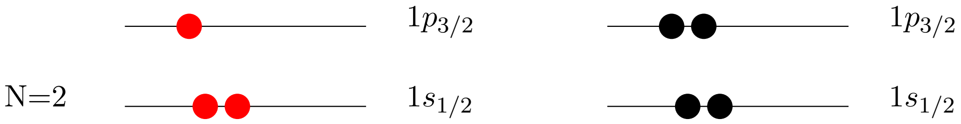
Z N A	Sym	J	a-	a+
1 0 1	p	½+	**-23.75**	+5.42 *
0 1 1	n	½+	**-18.59**	/
1 1 2	^{2}H	1-	+0.65*	+6.44
2 1 3	^{3}He	½+	+6.6*-3.7i	+3.5
1 2 3	^{3}H	½+	+3.9	+3.6
2 2 4	^{4}He	0+	+2.61	/
3 3 6	^{6}Li	1+	+4.0	+0.57
3 4 7	^{7}Li	$3/2^-$	+0.87	**-3.63**
2 6 8	^{8}He	0+	**-3**	
3 6 9	^{9}Li	$3/2^-$	**-14**	



For A=1 all a_{nA} are attractive

For A=2, a_{nA} starts being repulsive: strong Pauli repulsion dominates over **nN** attraction

For A=7, in ^{7}Li (J=$3/2^-$) an attractive channel appears again…

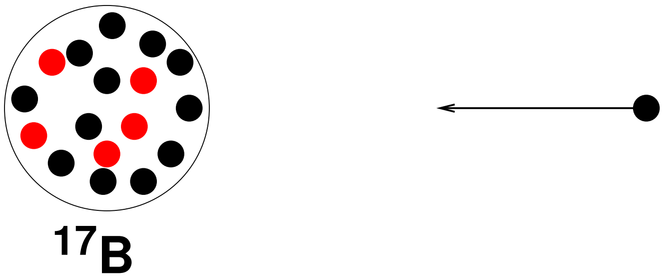


P-wave **n's** decrease Pauli repulsion: 2 $p_{3/2}$ n's are enough to result into "overall attractive" V_{nA}

The "attraction" persists in ^{9}Be,^{12}Be,^{15}B… **until something very spectacular occurs……**

^{18}B ONE OF THE MOST FASCINATING SYSTEMS IN NUCLEAR PHYSICS

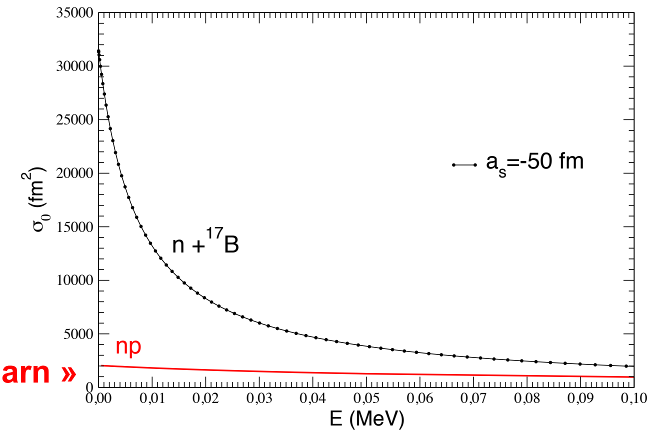
^{17}B is a (strong) stable nucleus with **$J^{\pi}=3/2^{-}$** consisting on a sea of **12n** sourrounding **5p**



The balance between the attractive π-exchange between **n** and **17 Nucleons** and the “Pauli repulsion” with the **12n**’s in **^{17}B** is **so fine-tuned** that the scattering length is **$a_{n\text{-}17B} \sim$ -100 fm**

A **<u>low energy</u> n scattering on ^{17}B “feels” a monster** of geometrical size D~400 fm

The « low energy region » where n feels the monster is « very low » …



« as big as a barn »

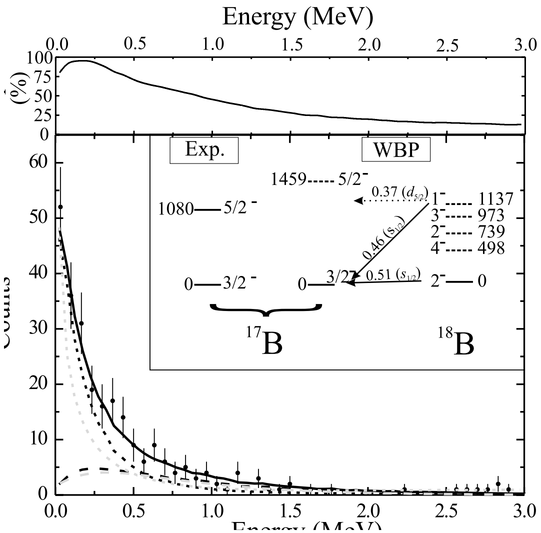
$$\sigma_L(k) = (2L+1)4\pi \frac{\sin^2 \delta_L(k)}{k^2}$$

$$\sigma(0) = 4\pi a^2$$

Nevertheless the effect is huge, even with respect to what was considered huge untill now !

EXPERIMENTAL

How do we know that this history is true ?



I. A first MSU measurement

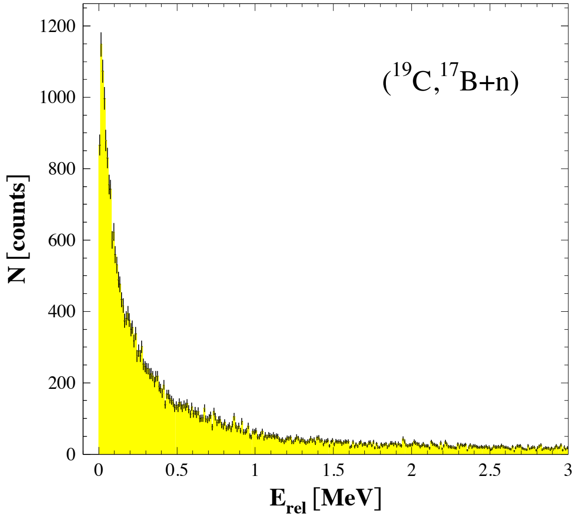
Spyrou et al. PLB683(2010)129

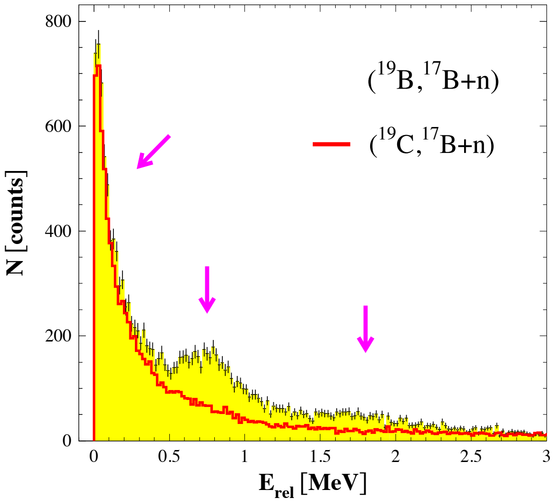
claimed the existence of a **^{18}B** “virtual” (unbound) state

and a **n-^{17}B** **a_s <- 50 fm**

II. A recent RIKEN result

observed this state in other channels (J. Gibelin,M. Marquès,N. Orr)





S.Leblond PhD (2015)
M. marquès, E. Oliveira
EPJ Meb of Conferences 311, 00006 (2024)

The **precise value of a_s is still not (yet) known**, most probably <-100 fm

THEORY

The large value of a_s indicates the existence of a “ **^{18}B virtual state”** very close to threshold
It corresponds to a pole in the **n-^{17}B** scattering amplitude **f(k)** at Im(k)<0, as in **nn** case

One of **the most interesting virtual states in Nucl Physics:**

- the scattering length a_s is the **« nuclear chart record »** ….waiting for a final result !
- much larger than the highly celebrated $\mathbf{a_{NN}}$=-24 fm, which, « controls the nuclear chart »

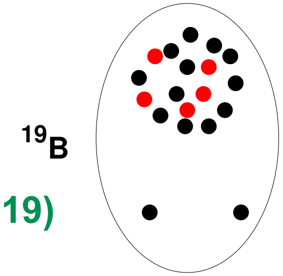
S. König, Griesshammer, Hammer, van Kolck, Phys. Rev. Lett 118, 202501 (2017)
« We argue that many features of the structure of nuclei emerge from a strictly perturbative expansion around the unitarity limit, where the two-nucleon S waves have bound states at zero energy”

- It is even comparable to atomic physics cases ! and a **candidate to Efimov martyrology**

But this not all….

- **^{19}B** is bound with a binding energy **B in [0,0.53] MeV**
- **^{19}B** has several resonant states
- A series of **^{20}B,^{21}B** resonances were recently discovered **S.Leblond et al, PRL121,262502(2018)**

All that gave a strong motivation to model ^{19}B as a ^{17}B-n-n 3-body cluster
- built wit 2 resonant scattering lengths (exemple of Borromean state)
- with possible extensions to ^{17}B-n-n-n and ^{17}B-n-n-n-n



First results in **E. Hiyama, R. Lazauskas, M. Marqués, J. Carbonell, PRC100, 011603R (2019)**

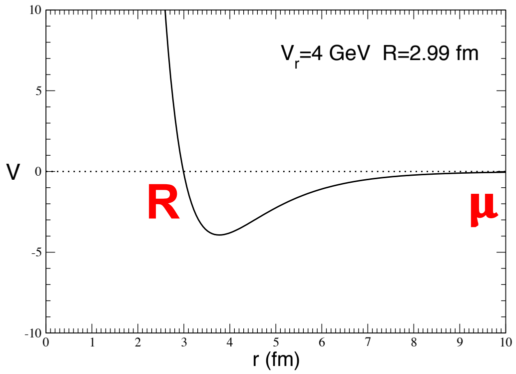
MODELING THE n-^{17}B SYSTEM

Ingredients:

- Repulsive+Attractive part : **V_r,V_a, μ**

- Hard core radius : **n** cannot penetrate at r<**R** = size parameter
  R can be (matter radius **R_m**=3.0 or **R_{LD}**=1.2A$^{1/3}$=3.0 fm) x 0.77

- Pion exchange (dominant at large r) **μ**=0.70 fm^{-1}



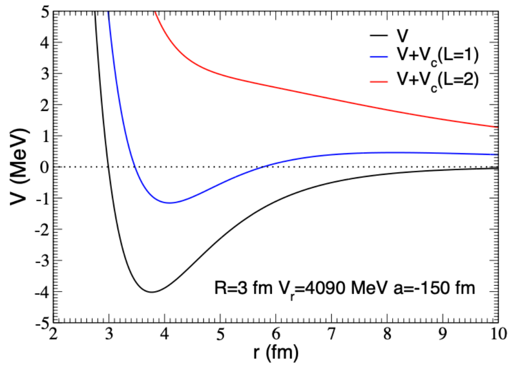
Simplest ansatz

$$\boxed{V(r) = V_r \left(e^{-\mu r} - e^{-\mu R}\right) \frac{e^{-\mu r}}{r}}$$

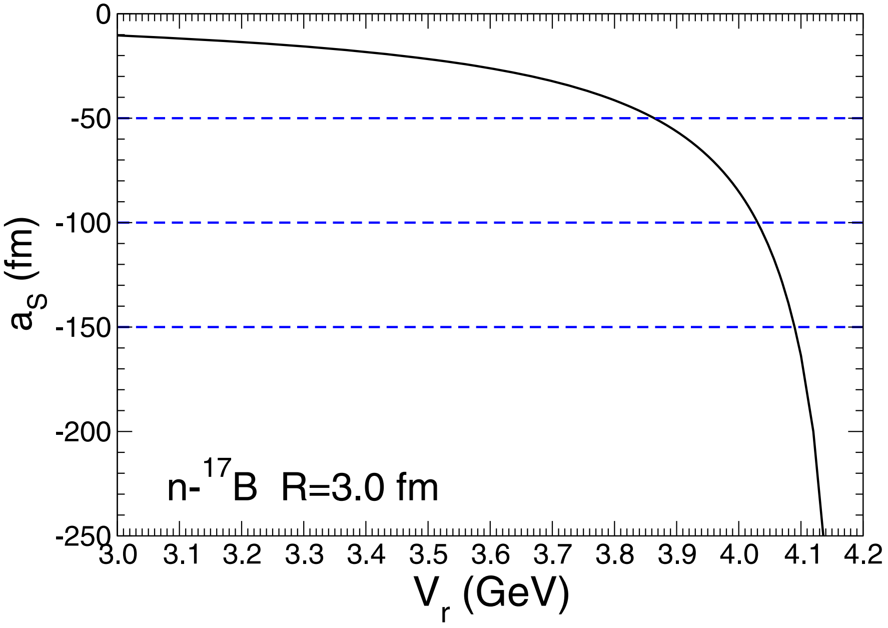
μ and **R** being fixed, **there is one single parameter V_r**

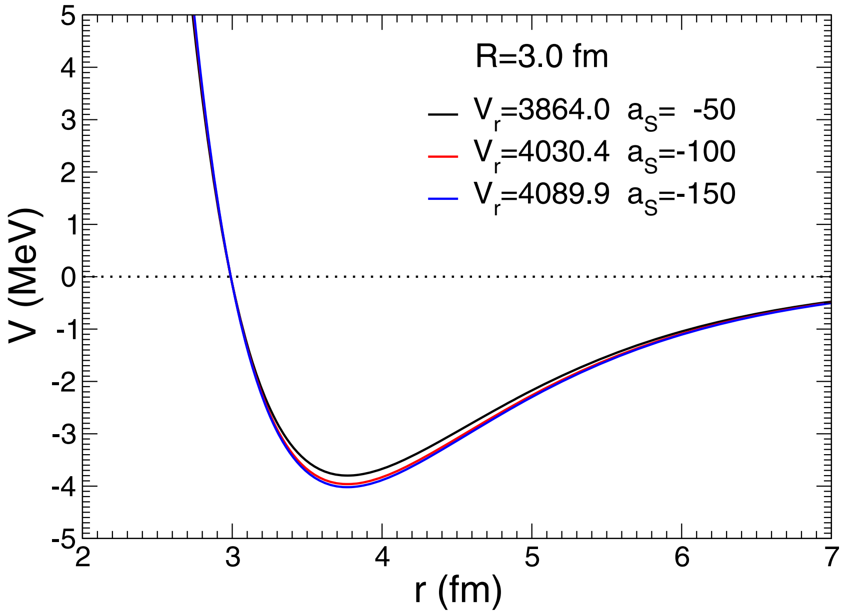
V_r is adjusted to reproduce the experimental value of **a_s**

Since we are still waiting for it, we parametrize all in terms of **a_s**



Determining a_s =f(V_r)





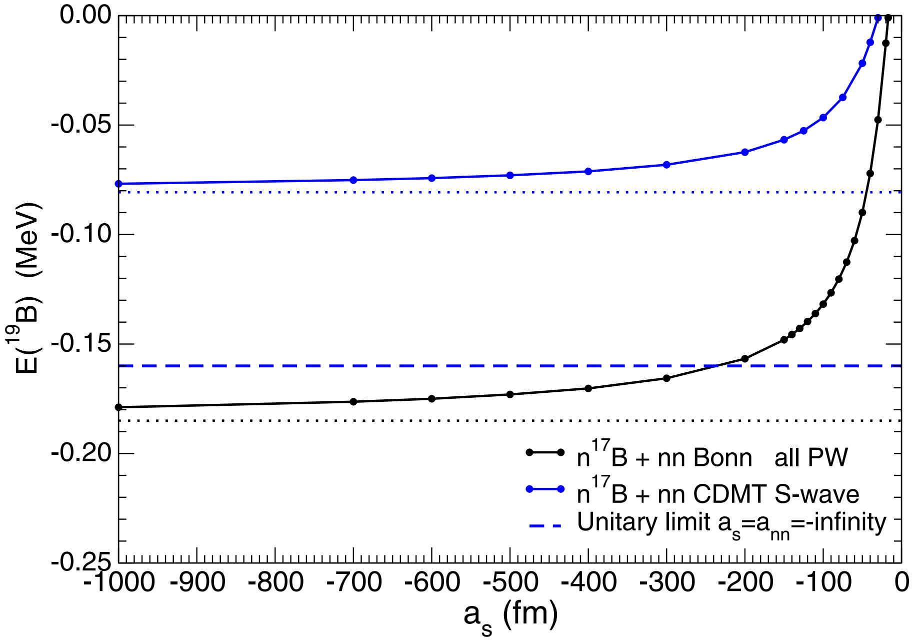
Dashed lines correspond to a_s **=-50** (3864 MeV), **-100** (4030), **-150** (4090) **fm** with R=3.0

Singularity of a_s (r.h.s) would correspond to appearance of an (unphysical) bound ^{18}B state

Corresponding potentials saturates for a_s ~ -100 fm

MODELING ^{19}B as ^{17}B-n-n CLUSTER

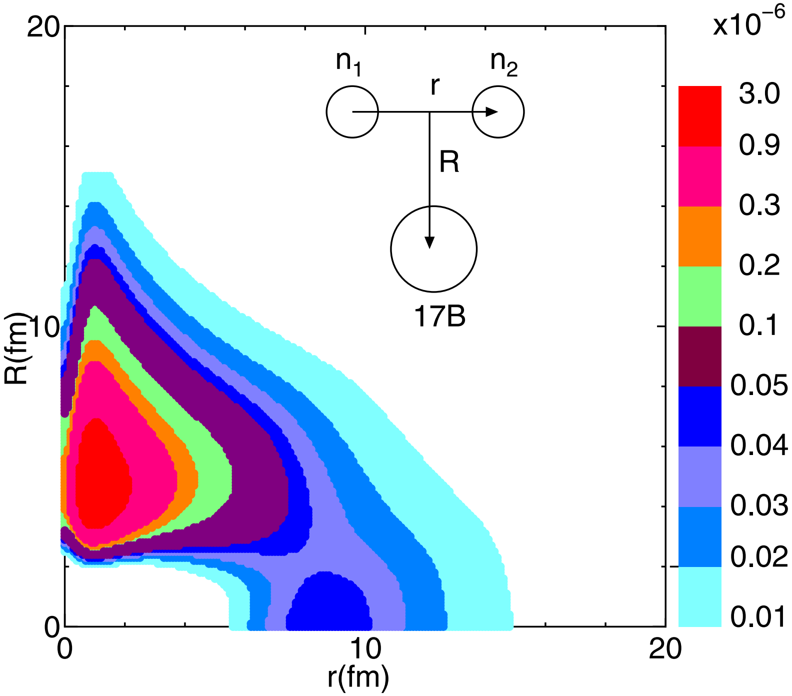
Solve the 3-body problem (Faddeev+Gaussian) with $\mathbf{V}_{\mathbf{n\text{-}17B}}$ and some realistic $\mathbf{V}_{\mathbf{nn}}$
^{19}**B** appears to be bound for $a_s<-50$ (the only parameter!) in a $J^\pi=3/2^-$ state (L=0,S=0)



We used 2 different **nn** interactions and let $\mathbf{V}_{\mathbf{n\text{-}17B}}$ act in S-wave (s. blue) or in all PW (s. black)
The energy is always compatible with the experimental value E=-0.14+/-0.39 MeV

In the S-wave case we consider the **unitary limit: $a_s=a_{nn} \rightarrow -\infty$** (blue dashed)
The result is still compatible with experimental value and constitutes a first illustration of this interesting limit in Nuclear Physics.

Spatial probability amplitude $\mid \Psi(r,R) \mid^2$ fixing a_s=-100 fm



We also found two ^{19}**B** resonances: fixing a_s=-150 and using the S-wave model

L=1 E_1=0.24-0.31i MeV
L=2 E_2=1.02-1.22i MeV

Their existence is in agreement with experimental findings

J. Gibelin et al., Contribution to FB22, Caen july 2018, Springer Proc in Press

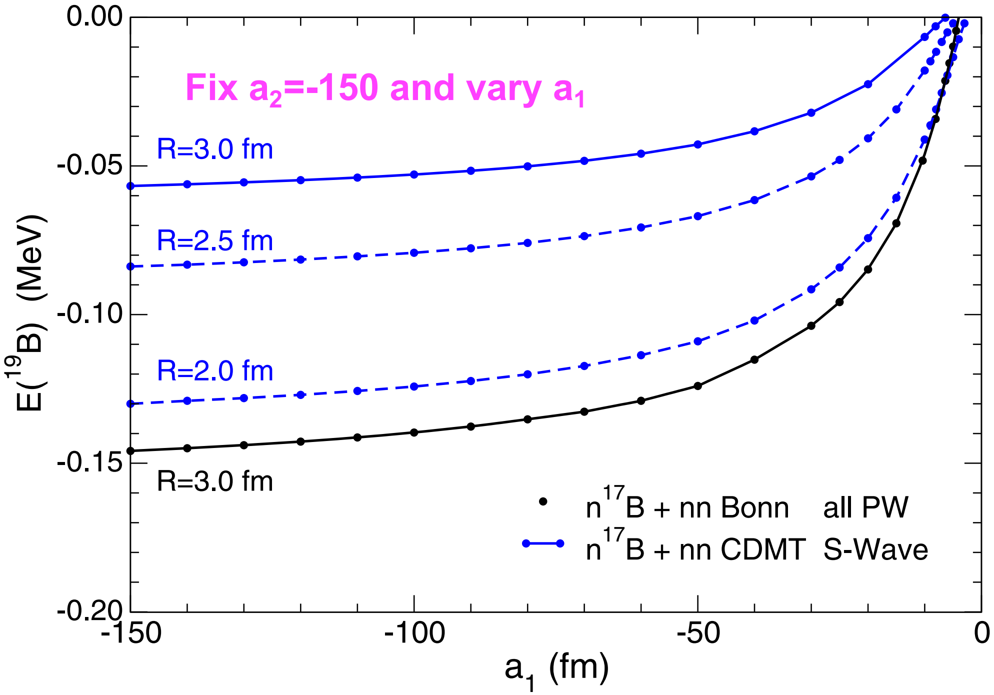
Very simple and successful model: local S-wave potential, no 3-body force, one single parameter
The key of the succes is the double resonant character of nn and n-Core

Some refinements : the spin-spin dependence

^{17}B being **$J^\pi=3/2^-$** , there are two different scattering lengths **a_s** corresponding to S=1,2. Assuming that the virtual state we adjusted was **a_2** there is no reason that **$a_1= a_2$**

Introduced a spin-spin dependence with different $V_{n\text{-}17B}$ for each S, keeping the same form

$$V^{(S)}_{n^{17}B}(r) = V^{(S)}_r \left(e^{-\mu r} - e^{-\mu R}\right) \frac{e^{-\mu r}}{r} \qquad S = 1,2$$



There exists a critical value **a_1^c** above which **^{17}B** binding disappears but this requires unphysical SS beaking $V_r^{(1)}/V_r^{(2)}$=2: results are stable even when varying R

GOING BEYOND: MODELING ^{20}B (as ^{17}B-n-n-n) and ^{21}B (as ^{17}B-n-n-n)

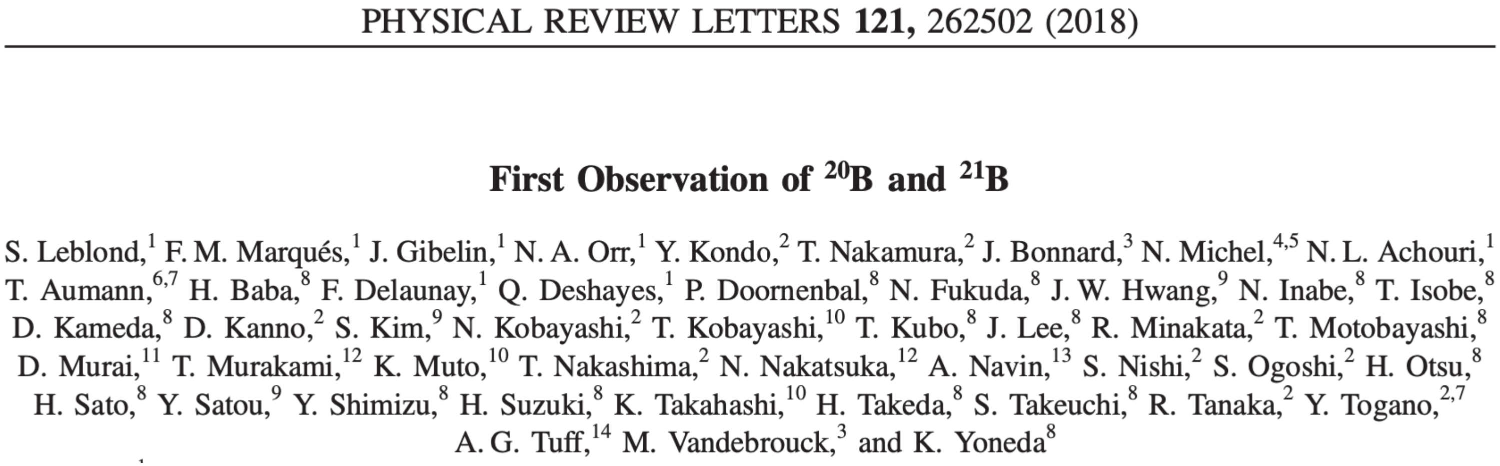
The success in describing ^{19}B encourage us to go beyond and add more n's **to the same core**

This implies solving the 4- and 5-body problem, for what we used the same techniques than previously.

Notice that what we have added is, in principle, a trivial part : more n's !!!

The delicate, and so questionable, part is the n-Core interaction…that was already tested in ^{19}B, for ground as well as for resonant states

Not only a curiosity but recent experimental data claim for resonant states in the, supposed unbound, **B** heaviest isotopes : **^{20}B and ^{21}B**



PHYSICAL REVIEW LETTERS **121,** 262502 (2018)

First Observation of ^{20}B and ^{21}B

S. Leblond,[1] F. M. Marqués,[1] J. Gibelin,[1] N. A. Orr,[1] Y. Kondo,[2] T. Nakamura,[2] J. Bonnard,[3] N. Michel,[4,5] N. L. Achouri,[1] T. Aumann,[6,7] H. Baba,[8] F. Delaunay,[1] Q. Deshayes,[1] P. Doornenbal,[8] N. Fukuda,[8] J. W. Hwang,[9] N. Inabe,[8] T. Isobe,[8] D. Kameda,[8] D. Kanno,[2] S. Kim,[9] N. Kobayashi,[2] T. Kobayashi,[10] T. Kubo,[8] J. Lee,[8] R. Minakata,[2] T. Motobayashi,[8] D. Murai,[11] T. Murakami,[12] K. Muto,[10] T. Nakashima,[2] N. Nakatsuka,[12] A. Navin,[13] S. Nishi,[2] S. Ogoshi,[2] H. Otsu,[8] H. Sato,[8] Y. Satou,[9] Y. Shimizu,[8] H. Suzuki,[8] K. Takahashi,[10] H. Takeda,[8] S. Takeuchi,[8] R. Tanaka,[2] Y. Togano,[2,7] A. G. Tuff,[14] M. Vandebrouck,[3] and K. Yoneda[8]

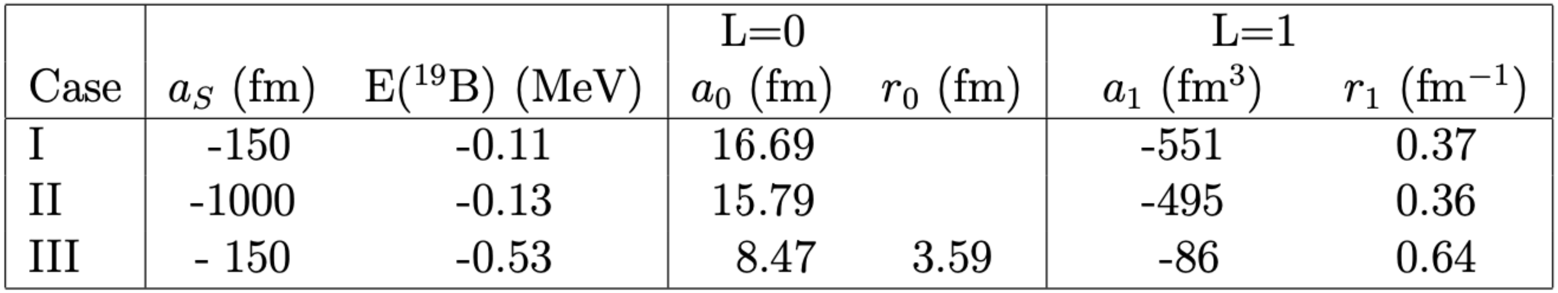
Results for ^{20}B

Direct calculations shows no bound state in the ^{17}B+3n system (agreement with data)

The situation is similar than in ^{6}He= ^{4}He+n+n bound but ^{7}He=4He+n+n+n unbound

We computed the n-[^{17}B-n-n] scattering with several choices (I,II,III) of model parameters

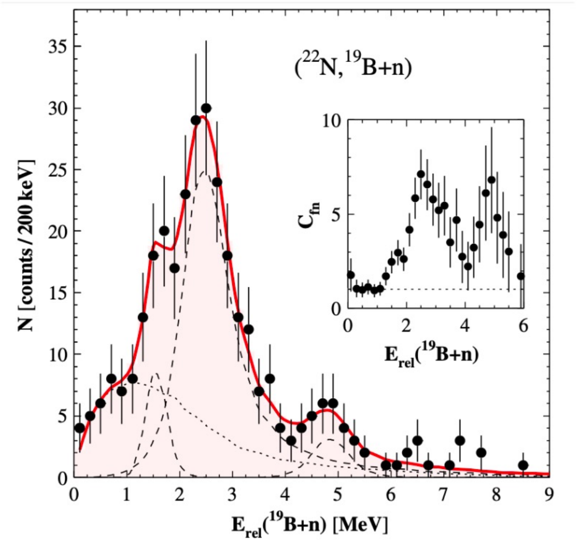
- **S waves are repulsive**
- **P waves are attractive, but not enough to create a resonant state**

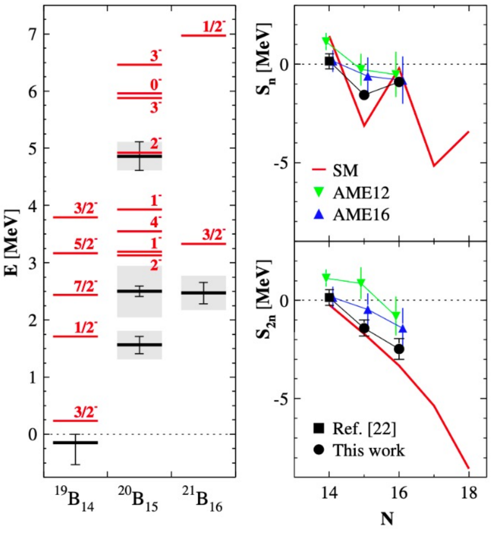


			L=0		L=1	
Case	a_S (fm)	E(^{19}B) (MeV)	a_0 (fm)	r_0 (fm)	a_1 (fm^3)	r_1 (fm^{-1})
I	-150	-0.11	16.69		-551	0.37
II	-1000	-0.13	15.79		-495	0.36
III	- 150	-0.53	8.47	3.59	-86	0.64

There are recent experimental claims about several resonances in this system

First observation of ^{20}B and ^{21}B
S. Leblond et al, Phys. Rev. Lett. 121, 262502 (2018)





By assuming a single resonance, they get $E_R = 2.44 \pm 0.09$ MeV and $\Gamma = 1.2 \pm 0.4$

A more detailed analysis shows a superposition of 3 resonant states

$$E_r = 1.56 \pm 0.15\,\text{MeV} \;\; \text{with} \;\; \Gamma < 0.5\,\text{MeV}$$

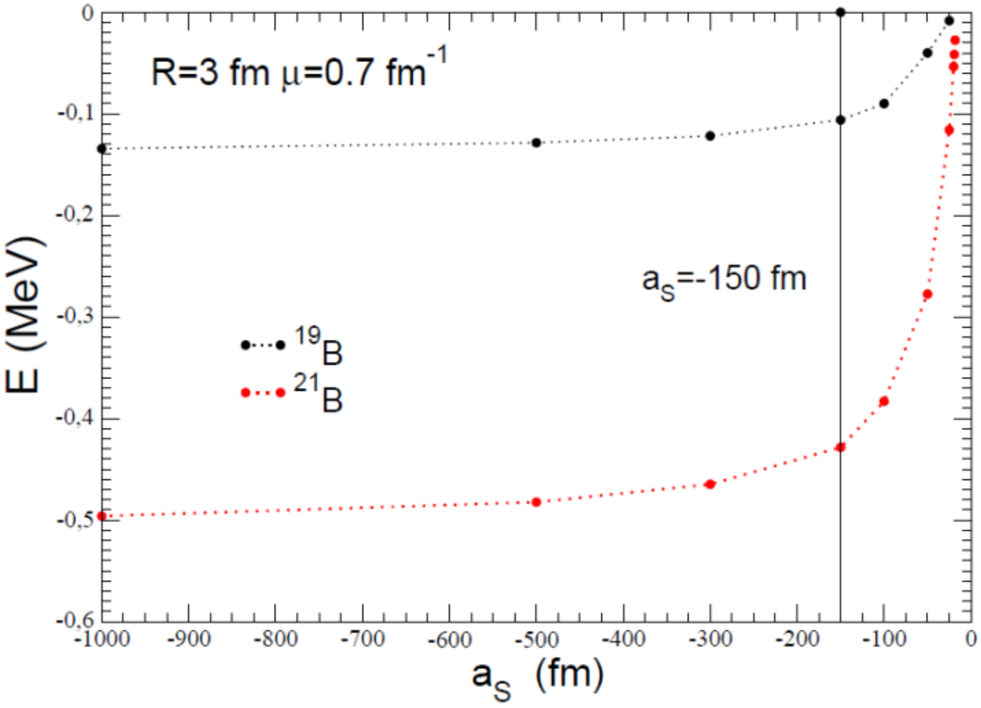
$$E_r = 2.50 \pm 0.09\,\text{MeV} \;\; \text{with} \;\; \Gamma < 0.9 \pm 0.3\,\text{MeV},$$

$$E_r = 4.86 \pm 0.25\,\text{MeV} \;\; \text{with} \;\; \Gamma < 0.5\,\text{MeV}.$$

Nothing within our cluster model : neither by S-matrix poles nor by « real scaling » method

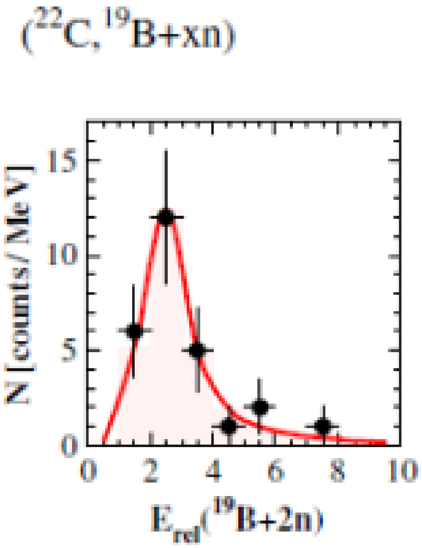
Results for ^{21}B

We found ^{21}B **bound**, for any parameter set binding ^{19}B
The value of its binding energy is related to the ^{19}B one, i.e. to scattering length
It is very hard to imagine a mechanism inverting (cross) the black and red curves !!!



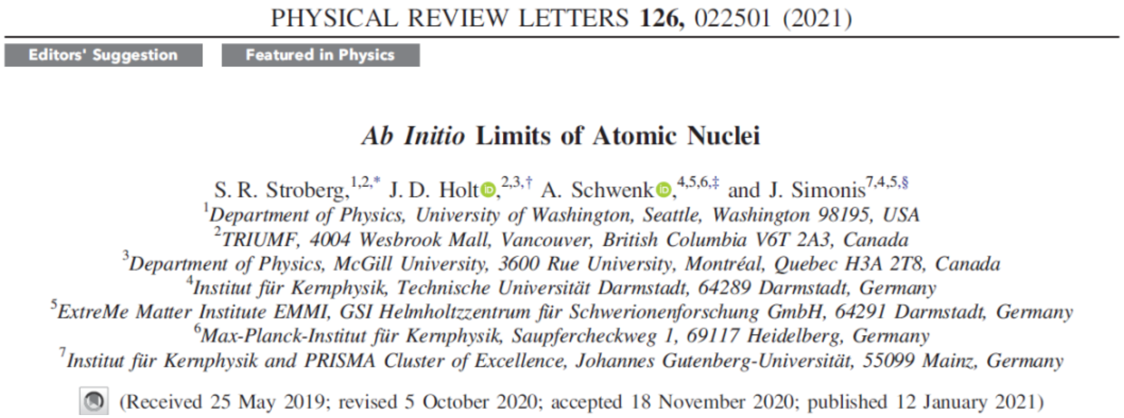
There is a general agreement among the experimentalst that ^{21}B is unbound
Traditional SHM (2005) predicts an unbound g.s. by 3 MeV (but also for 19B)

First observation of ^{20}B and ^{21}B
S. Leblond et al, Phys. Rev. Lett. 121, 262502 (2018)



By proton removal from ^{22}C, they observed ^{21}B to be resonant state by 2.47 ± 0.19 MeV with respect to ^{19}B+2n threshold.

A recent « ab initio » result of **^{8}B-^{21}**B (binding **^{19}B**) found **^{21}B** bound (with small probability)



PHYSICAL REVIEW LETTERS **126,** 022501 (2021)

Editors' Suggestion **Featured in Physics**

Ab Initio Limits of Atomic Nuclei

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CONCLUSIONS

We built a local potential to describe the **n-^{17}B** interaction and its virtual state
It depends on one parameter, adjusted to reproduce the huge **n-^{17}B** scattering length (a_s<-50 fm)

Supplemented with the nn interaction it describes well **^{19}B** as a 3-body **^{17}B-n-n** cluster:
- Its ground state (E=-0.14 +/- 0.40) MeV
- Two (L=1, and L=2) resonances

all in agreement with experimental findings.

The model is extended to describe the recently measured B isotopes **(S. Leblond et al)** as
^{20}B=^{17}B-n-n-n
^{21}B=^{17}B-n-n-n-n
^{21}B is found to be bound and no any resonance states are obtained in **^{20}B** and **^{21}B**

Either the resonance in **S. Leblond et al** corresponds to an excited state (and ^{21}B is bound)
or
this cluster model is unable to describe **^{20}B and ^{21}B** as 3n and 4n system around a **^{17}B** core.

In favour of our result is the fact the chain **^{15}B-^{17}B-^{19}B** is similar and ends with a bound **^{19}B** !
But in this subttle physics, **any small approximation can kill you** !

We badly need a more precise **direct measurement** of **^{19}B** S_{2n} : too big error bars and dB/dE is not a direct measurment !!!