Low-energy neutron scattering on Light Nuclei
and
^{19}B isotope as a ^{17}B-n-n three-body cluster in the unitary limit

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Grouping several Labs from Orsay Campus
IPN, LAL,CSNSM,LPT….

In collaboration with **E. Hiyama**, **R. Lazauskas** and **M. Marqués**

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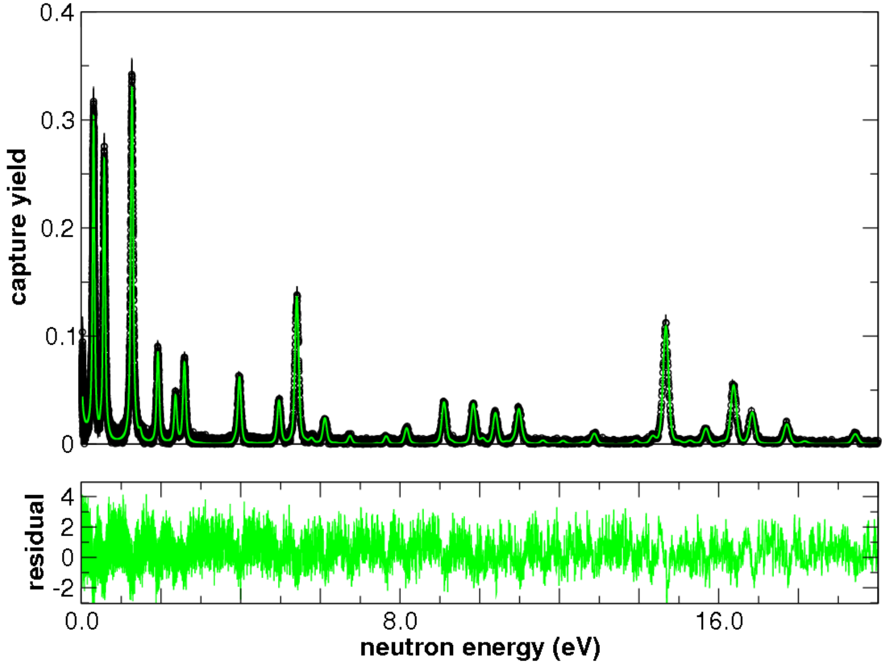
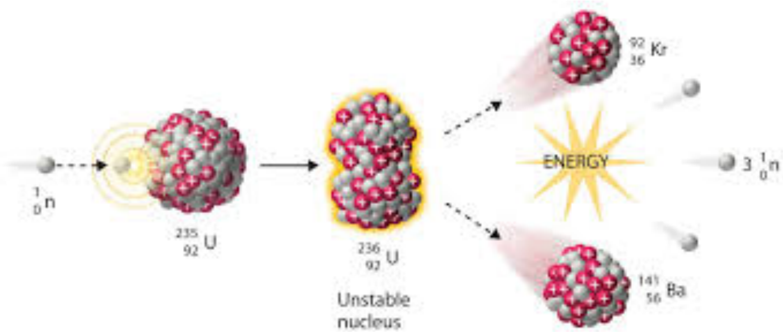
Beppu, January 25, 2020

INTRODUCTION

In Nuclear Physics, few things are more interesting than the very low energy (S-wave) scattering of n's

On heavy nuclei it gives rise to the fantastic forest of « resonances » (see the scale!)





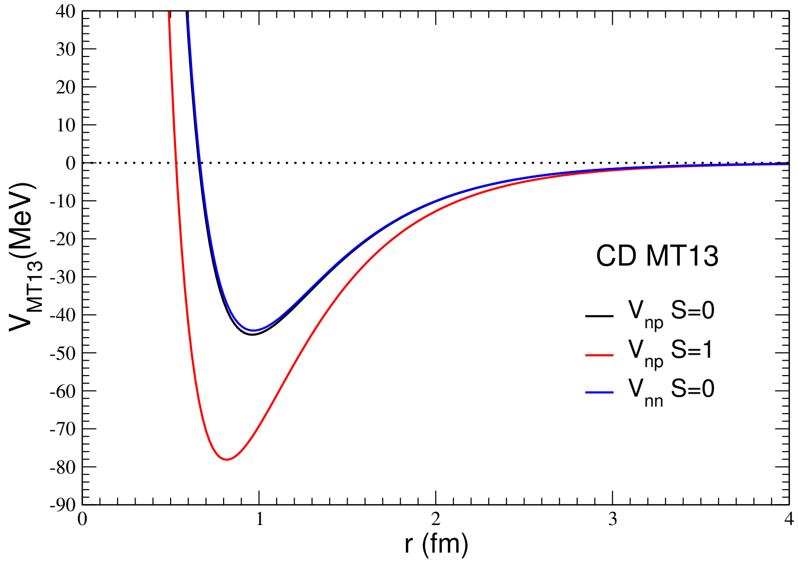
and can be even **very dangerous….**

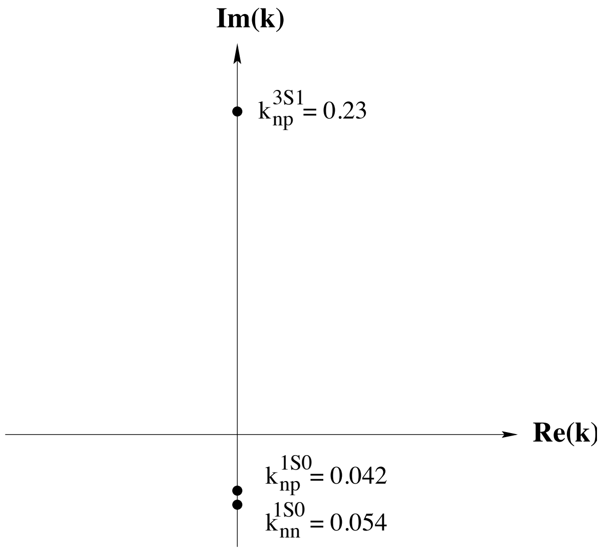
In any case, free from Coulomb, partial waves, centrifugal barrier, spins-orbit, tensor, … it makes the delicious of theorists and it is very sensitive to the interaction

On light nuclei is certainly less spectacular, **ALTHOUGH** ….

INTRODUCTION

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





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

The S=0 **np** and **nn** 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

Despite **all V_{nN} are attractive,** a low energy **n** scattering on a light nucleus soon (^{2}H) behaves **as if the V_{nA} was repulsive**…

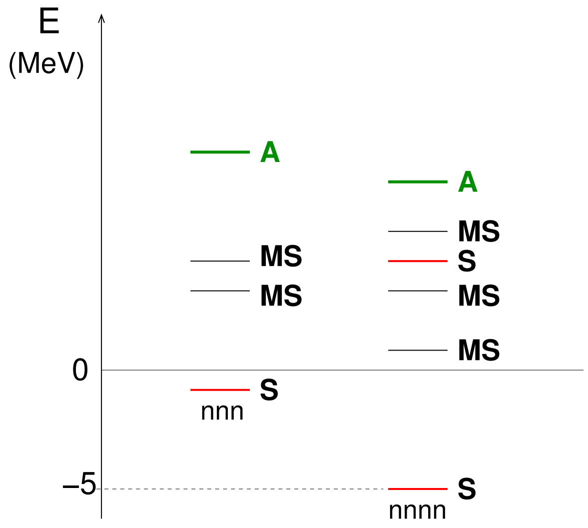
A **n** approaching a nucleus **"feels"** the others **n's** in the target and **it doesn't like it !** **(Pauli)**

INTRODUCTION

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

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

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



The lowest state of $\mathbf{H_{3n}}$ and $\mathbf{H_{4n}}$ is symmetric

The first antisymmetric state is much higher in spectrum

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

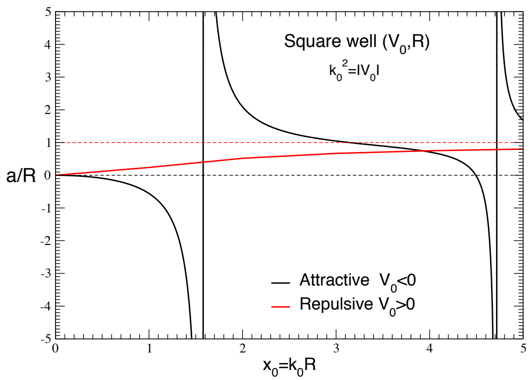
the "Pauli repulsion"

An interesting quantity to measure the repulsive/attractive character of $\mathbf{V_{nA}}$ **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

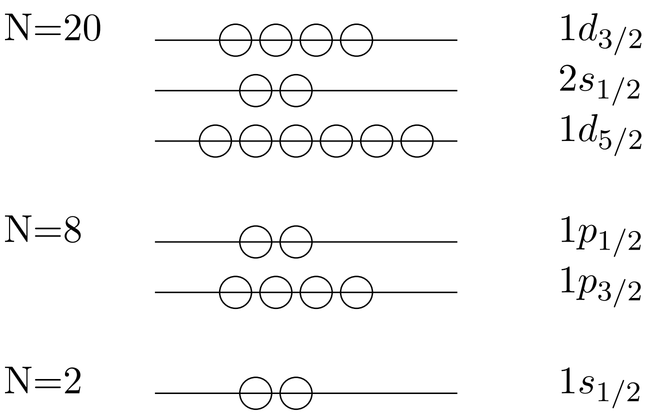


For a realistic interaction – mixing repulsive core with attractive parts – it will result as a balance of both tendencies

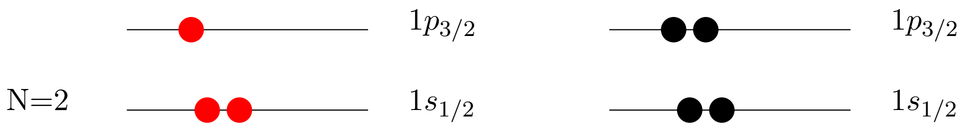
INTRODUCTION

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

Z N A	Sym	J	a-	a+
1 0 1	p	½+	**-23.71**	+5.41 *
0 1 1	n	½+	**-18.59**	/
1 1 2	^{2}H	1-	+0.65*	+6.35
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+	**-3.17**	
3 6 9	^{9}Li	$3/2^{-}$	**-14**	



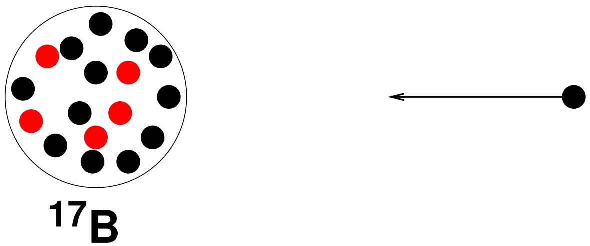
For A=n,p all channels are attractive, as expected (despite its sign, like for +5.41*)
with A=2, the quartet state (S=3/2) starts being repulsive: Pauli repulsion dominates over **nN** attraction
In A=7 an attractive channel appears again: ^{7}Li ($J=3/2^{-}$)



P-wave **n's** decrease the Pauli repulsion: 2 $p_{3/2}$ n's enough to balance into an "attractive" V_{nA}
Rm: previous repulsion were only in S-wave : P-wave were attractive, even resonant (n-^{3}H,n-^{4}He)
The "attraction" persists in ^{12}Be,^{15}B… **until something spectacular occurs……**

ONE OF THE MOST FASCINATING SYSTEMS IN NUCLEAR PHYSICS

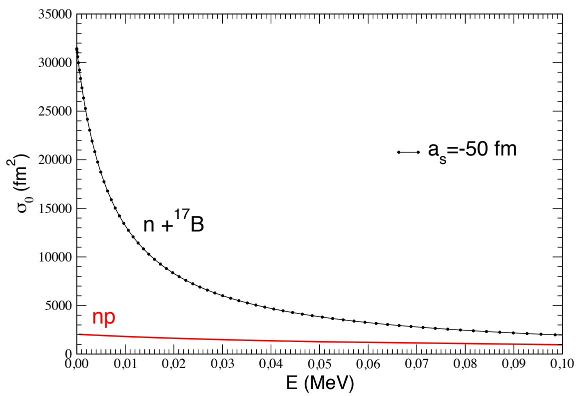
^{17}B is a (strong) stable nucleus with **$J^{\pi}=3/2^{-}$** consisting on a sea of **12n** sourrounding **5p**



The balance between attractive π-exchange between **n** and **17 Nucleon** and "Pauli repulsion" with **12n**'s of **^{17}B** is **so fine-tuned** that the scattering length is **$a_{n\text{-}17B} \sim -100$ fm (max χ^2)**

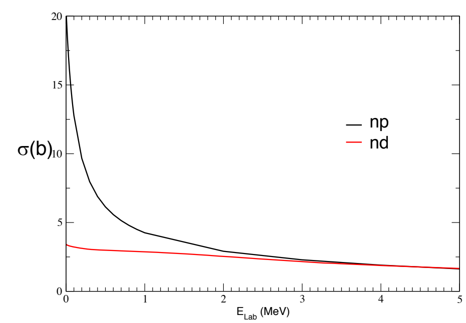
A **<u>low energy</u> n scattering on ^{17}B** will **"feel" a monster** of geometrical size D~400 fm
Not yet a virus but we are getting close ! ("visible" ?)

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



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

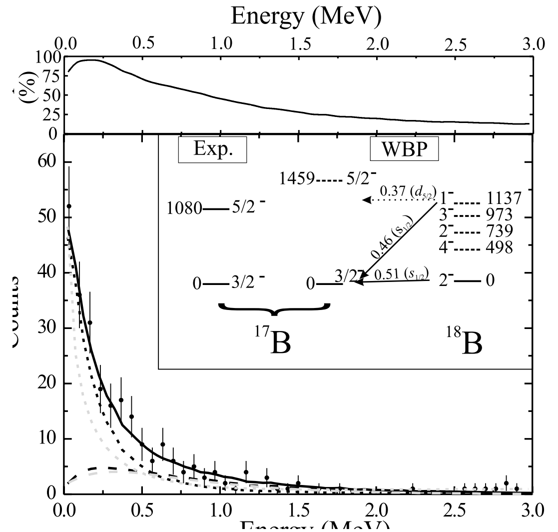
$$\sigma(0) = 4\pi a^2$$



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**

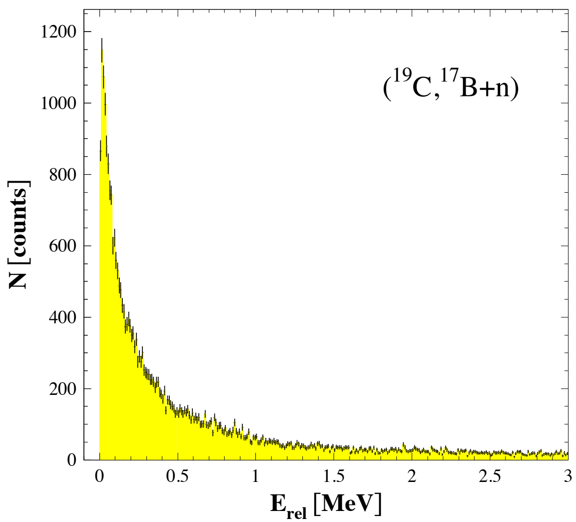
claimed the existence of a ^{18}B "virtual" (unbound) state

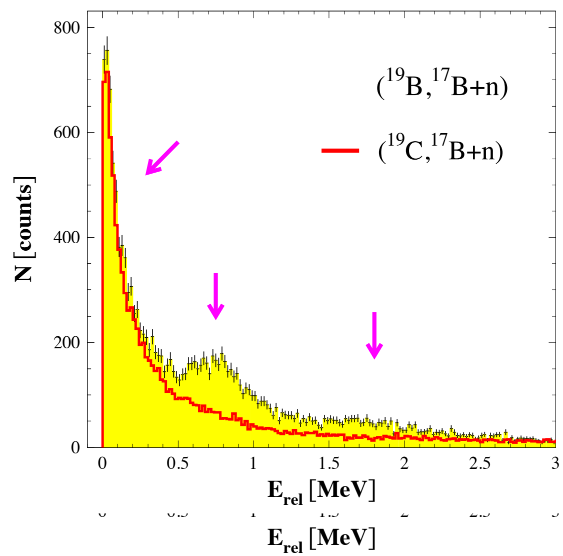
and a **n-^{17}B** a_s <- 50 fm (max χ^2 at a_s=-100 fm)

Claims for $J^\pi=2^-$

II. A recent RIKEN result **(SAMURAI Collaboration)**

this state was observed in other channels





S.Leblond PhD (2015)
M. Marques, Fukuoka 2018

The **precise value of a_s it is 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 »

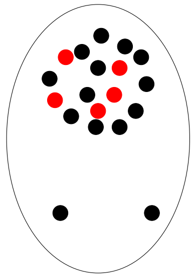
  S. König, H. Griesshammer, H.W. Hammer, U. van Kolck, Phys. Rev. Lett 118, 202501 (2017)
  We argue that many features of the structure of nuclei emerge from a strictly perturbative expansion around the unitarity limit, where the two-nucleon S waves have bound states at zero energy"
- It is even comparable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

^{19}B



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, experimentally known R_m=299)

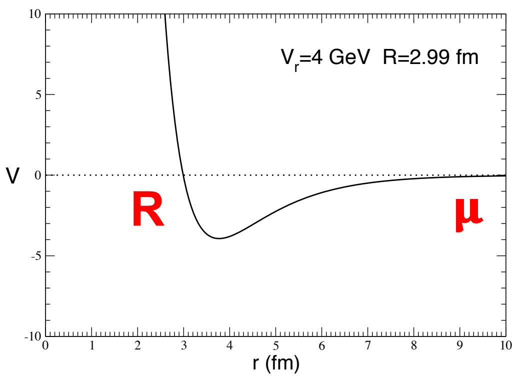
- Pion exchange (dominant at large r) μ=0.70 fm^{-1}

Simplest ansatz
$$V(r) = V_r \frac{\exp(-2\mu r)}{r} - V_a \frac{\exp(-\mu r)}{r}$$

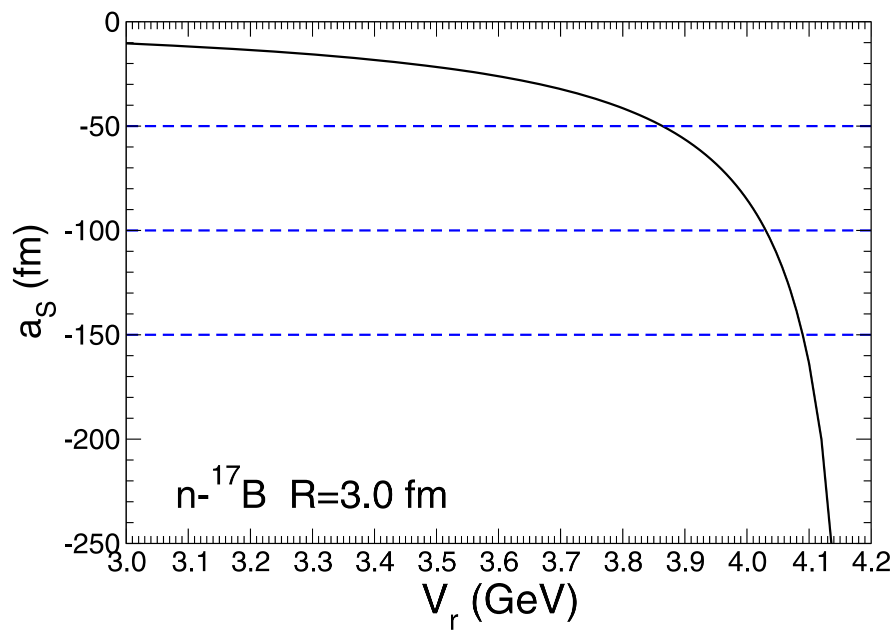
Equivalent to
$$\boxed{V(r) = V_r \left(e^{-\mu r} - e^{-\mu R}\right) \frac{e^{-\mu r}}{r}}$$

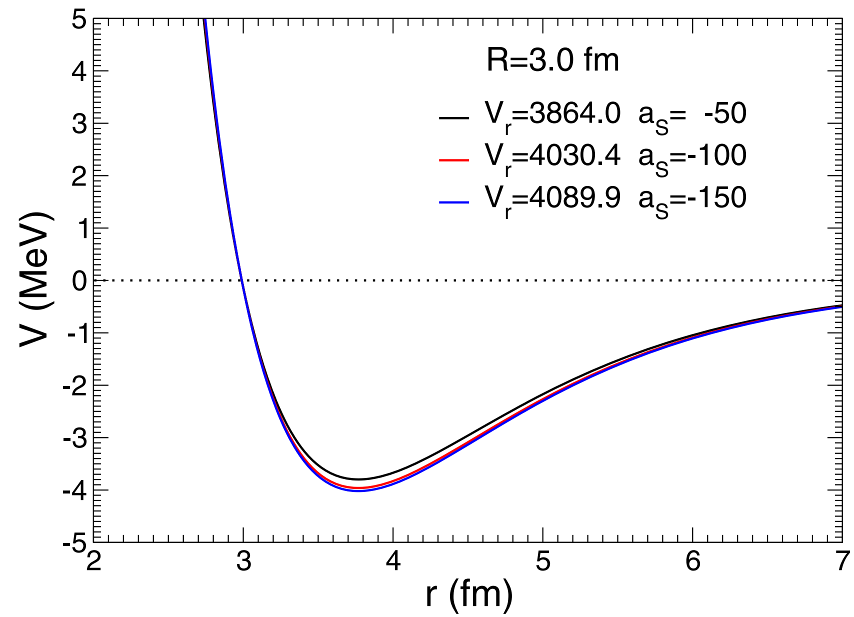
μ and **R** being fixed, **there is one single parameter** V_r

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

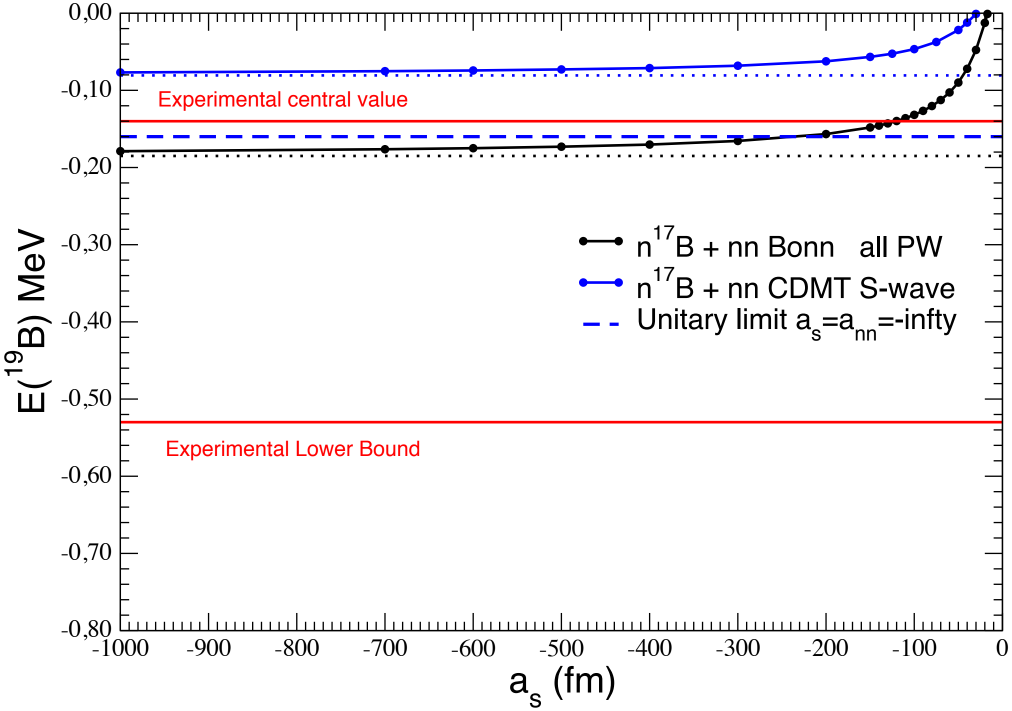
Singularity on right would corresponds to the (unphysical) bound ^{18}B state

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 $\mathbf{V_{n\text{-}17B}}$ and some realistic $\mathbf{V_{nn}}$

^{19}B appears to be bound for $a_s<-50$ (the only parameter!) in a $J^\pi=3/2^-$ state (L=0,S=0)



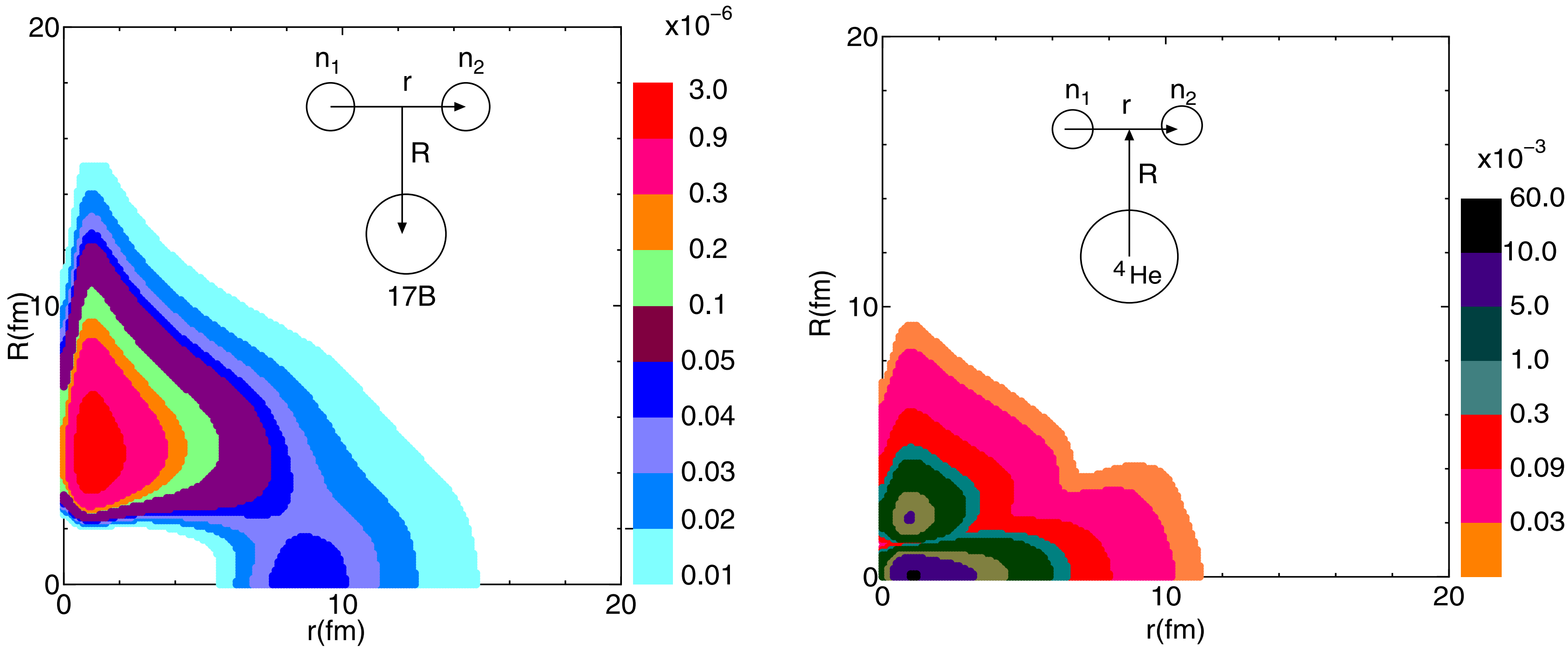
We used 2 different **nn** interactions and let $\mathbf{V_{n\text{-}17B}}$ act in S-wave (s. blue) or in all PW (s. black)

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 $|\Psi(r,R)|^2$ fixing a_s=-100 fm



Compared with a similar system ^{6}He=^{4}He+n+n

$RMS_{nC}(^{19}B)$=12.0 fm

$RMS_{nC}(^{6}He)$=4.5 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

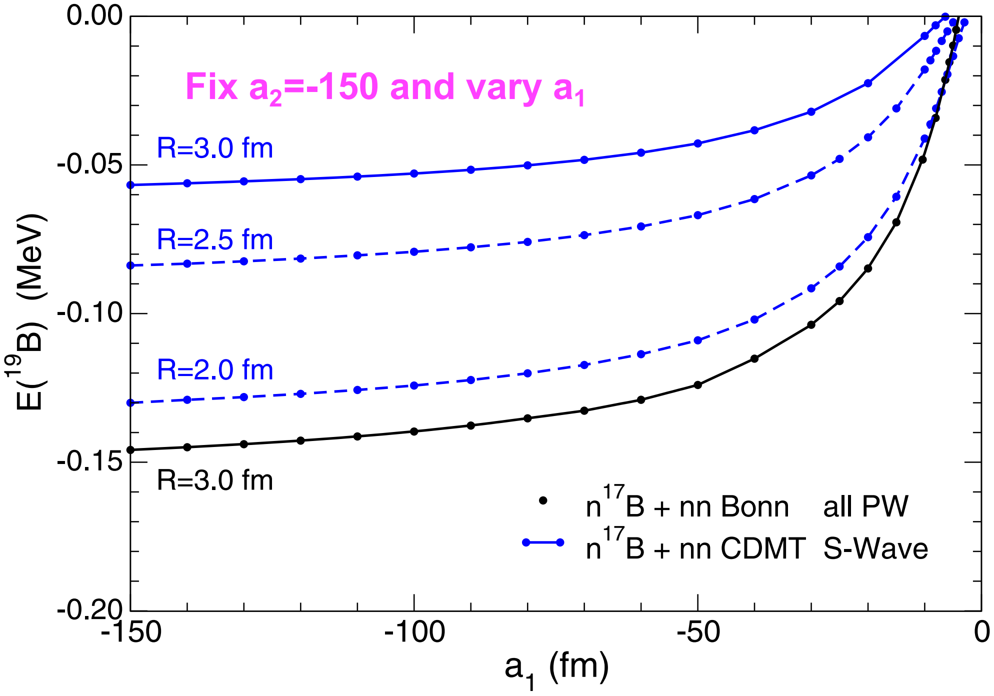
The key of the « succes » is the double resonant character

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

CONCLUSIONS

We present a local S-wave potential to describe the **n-^{17}B** interaction and its virtual state
It depends on 1 parameter, adjusted to reproduce the huge **n-^{17}B** scattering length (a_s≈-100 fm)

Supplemented with the **nn** interaction we describe well the **^{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 **^{19}B** ground state is a « double resonant » state compatible with the unitary limit in both **nn** and **n-^{17}B** interactions

MSU/RIKEN finding on **^{18}B virtual state** was quite fortuitous.
The possibility of finding similar resonant structures, bound (a_s >0) instead of virtual, in a systematic scanning of the nuclear chart cannot be excluded.
This will correspond to an extremely large and fragile (A+1**)** nuclear structure involving sizes still smaller but close to atomic sizes – and only accessible via scattering experiments.
They could offer a unique possibility to **"visualize"** a nucleus using microscopic techniques as it is currently done with atoms.

Resonant a_s leads to new clusterization mechanism: model extends to describe new B isotopes

^{19}B=^{17}B-n-n

^{20}B=^{17}B-n-n-n

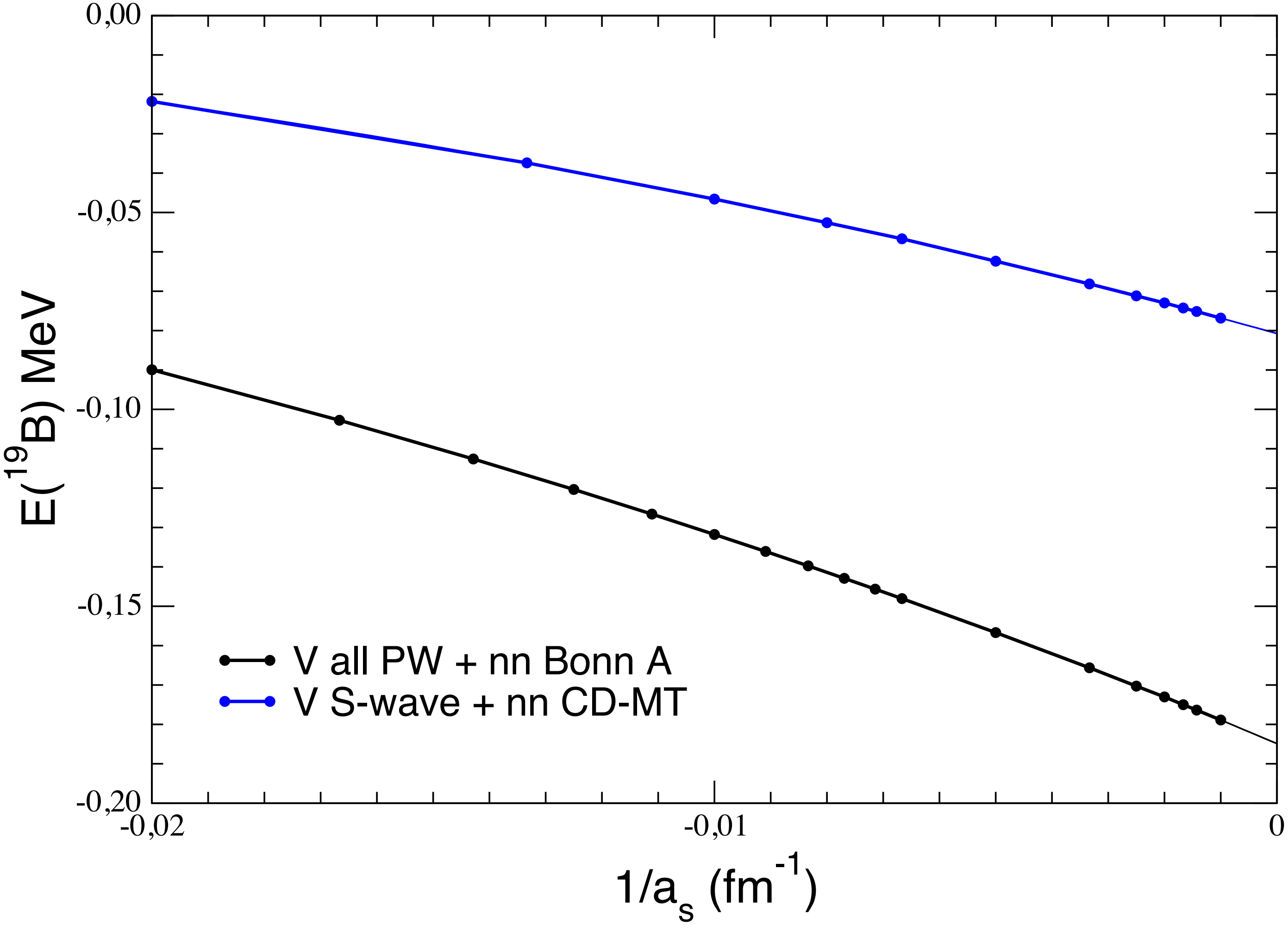
^{21}B=^{17}B-n-n-n-n

with the methods used in computing **^{4}H** and **^{5}H** **(L.H.C., PLB 791, 335 (2019)**

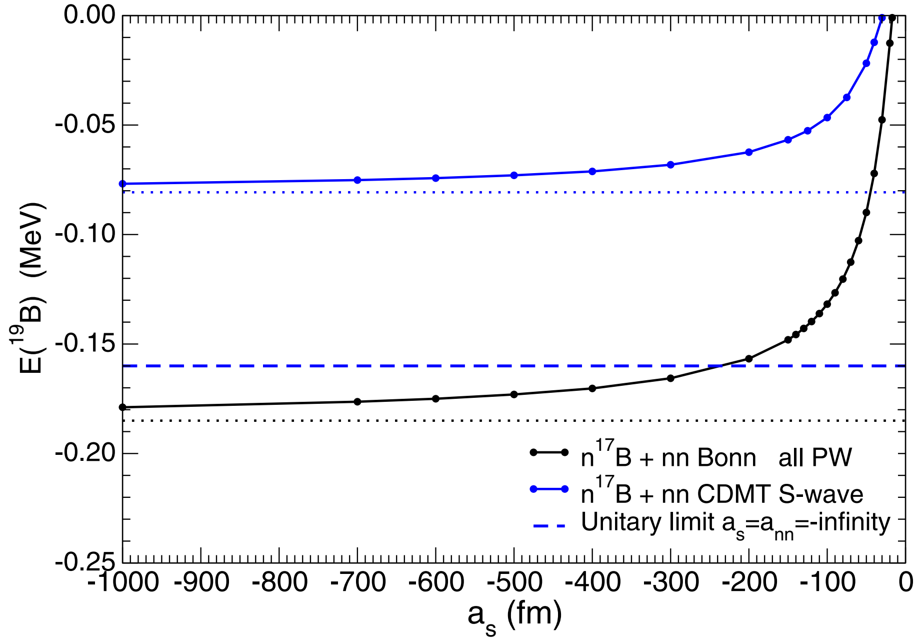
CONCLUSIONS

Despite the large values of the scattering length in both **n-^{17}B** and **nn** channels, we found that the appearence of the first Efimow excitation is excluded (would require $\mathbf{a_s} \sim$ few thousands fm)

To fix the model parameter $\mathbf{V_r}$ it is mandatory to determine $\mathbf{a_2}$ and $\mathbf{a_1}$ and obtain a more accurate value of **E(^{19}B)**



0,00
-0,05
-0,10
-0,15
-0,20
-0,02
-0,01
0
E(^{19}B) MeV
1/a_s (fm^{-1})
V all PW + nn Bonn A
V S-wave + nn CD-MT



E(^{19}B) (MeV)
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
-1000
-900
-800
-700
-600
-500
-400
-300
-200
-100
0
a_s (fm)
n^{17}B + nn Bonn all PW
n^{17}B + nn CDMT S-wave
Unitary limit a_s=a_{nn}=-infinity