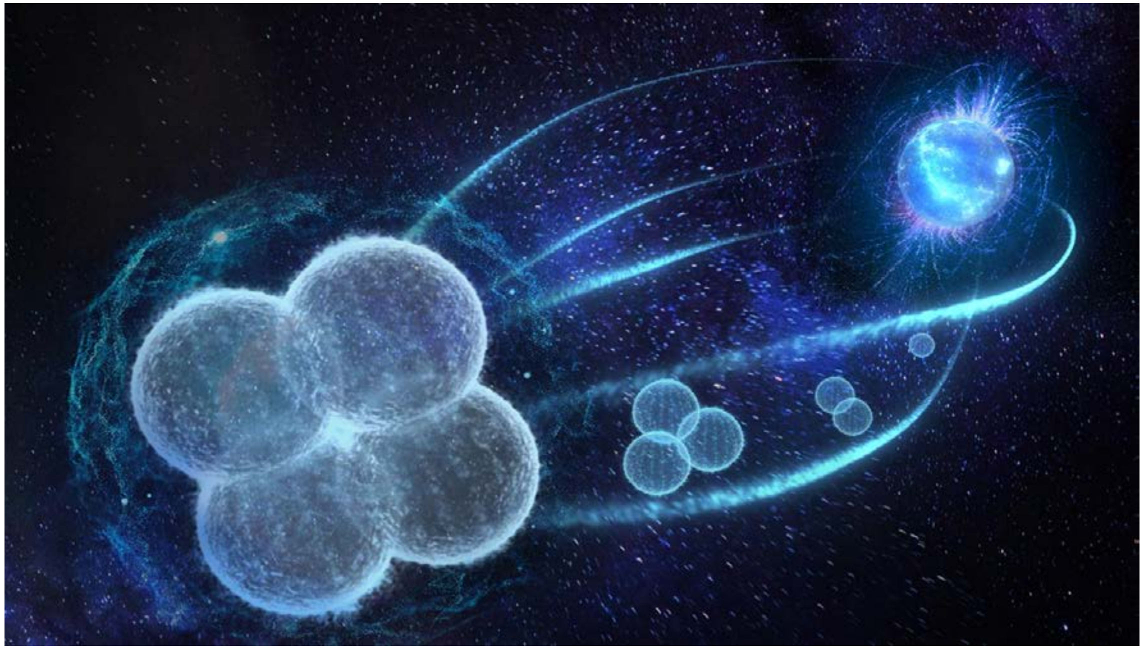
GDR RESANET

Scientific Colloquium Webinars *(Planet Earth, December 7, 2020)*



Sixty years of multineutron quest: game over or game on?

F. Miguel Marqués

lpc caen
Laboratoire de physique corpusculaire

FMM & Jaume Carbonell, European Physical Journal A (2020)

Lord Chadwick : the first multineutron (A=1)

NATURE FEBRUARY 27, 1932

Possible Existence of a Neutron

IT has been shown by Bothe and others that beryllium when bombarded by α-particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about 0·3 (cm.)$^{-1}$. Recently Mme. Curie-Joliot and M. Joliot found that the transference of energy to the proton was by a process similar to the Compton effect, and estimated that the beryllium radiation had a quantum energy of 50×10^6 electron volts.

I have shown that the radiation ejects particles from hydrogen, helium, lithium, beryllium, carbon, air, and argon. The particles ejected from hydrogen behave, as regards range and ionising power, like protons with speeds up to about $3{\cdot}2 \times 10^9$ cm. per sec. The particles from the other elements have a large ionising power, and appear to be in each case recoil atoms of the elements.

These results, and others I have obtained in the course of the work, are very difficult to explain on the assumption that the radiation from beryllium is a quantum radiation, if energy and momentum are to be conserved in the collisions. The difficulties disappear, however, if it be assumed that the radiation consists of particles of mass 1 and charge 0, or neutrons.

The collisions of this neutron with the atoms through which it passes give rise to the recoil atoms, and the observed energies of the recoil atoms are in fair agreement with this view.

J. CHADWICK.

Cavendish Laboratory,
Cambridge, Feb. 17.

"But there was no doubt whatever in my mind, or I should not have written the Letter"

Lord Chadwick : the first multineutron (A=1)

NATURE FEBRUARY 27, 1932

Possible Existence of a Neutron

IT has been shown by Bothe and others that beryllium when bombarded by α-particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about 0·3 (cm.)$^{-1}$. Recently Mme. Curie-Joliot and M. Joliot found that the transference of energy to the proton was by a process similar to the Compton effect, and estimated that the beryllium radiation had a quantum energy of 50×10^6 electron volts.

I have shown that the radiation ejects particles from hydrogen, helium, lithium, beryllium, carbon, air, and argon. The particles ejected from hydrogen behave, as regards range and ionising power, like protons with speeds up to about $3{\cdot}2 \times 10^9$ cm. per sec. The particles from the other elements have a large ionising power, and appear to be in each case recoil atoms of the elements.

These results, and others I have obtained in the course of the work, are very difficult to explain on the assumption that the radiation from beryllium is a quantum radiation, if energy and momentum are to be conserved in the collisions. The difficulties disappear, however, if it be assumed that the radiation consists of particles of mass 1 and charge 0, or neutrons.

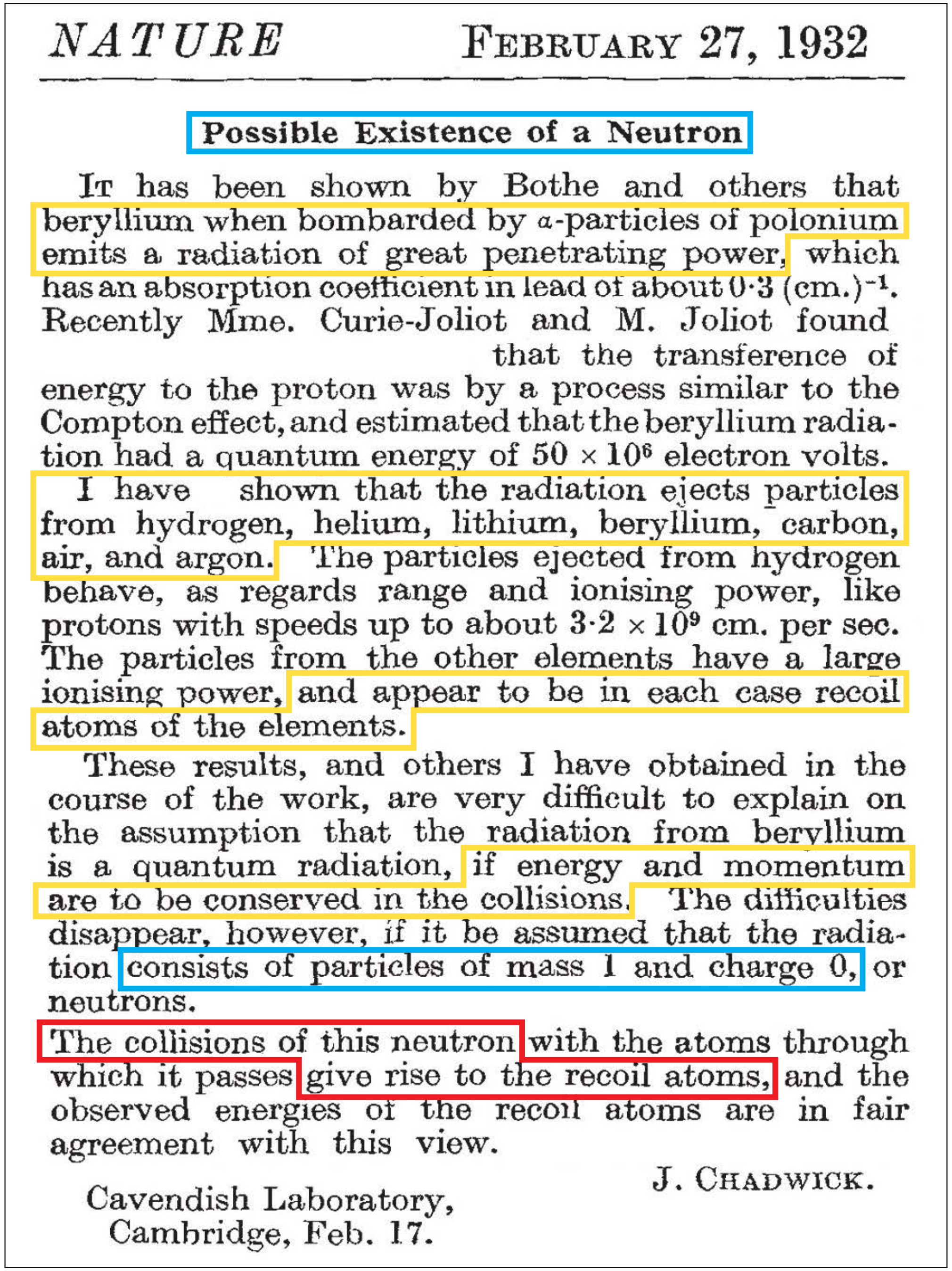
The collisions of this neutron with the atoms through which it passes give rise to the recoil atoms, and the observed energies of the recoil atoms are in fair agreement with this view.

J. CHADWICK.

Cavendish Laboratory,
Cambridge, Feb. 17.

"But there was no doubt whatever in my mind, or I should not have written the Letter"

Lord Chadwick : the first multineutron (A=1)



NATURE FEBRUARY 27, 1932

Possible Existence of a Neutron

IT has been shown by Bothe and others that beryllium when bombarded by α-particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about 0·3 (cm.)$^{-1}$. Recently Mme. Curie-Joliot and M. Joliot found that the transference of energy to the proton was by a process similar to the Compton effect, and estimated that the beryllium radiation had a quantum energy of 50 × 10^6 electron volts.

I have shown that the radiation ejects particles from hydrogen, helium, lithium, beryllium, carbon, air, and argon. The particles ejected from hydrogen behave, as regards range and ionising power, like protons with speeds up to about 3·2 × 10^9 cm. per sec. The particles from the other elements have a large ionising power, and appear to be in each case recoil atoms of the elements.

These results, and others I have obtained in the course of the work, are very difficult to explain on the assumption that the radiation from beryllium is a quantum radiation, if energy and momentum are to be conserved in the collisions. The difficulties disappear, however, if it be assumed that the radiation consists of particles of mass 1 and charge 0, or neutrons.

The collisions of this neutron with the atoms through which it passes give rise to the recoil atoms, and the observed energies of the recoil atoms are in fair agreement with this view.

J. CHADWICK.

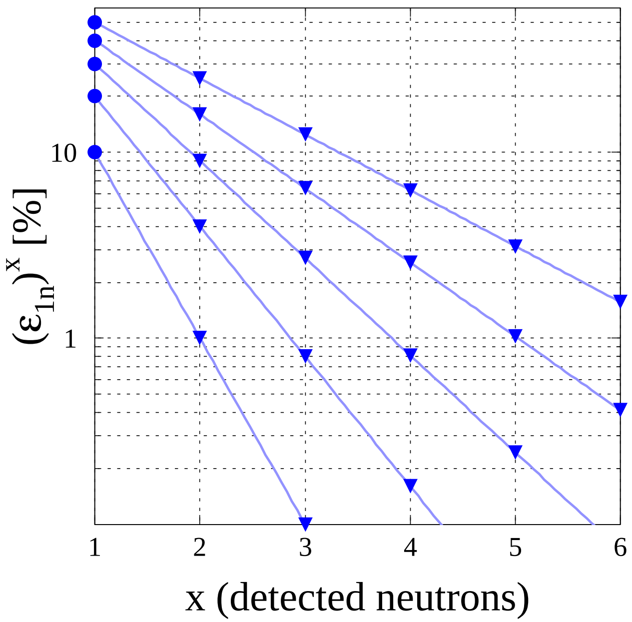
Cavendish Laboratory,
Cambridge, Feb. 17.

"But there was no doubt whatever in my mind, or I should not have written the Letter"

- by "atoms" he means "nuclei" :

  → $\varepsilon_n \sim$ few % (●)

  → $\varepsilon_{xn} \approx (\varepsilon_{1n})^x$ (●● · · · ●)



Lord Chadwick : the first multineutron (A=1)

NATURE FEBRUARY 27, 1932

Possible Existence of a Neutron

IT has been shown by Bothe and others that beryllium when bombarded by α-particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about 0·3 (cm.)$^{-1}$. Recently Mme. Curie-Joliot and M. Joliot found that the transference of energy to the proton was by a process similar to the Compton effect, and estimated that the beryllium radiation had a quantum energy of 50 × 10^{6} electron volts. I have shown that the radiation ejects particles from hydrogen, helium, lithium, beryllium, carbon, air, and argon. The particles ejected from hydrogen behave, as regards range and ionising power, like protons with speeds up to about 3·2 × 10^{9} cm. per sec. The particles from the other elements have a large ionising power, and appear to be in each case recoil atoms of the elements.

These results, and others I have obtained in the course of the work, are very difficult to explain on the assumption that the radiation from beryllium is a quantum radiation, if energy and momentum are to be conserved in the collisions. The difficulties disappear, however, if it be assumed that the radiation consists of particles of mass 1 and charge 0, or neutrons.

The collisions of this neutron with the atoms through which it passes give rise to the recoil atoms, and the observed energies of the recoil atoms are in fair agreement with this view.

J. CHADWICK.

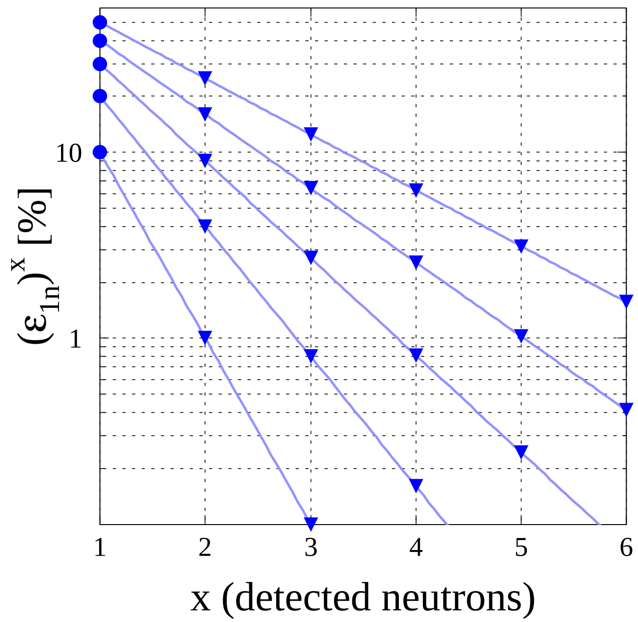
Cavendish Laboratory,
Cambridge, Feb. 17.

"But there was no doubt whatever in my mind, or I should not have written the Letter"

- by "atoms" he means "nuclei" :

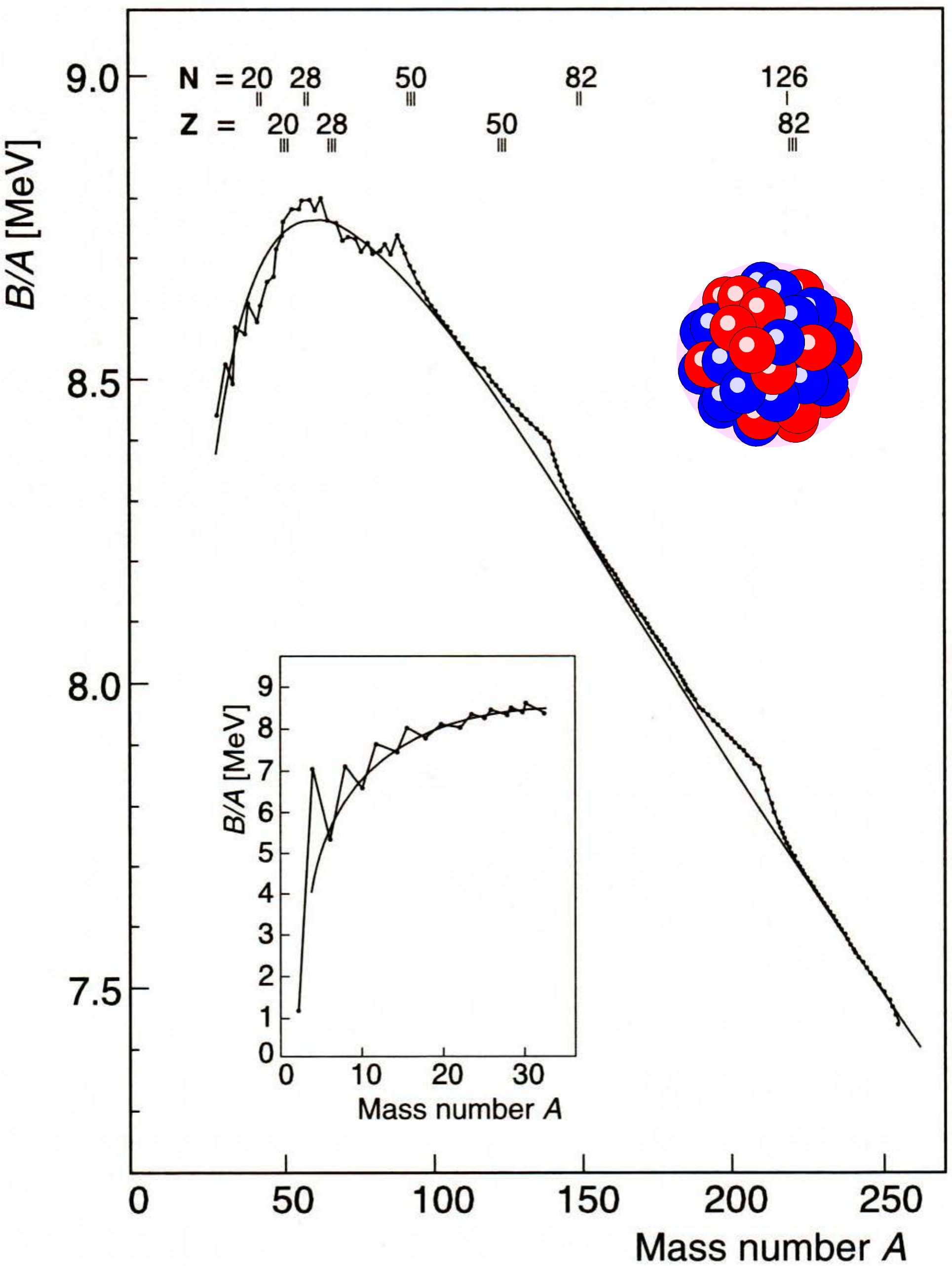
→ $\varepsilon_n \sim$ few % (●)

→ $\varepsilon_{xn} \approx (\varepsilon_{1n})^x$ (●● · · · ●)



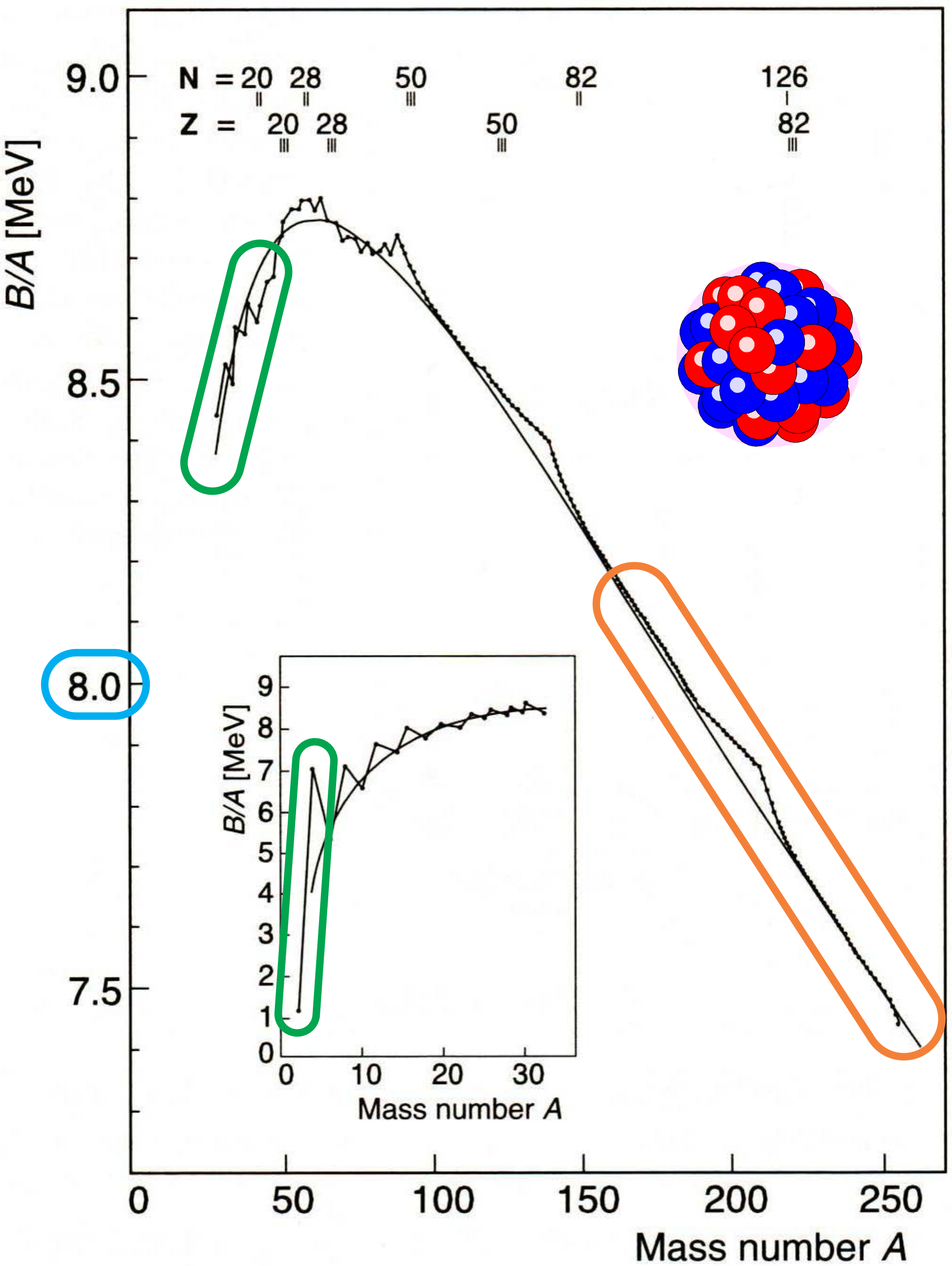
→ $\varepsilon_{xn} < (\varepsilon_{1n})^x$ due to "cross-talk" ...

The nucleus : a 'liquid drop'



$$B(N,Z) = N\,M_n + Z\,M_p - M(N,Z)$$

The nucleus : a 'liquid drop'



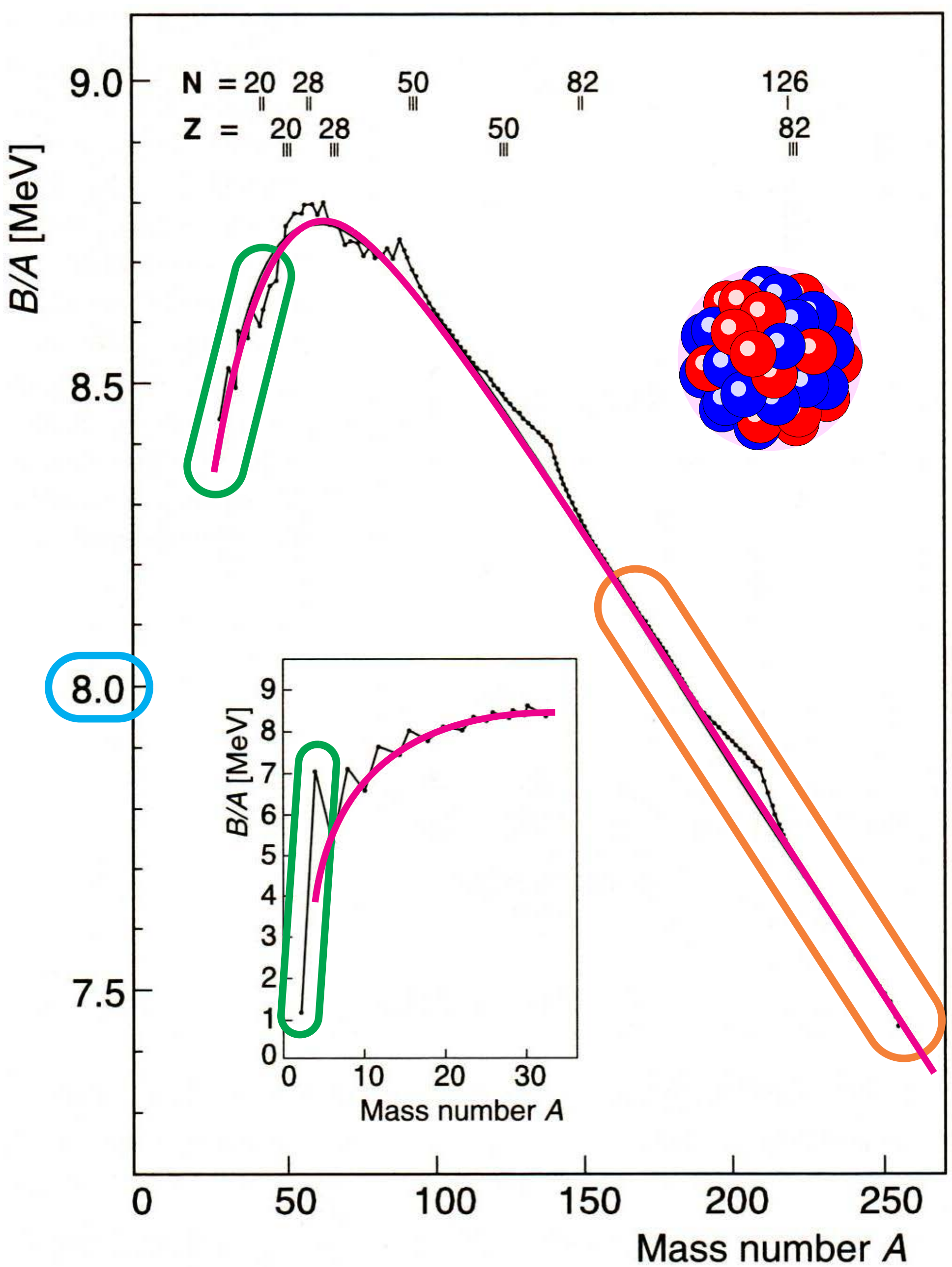
$$B(N,Z) = N\,M_n + Z\,M_p - M(N,Z)$$

$\sim$
- short range force : $\rho_0 \approx 2{\times}10^{14}$ g/cm^3
- about 1% of nuclear mass !

$\searrow$
- spontaneous & induced fission !
- nuclear energy / "atomic" bomb

$\nearrow$
- fusion in stars !
- H bomb / **ITER** !!!

The nucleus : a 'liquid drop'



$$B(N,Z) = N\,M_n + Z\,M_p - M(N,Z)$$

$\sim$ short range force : $\rho_0 \approx 2{\times}10^{14}$ g/cm^3; about 1% of nuclear mass !

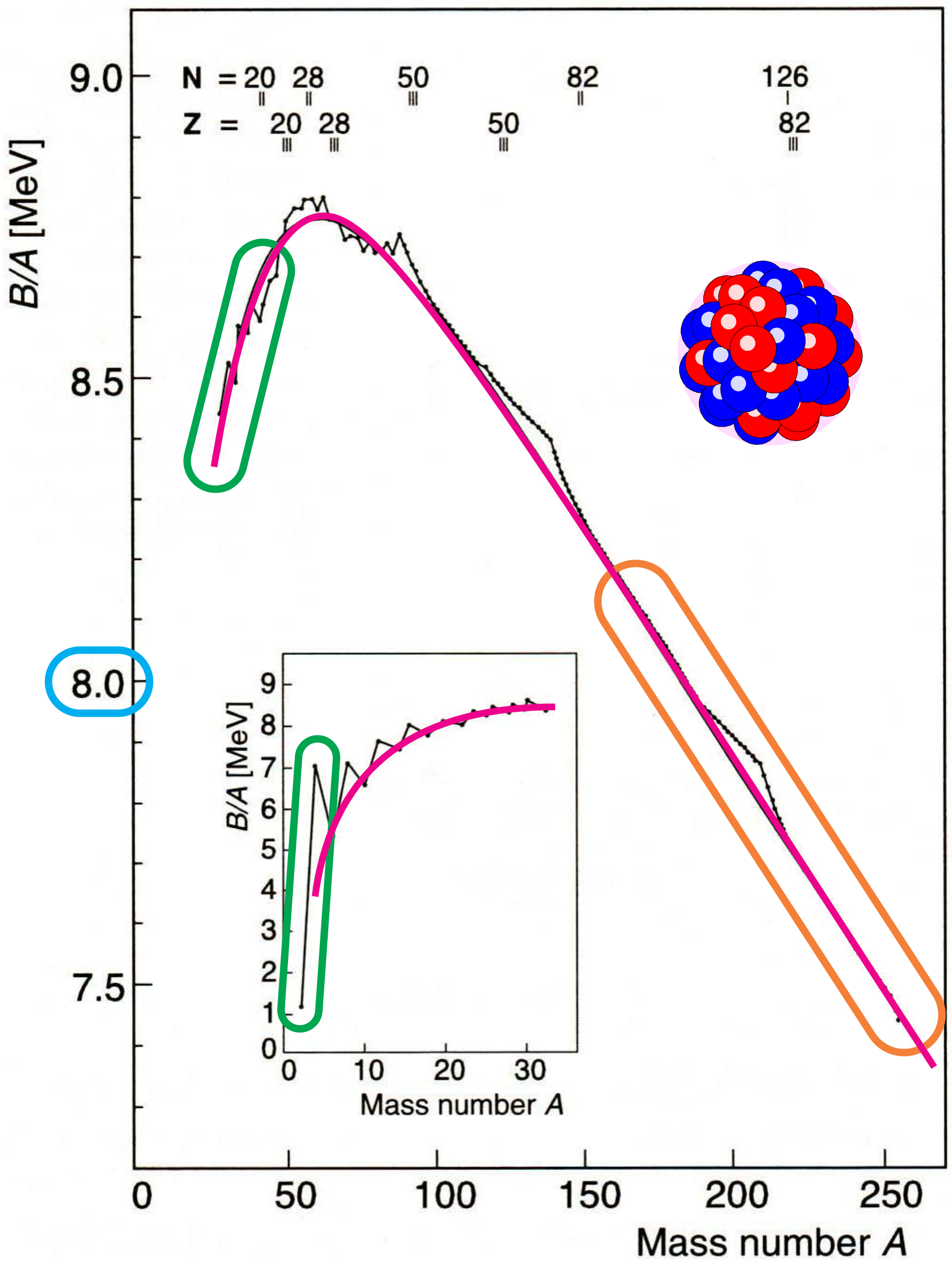
$\searrow$ spontaneous & induced fission ! nuclear energy / "atomic" bomb

$\nearrow$ fusion in stars ! H bomb / **ITER** !!!

▶ Semi-empirical liquid-drop formula :

15.67	$a_v\,A$	*volume*
17.23	$-\,a_s\,A^{2/3}$	*surface*
0.714	$-\,a_c\,Z^2/A^{1/3}$	*Coulomb*
23.29	$-\,a_a\,(N-Z)^2/A$	*asymmetry*
11.2	$\pm\,\delta/A^{1/2}$	*pairing*
[MeV]		

The nucleus : a 'liquid drop'



$$B(N,Z) = N\,M_n + Z\,M_p - M(N,Z)$$

$\sim$ short range force : $\rho_0 \approx 2{\times}10^{14}$ g/cm^3; about 1% of nuclear mass !

$\searrow$ spontaneous & induced fission ! nuclear energy / "atomic" bomb

$\nearrow$ fusion in stars ! H bomb / **ITER** !!!

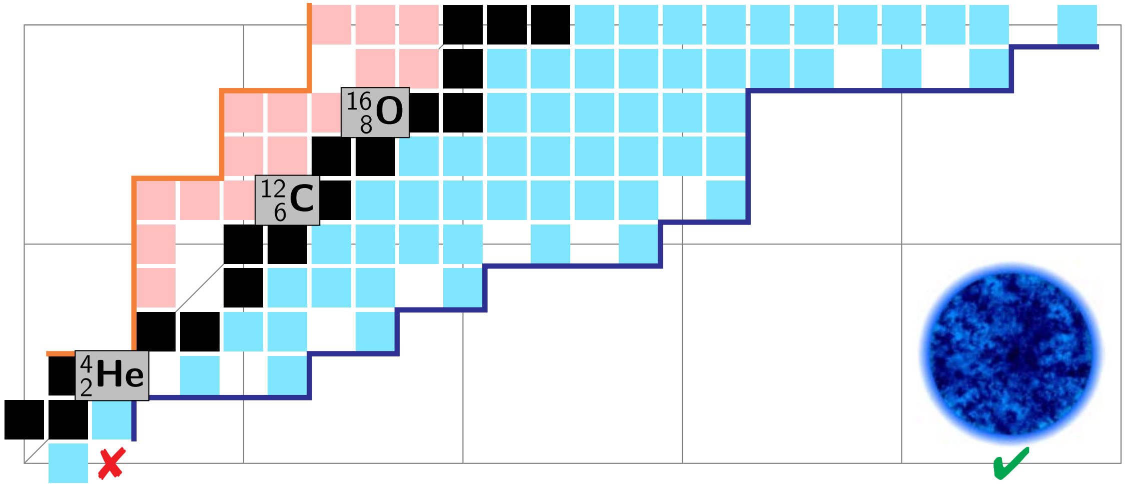
▶ Semi-empirical liquid-drop formula :

[MeV]		
15.67	$a_v\,A$	*volume*
17.23	$-\,a_s\,A^{2/3}$	*surface*
0.714	$-\,a_c\,Z^2/A^{1/3}$	*Coulomb*
23.29	$-\,a_a\,(N-Z)^2/A$	*asymmetry*
11.2	$\pm\,\delta/A^{1/2}$	*pairing*

$B/A\,(4{,}0) = -17$ MeV !!!

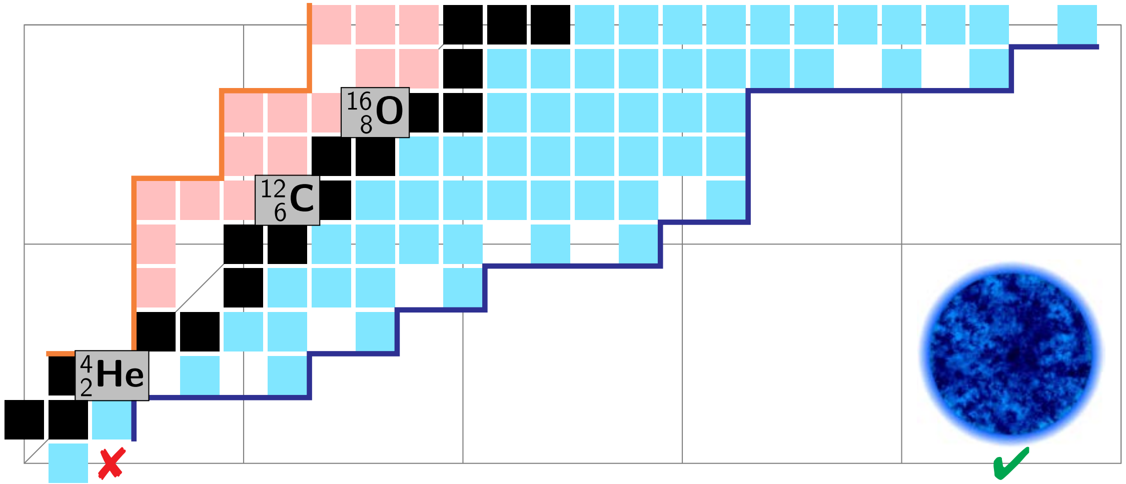
$B/A\,(3{,}0) = -22$ MeV !!!

Multineutrons : Tetraneutrons ?



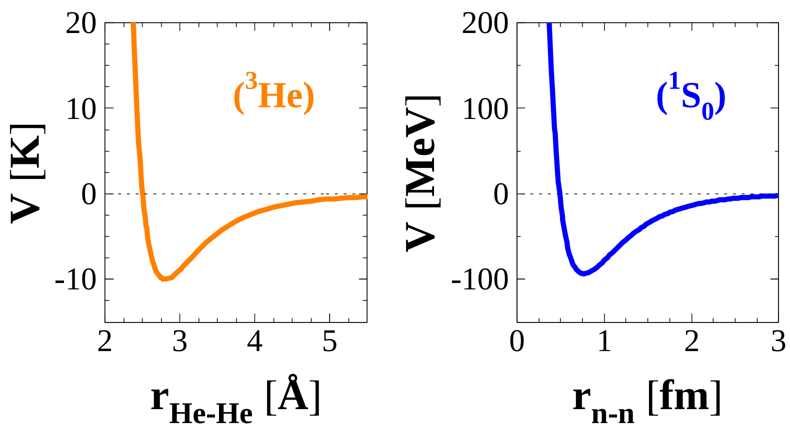
- Well-established facts :
  - N = 2 (✘) · · · 10^{57} (✔)

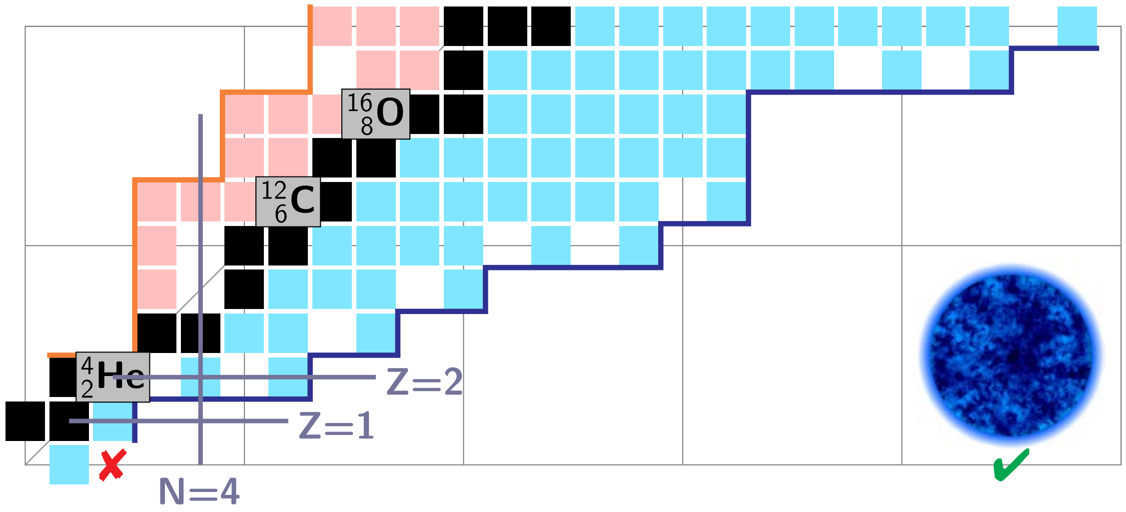
Multineutrons : Tetraneutrons ?



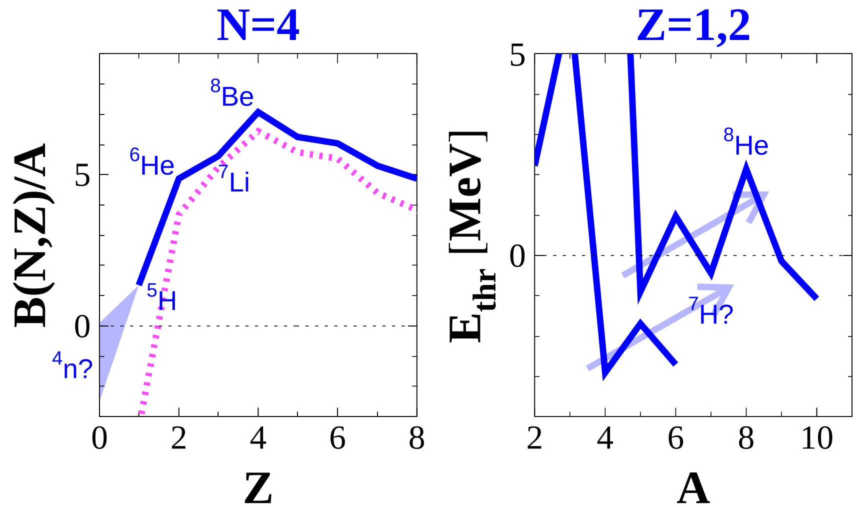
- Well-established facts :
  - N = 2 (✘) · · · 10^{57} (✔)
  - $(^3He)_2$ (✘) · · · $(^3He)_N$ (✔) : N ∼ 30

Guardiola, PRL 84 (2000) 1144



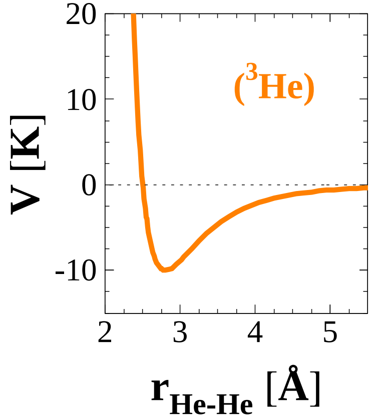


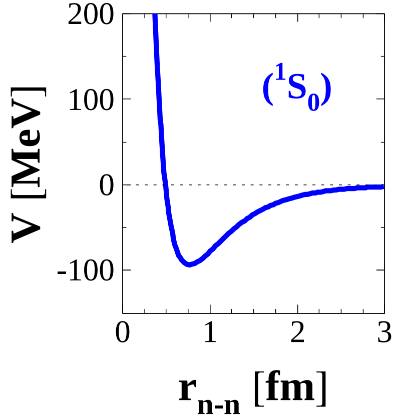
- Known $M(N,Z)$:



- Well-established facts :
  - N = 2 (✘) ··· 10^{57} (✔)
  - $(^{3}\mathrm{He})_2$ (✘) ··· $(^{3}\mathrm{He})_N$ (✔) : N ∼ 30

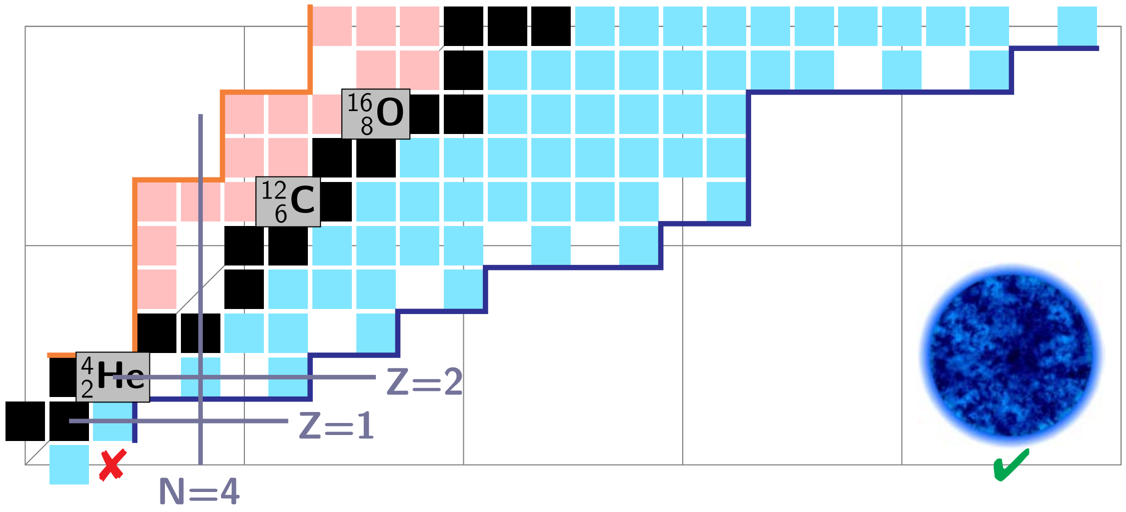
Guardiola, PRL 84 (2000) 1144





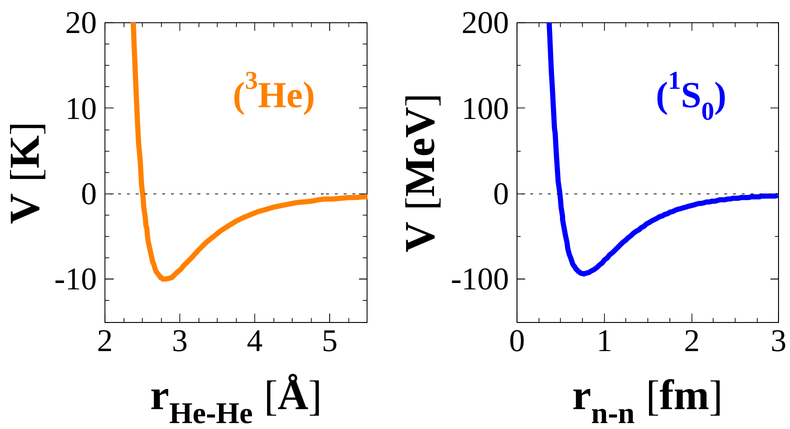
- $B(^{5}\mathrm{H}) > 0$! $[M(4,1) < 4m_n + m_p]$
- LD$(N \neq Z)$?

Multineutrons : Tetraneutrons ?

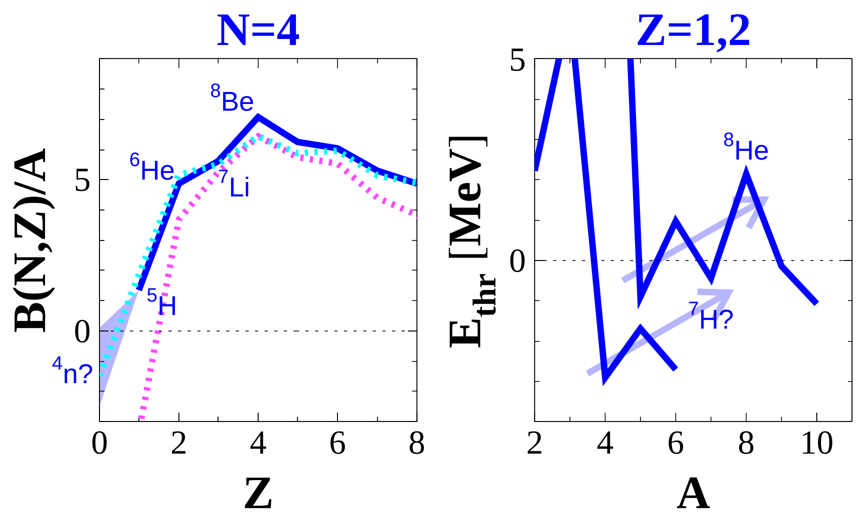


- Well-established facts :
  - N = 2 (✘) ··· 10^{57} (✔)
  - (^{3}He)$_2$ (✘) ··· (^{3}He)$_N$ (✔) : N ∼ 30

Guardiola, PRL 84 (2000) 1144

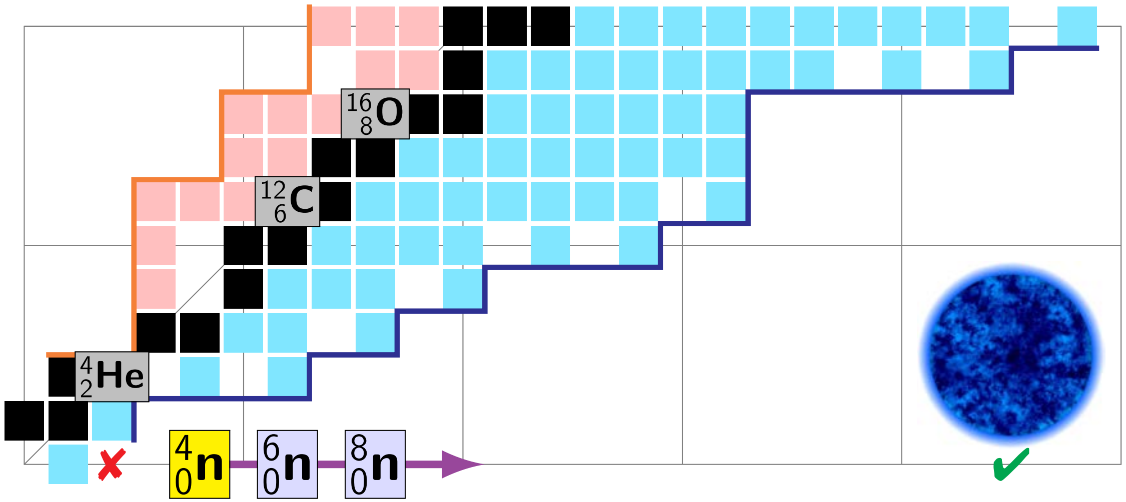


- Known $M(N, Z)$:



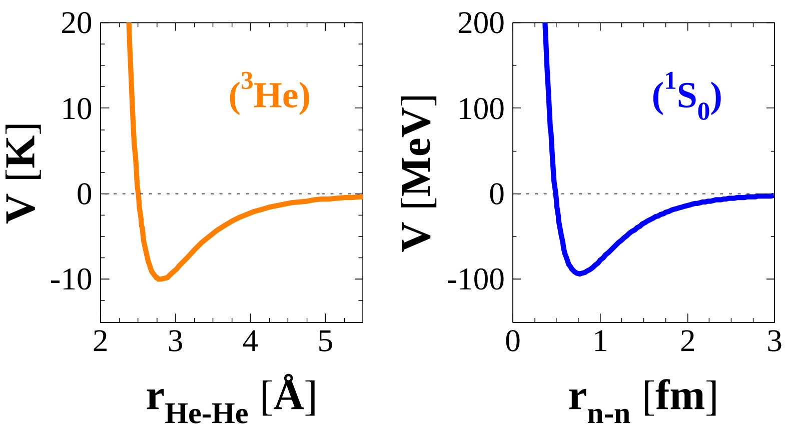
- $B(^5\mathrm{H}) > 0$! $[M(4,1) < 4m_n + m_p]$
- LD$(N \neq Z)$? LD with surface-corr. a_a ...
- "multineutron anomaly" ?

Multineutrons : Tetraneutrons ?

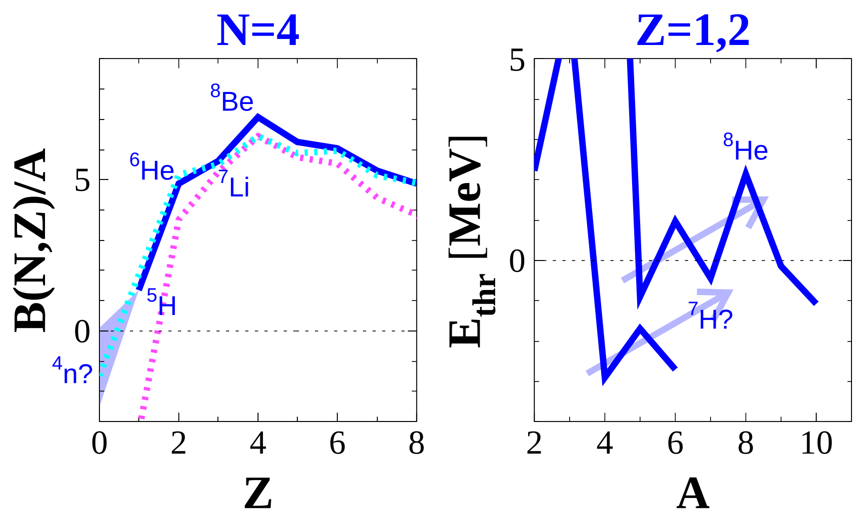


- Well-established facts :
  - N = 2 (✘) ··· 10^{57} (✔)
  - $(^3\mathrm{He})_2$ (✘) ··· $(^3\mathrm{He})_N$ (✔) : N ∼ 30

Guardiola, PRL 84 (2000) 1144

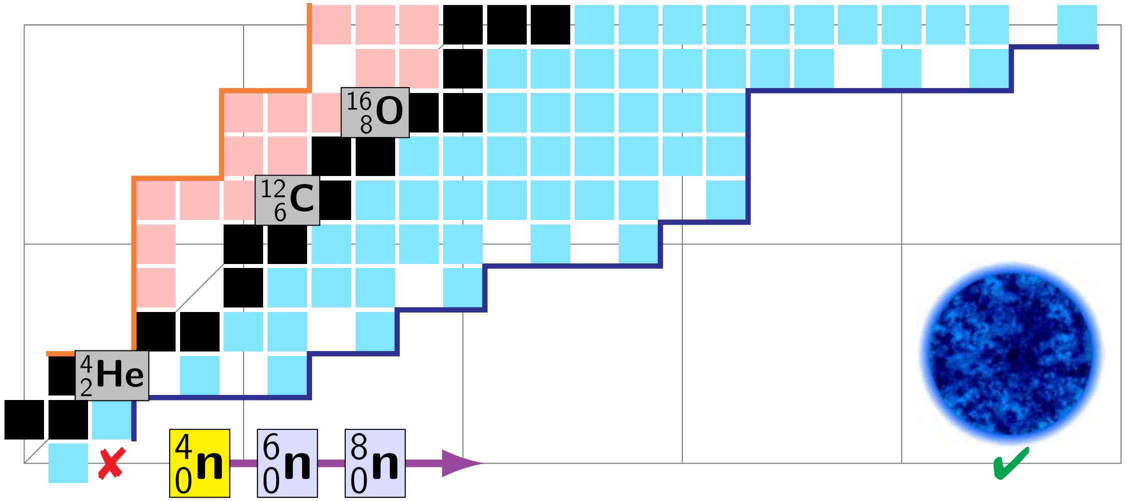


- Known $M(N,Z)$:

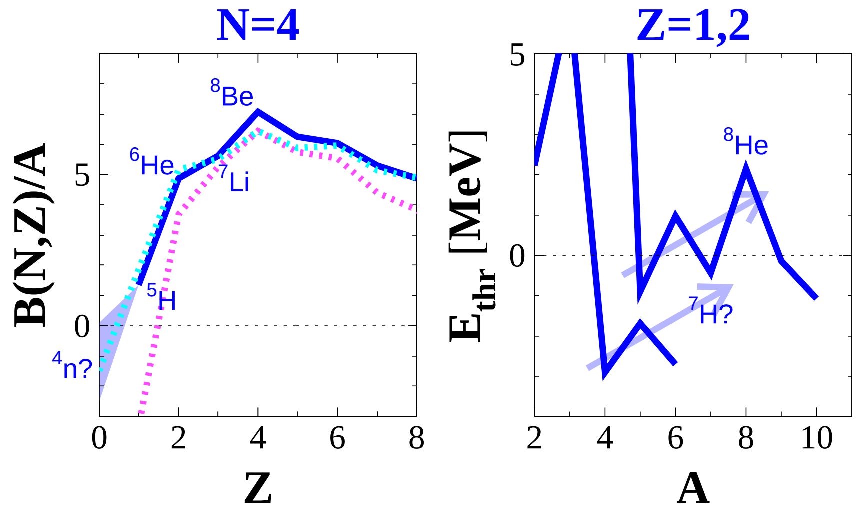


- $B(^5\mathrm{H}) > 0$! $[M(4,1) < 4m_n + m_p]$
- LD$(N \neq Z)$? LD with surface-corr. a_a ...
- "multineutron anomaly" ?
- even neutron numbers : $^{4}_{0}$n

Multineutrons : Tetraneutrons ?



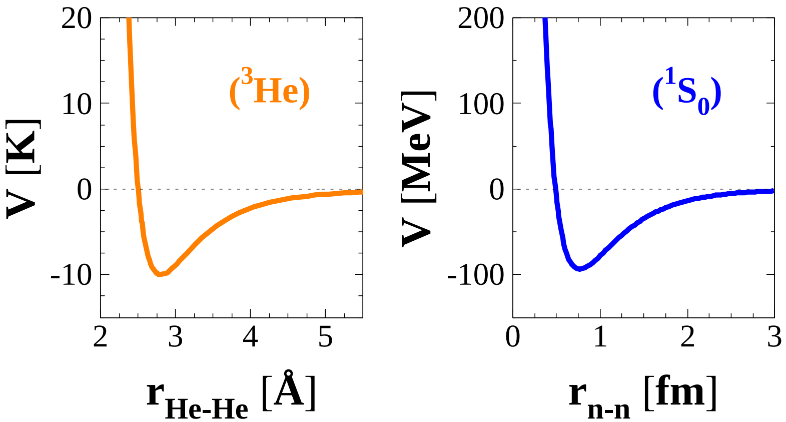
▶ Known $M(N,Z)$:



▶ Well-established facts :

- N = 2 (✘) ··· 10^{57} (✔)
- $(^3\text{He})_2$ (✘) ··· $(^3\text{He})_N$ (✔) : N ∼ 30

Guardiola, PRL 84 (2000) 1144



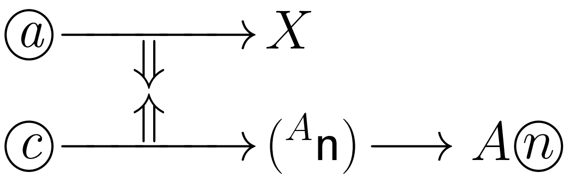
- $B(^5\text{H}) > 0$! $[M(4,1) < 4m_n + m_p]$
- LD$(N \neq Z)$? LD with surface-corr. a_a ...
- "multineutron anomaly" ?
- even neutron numbers : $^{4}_{0}$n

▶ Two important issues :

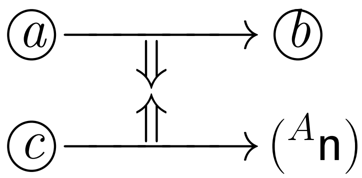
- production (unstable)
- detection (extremely low ε)

Multineutron experiments & probes

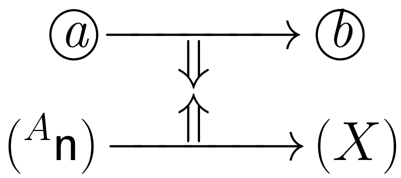
neutron detection



missing mass

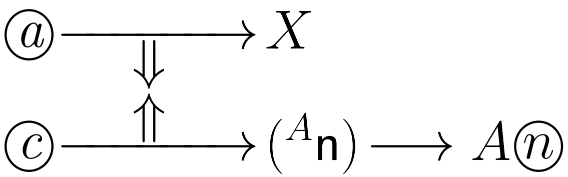


two step



Multineutron experiments & probes

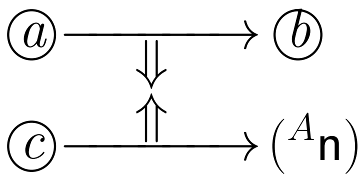
neutron detection



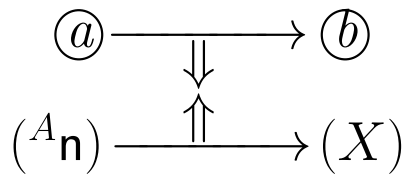
- ✔ unambiguous detection
- ✔ breakup or resonant decay
- ✔ neutron correlations
- ✘ extremely low efficiency

3 experiments

missing mass



two step



neutron detection

$$\textcircled{a} \longrightarrow X$$
$$\Downarrow \Uparrow$$
$$\textcircled{c} \longrightarrow (^{A}\mathsf{n}) \longrightarrow A\textcircled{n}$$

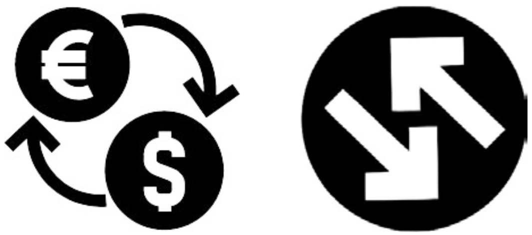
- ✔ unambiguous detection
- ✔ breakup or resonant decay
- ✔ neutron correlations
- ✘ extremely low efficiency

3 experiments

missing mass

$$\textcircled{a} \longrightarrow \textcircled{b}$$
$$\Downarrow \Uparrow$$
$$\textcircled{c} \longrightarrow (^{A}\mathsf{n})$$

- ✔ detection of 1 charged particle
- ✔ both bound & resonant states
- ✔ mass number well defined
- ✘ insensitive to internal structure
- ✘ cross-section of all protons into $\textcircled{b}$
- ✘ beam/target contaminant $\neq \textcircled{a}/\textcircled{c}$



24 experiments

two step

$$\textcircled{a} \longrightarrow \textcircled{b}$$
$$\Downarrow \Uparrow$$
$$(^{A}\mathsf{n}) \longrightarrow (X)$$

neutron detection

$$\begin{array}{l} ⓐ \longrightarrow X \\ \quad\Downarrow\Uparrow \\ ⓒ \longrightarrow (^A\mathrm{n}) \longrightarrow A ⓝ \end{array}$$

- ✔ unambiguous detection
- ✔ breakup or resonant decay
- ✔ neutron correlations
- ✘ extremely low efficiency


3 experiments

missing mass

$$\begin{array}{l} ⓐ \longrightarrow ⓑ \\ \quad\Downarrow\Uparrow \\ ⓒ \longrightarrow (^A\mathrm{n}) \end{array}$$

- ✔ detection of 1 charged particle
- ✔ both bound & resonant states
- ✔ mass number well defined
- ✘ insensitive to internal structure
- ✘ cross-section of all protons into ⓑ
- ✘ beam/target contaminant $\neq$ ⓐ/ⓒ


24 experiments

two step

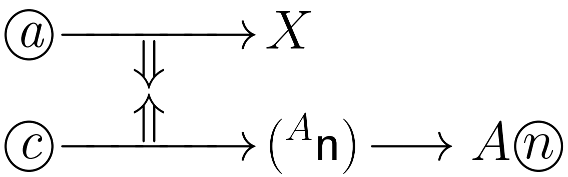
$$\begin{array}{l} ⓐ \longrightarrow ⓑ \\ \quad\Downarrow\Uparrow \\ (^A\mathrm{n}) \longrightarrow (X) \end{array}$$

- ✔ detection of 1 charged particle
- ✘ only bound states in second step
- ✘ insensitive to the energy
- ✘ only lower limit of A inferred
- ✘ contaminant $\neq$ ⓐ can lead to ⓑ
- ✘ uncontrolled previous step generates huge background, that may lead to ⓑ


7 experiments

Multineutron experiments & probes

neutron detection



- ✔ unambiguous detection
- ✔ breakup or resonant decay
- ✔ neutron correlations
- ✘ extremely low efficiency

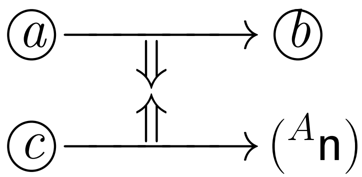
3 experiments

FMM, PRC 65 (2002) 044006

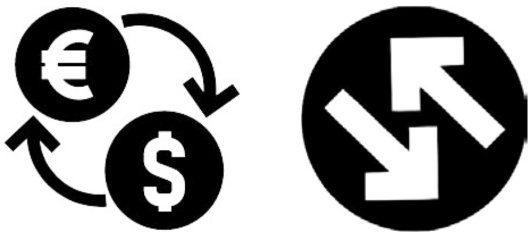
Brill, PL 12 (1964) 51

Bystritsky, NIM A834 (2016) 164

missing mass



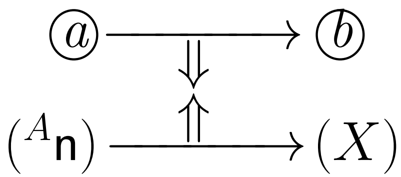
- ✔ detection of 1 charged particle
- ✔ both bound & resonant states
- ✔ mass number well defined
- ✘ insensitive to internal structure
- ✘ cross-section of all protons into ⓑ
- ✘ beam/target contaminant ≠ ⓐ/ⓒ



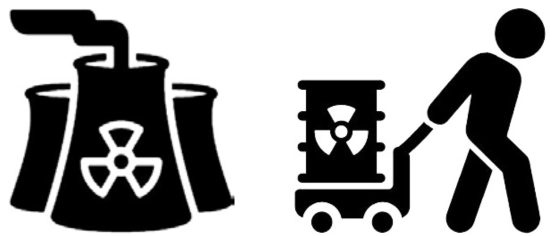
24 experiments

Kisamori, PRL 116 (2016) 052501

two step



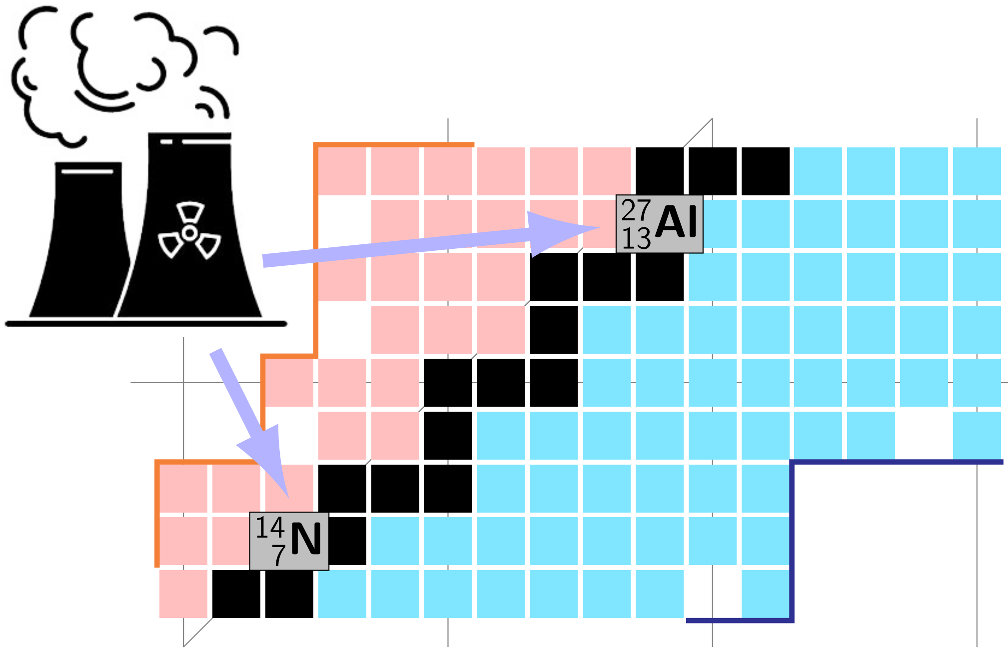
- ✔ detection of 1 charged particle
- ✘ only bound states in second step
- ✘ insensitive to the energy
- ✘ only lower limit of A inferred
- ✘ contaminant ≠ ⓐ can lead to ⓑ
- ✘ uncontrolled previous step generates huge background, that may lead to ⓑ



7 experiments

Détraz, PL 66B (1977) 333

The quest starts in a reactor



Volume 5, number 4 PHYSICS LETTERS 15 July 1963

SEARCH FOR A PARTICLE-STABLE TETRA NEUTRON

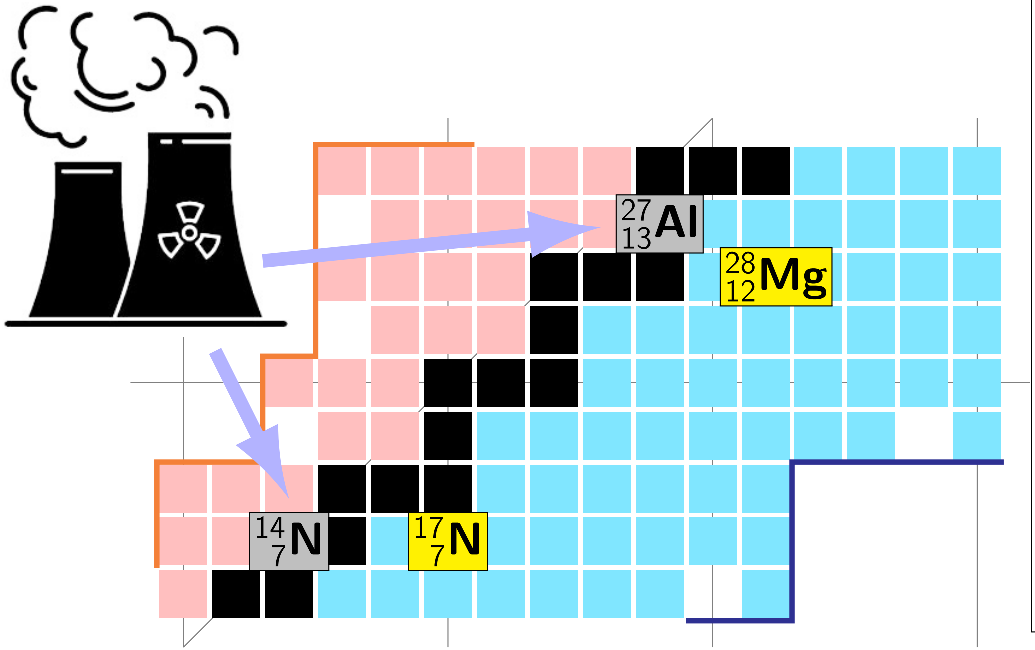
J. P. SCHIFFER and R. VANDENBOSCH
Argonne National Laboratory, Argonne, Illinois

It then seems reasonable that tetra neutrons should be observed inside nuclear reactors in locations where the absorption by nuclei in the moderator is negligible.

As in most experiments of this sort, however, a negative result cannot be regarded as conclusive and further experiments are needed to give additional weight to our result.

We are indebted to Professor R. H. Dalitz for calling this problem to our attention

The quest starts in a reactor



$\rightarrow$ $^{14}\text{N}(^{4}\text{n}, n)^{17}\text{N}$ ✘

$\rightarrow$ $^{27}\text{Al}(^{4}\text{n}, t)^{28}\text{Mg}$ ✘

Schiffer, PL 5 (1963) 292

Volume 5, number 4 PHYSICS LETTERS 15 July 1963

SEARCH FOR A PARTICLE-STABLE TETRA NEUTRON

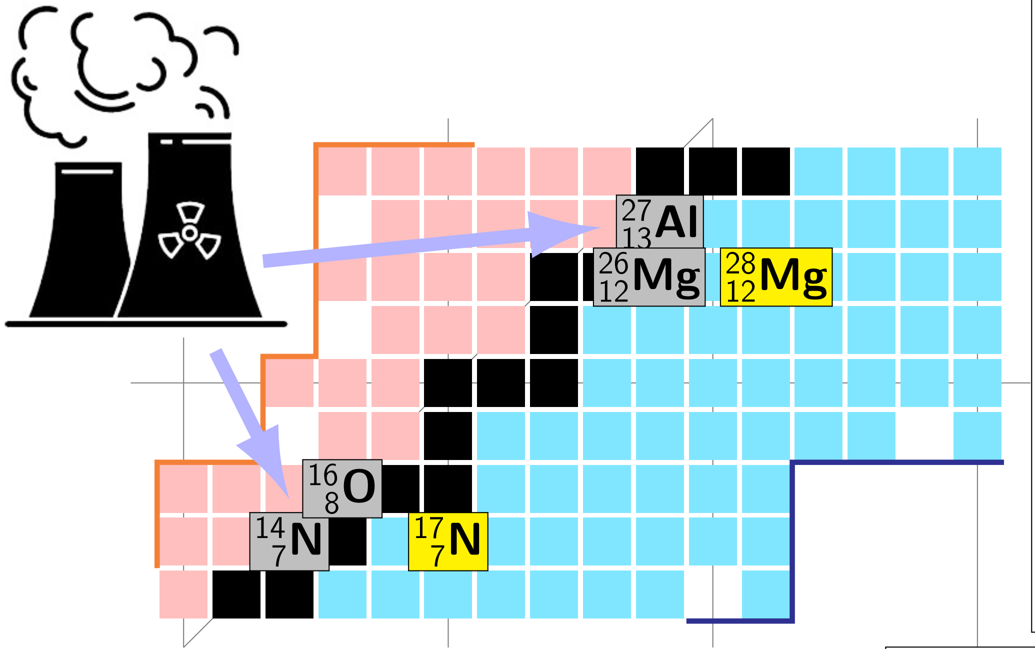
J. P. SCHIFFER and R. VANDENBOSCH
Argonne National Laboratory, Argonne, Illinois

It then seems reasonable that tetra neutrons should be observed inside nuclear reactors in locations where the absorption by nuclei in the moderator is negligible.

As in most experiments of this sort, however, a negative result cannot be regarded as conclusive and further experiments are needed to give additional weight to our result.

We are indebted to Professor R. H. Dalitz for calling this problem to our attention

The quest starts in a reactor



→ $^{14}\text{N}(^{4}\text{n}, n)^{17}\text{N}$ ✘

→ $^{27}\text{Al}(^{4}\text{n}, t)^{28}\text{Mg}$ ✘

Schiffer, PL 5 (1963) 292

→ $^{16}\text{O}(^{4}\text{n}, t)^{17}\text{N}$ ✘

→ $^{26}\text{Mg}(^{4}\text{n}, 2n)^{28}\text{Mg}$ ✘

Cierjacks, PR 137 (1965) B345

Volume 5, number 4 PHYSICS LETTERS 15 July 1963

SEARCH FOR A PARTICLE-STABLE TETRA NEUTRON

J. P. SCHIFFER and R. VANDENBOSCH
Argonne National Laboratory, Argonne, Illinois

It then seems reasonable that tetra neutrons should be observed inside nuclear reactors in locations where the absorption by nuclei in the moderator is negligible.

As in most experiments of this sort, however, a negative result cannot be regarded as conclusive and further experiments are needed to give additional weight to our result.

We are indebted to Professor R. H. Dalitz for calling this problem to our attention

PHYSICAL REVIEW VOLUME 137, NUMBER 2B 25 JANUARY 1965

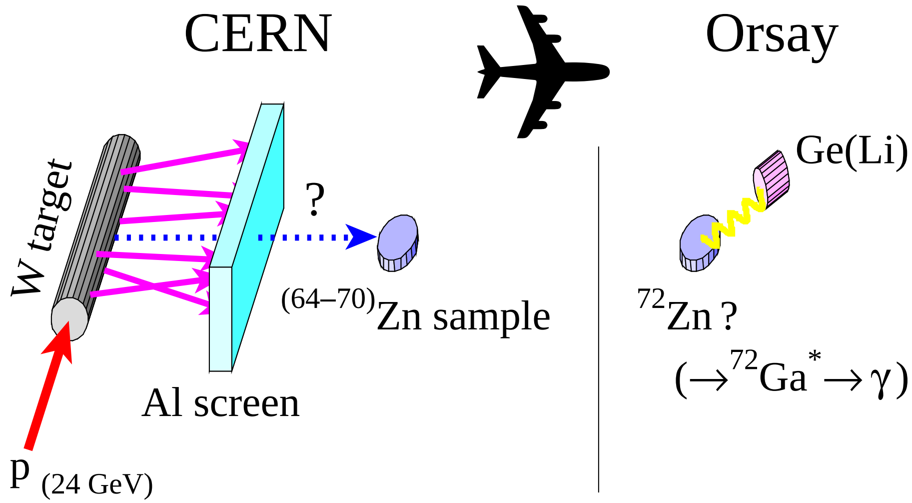
Further Evidence for the Nonexistence of Particle-Stable Tetraneutrons

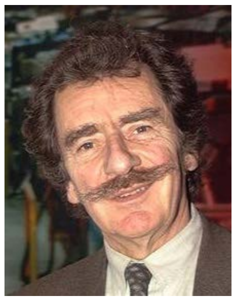
S. CIERJACKS, G. MARKUS, W. MICHAELIS, AND W. PÖNITZ
Institut für Angewandte Kernphysik, Kernforschungszentrum Karlsruhe, Karlsruhe, Germany

A search for tetraneutrons in the thermal-fission process had a negative result.[8] If tetraneutrons exist at all, the yield in the fast deuteron-induced fission is expected to be about two orders of magnitude higher than in thermal fission. This assumption is reasonable because of the much higher yield of alphas and tritons.[16]

Considering the absence of a Coulomb barrier for the tetraneutron, this particle should occur with a frequency comparable with that of alphas and tritons in spite of the much lower binding energy.[8] Therefore, it seems reasonable to conclude from Table I that the existence of tetraneutrons is most unlikely.

The quest ends at Orsay ?





$\rightarrow\ ^{64-70}\mathrm{Zn}(^{A}\mathrm{n}, xn)^{72}\mathrm{Zn}$?

Détraz, PL 66B (1977) 333

Volume 66B, number 4 PHYSICS LETTERS 14 February 1977

POSSIBLE EXISTENCE OF BOUND NEUTRAL NUCLEI

Claude DETRAZ
Institut de Physique Nucléaire, BP 1, 91406 Orsay, France

Two neutrons cannot form a bound nuclear system. That does not necessarily imply that several neutrons cannot constitute a bound nucleus. Unfortunately, the neutron-neutron interaction is not known so far with enough precision as to allow a reliable prediction of the binding energy of the lowest state of a multi-neutron system.

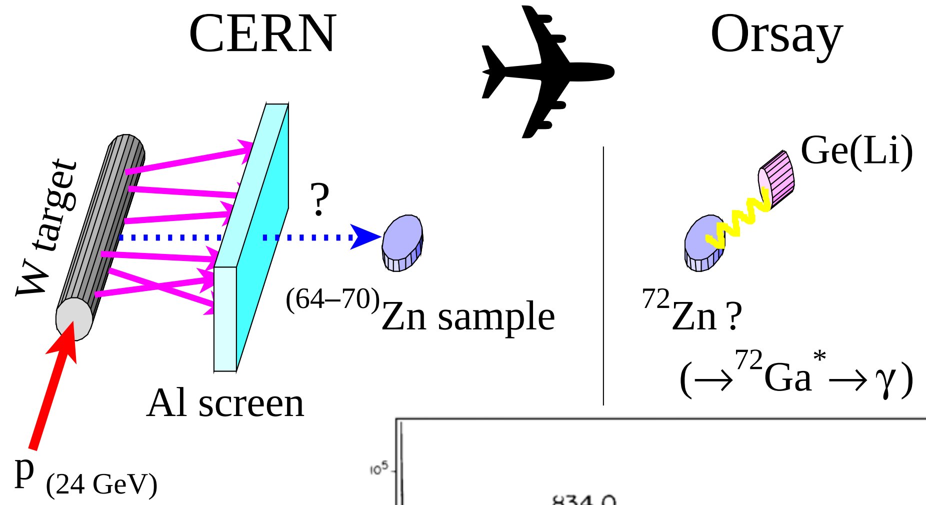
None of the experimental searches for bound nuclei of three neutrons [5] or four neutrons [6] were finally successful. Furthermore, the upper limits for the cross sections of the processes in which ^{3}n or ^{4}n could have been formed appear small enough to indicate that neither of these nuclei actually exists

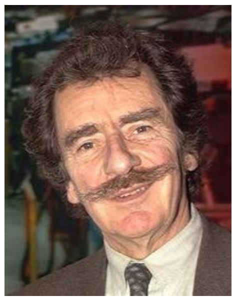
This paper reports a search for neutral nuclei heavier than those which were looked for so far. This requests an a-priori abundant source of nuclei such as ^{6}n or ^{8}n, and means of detecting them as efficiently as possible.

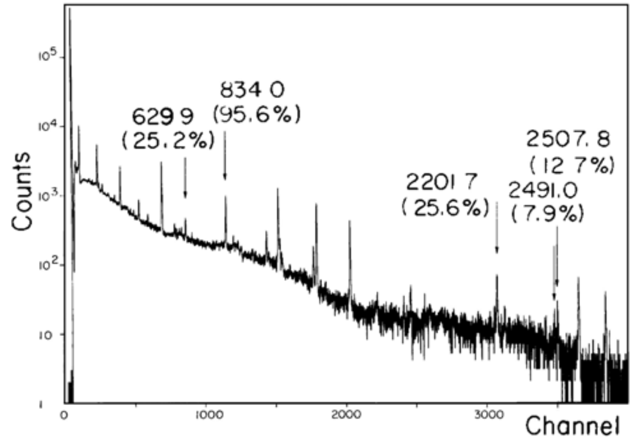
In view of the apparent failure of more conventional explanations, it is suggested that the observation of ^{72}Zn provides tentative evidence for the existence of bound neutral nuclei

up to mass 9. If ^{4}n is unbound [6], ^{8}n and to a lesser degree ^{6}n appear to be the most likely candidates

The quest ends at Orsay ?







$\rightarrow$ $^{64-70}\text{Zn}(^{A}\text{n}, xn)^{72}\text{Zn}$ ✔

Détraz, PL 66B (1977) 333

Volume 66B, number 4 PHYSICS LETTERS 14 February 1977

POSSIBLE EXISTENCE OF BOUND NEUTRAL NUCLEI

Claude DETRAZ

Institut de Physique Nucléaire, BP 1, 91406 Orsay, France

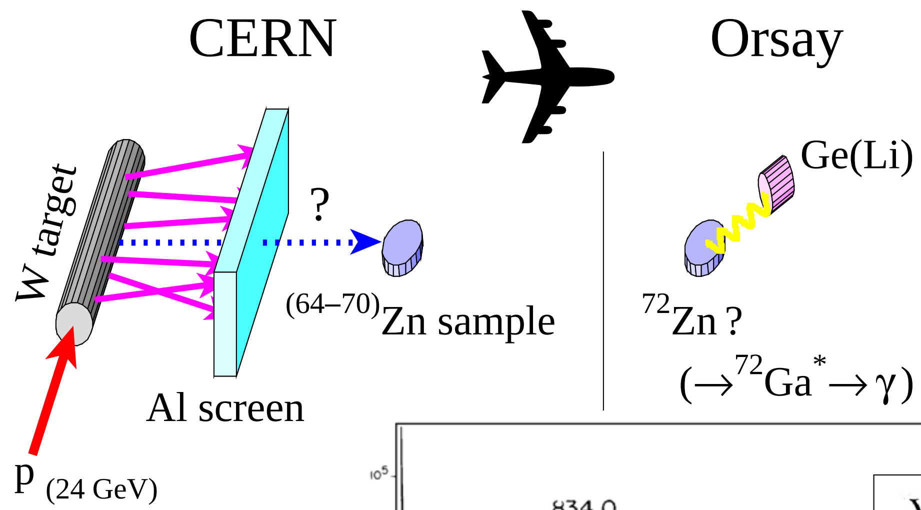
Two neutrons cannot form a bound nuclear system. That does not necessarily imply that several neutrons cannot constitute a bound nucleus. Unfortunately, the neutron-neutron interaction is not known so far with enough precision as to allow a reliable prediction of the binding energy of the lowest state of a multi-neutron system.

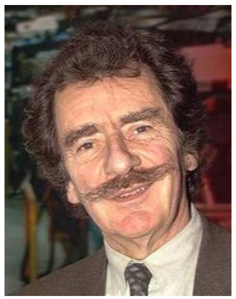
None of the experimental searches for bound nuclei of three neutrons [5] or four neutrons [6] were finally successful. Furthermore, the upper limits for the cross sections of the processes in which ^{3}n or ^{4}n could have been formed appear small enough to indicate that neither of these nuclei actually exists

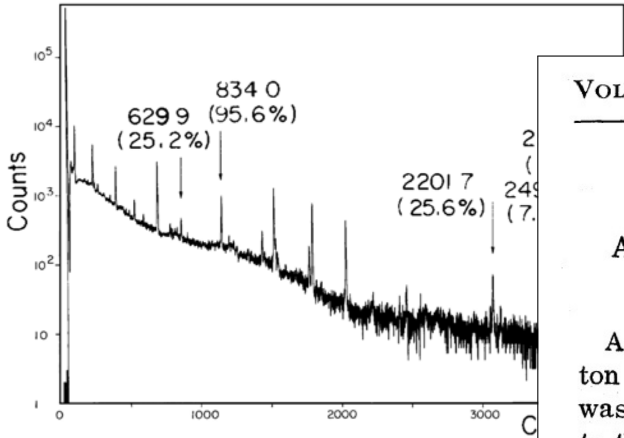
This paper reports a search for neutral nuclei heavier than those which were looked for so far. This requests an a-priori abundant source of nuclei such as ^{6}n or ^{8}n, and means of detecting them as efficiently as possible.

In view of the apparent failure of more conventional explanations, it is suggested that the observation of ^{72}Zn provides tentative evidence for the existence of bound neutral nuclei

up to mass 9. If ^{4}n is unbound [6], ^{8}n and to a lesser degree ^{6}n appear to be the most likely candidates







→ $^{64-70}$Zn(^{A}n, xn)^{72}Zn ✔

Détraz, PL 66B (1977) 333

→ [p+U] ^{208}Pb(^{A}n, xn)^{212}Pb ✘

Turkevich, PRL 38 (1977) 1129

Volume 66B, number 4 PHYSICS LETTERS 14 February 1977

POSSIBLE EXISTENCE OF BOUND NEUTRAL NUCLEI

Claude DETRAZ

Institut de Physique Nucléaire, BP 1, 91406 Orsay, France

Two neutrons cannot form a bound nuclear system. That does not necessarily imply that several neutrons cannot constitute a bound nucleus. Unfortunately, the neutron-neutron interaction is not known so far with enough precision as to allow a reliable prediction of

VOL 38, NUM 20 PHYSICAL REVIEW LETTERS 16 MAY 1977

Search for Particle-Bound Polyneutron Systems

Anthony Turkevich, James R. Cadieux, John Warren, Thanasis Economou, Jerome La Rosa, and H. Roland Heydegger

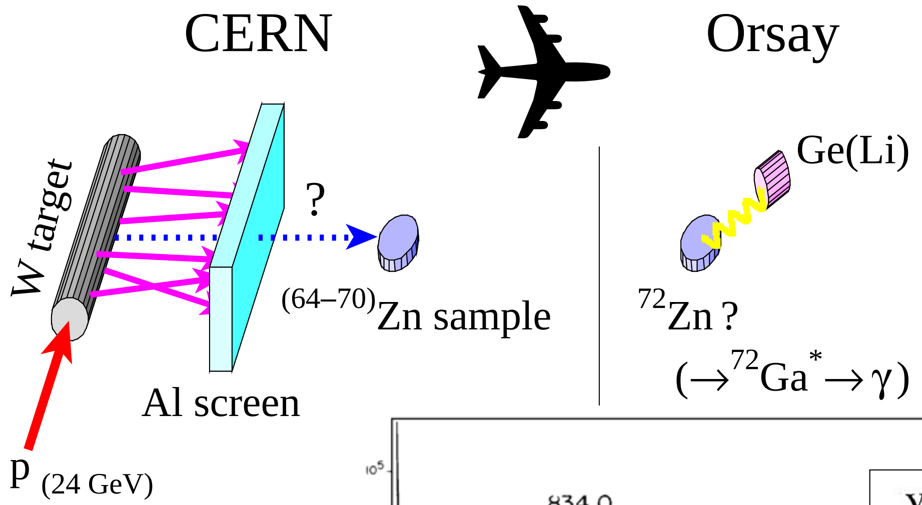
A search for particle-bound polyneutron systems (^{6}n–^{12}n) produced in ~ 700-MeV proton interactions with uranium has yielded negative results. A radiochemical technique was used. The limits on production cross section —10^{-3} to 10^{-5} μb— are in contrast to the positive results reported recently from work with 24-GeV protons on tungsten.

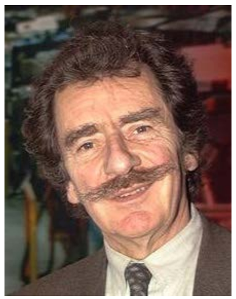
Thus Detraz's polyneutrons either have x = 4, to which the present experiment is insensitive, or their production has an exceedingly steep energy dependence.

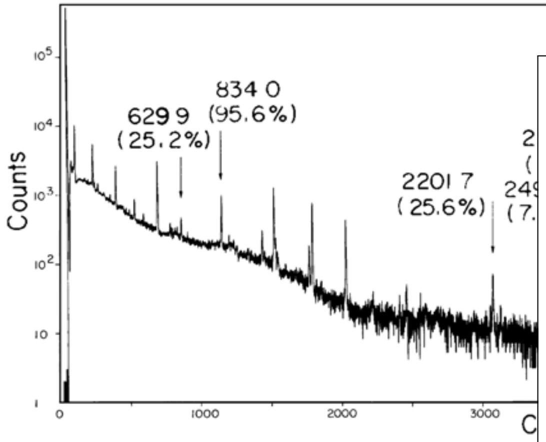
al explanations, it is suggested that the observation of ^{72}Zn provides tentative evidence for the existence of bound neutral nuclei

up to mass 9. If ^{4}n is unbound [6], ^{8}n and to a lesser degree ^{6}n appear to be the most likely candidates

The quest ends at Orsay ?







→ $^{64-70}\mathrm{Zn}(^{A}\mathrm{n}, xn)^{72}\mathrm{Zn}$ ✔

Détraz, PL 66B (1977) 333

→ $[p+\mathrm{U}]\ ^{208}\mathrm{Pb}(^{A}\mathrm{n}, xn)^{212}\mathrm{Pb}$ ✘

Turkevich, PRL 38 (1977) 1129

→ $[^{3}\mathrm{He}+\mathrm{Te}]\ ^{130}\mathrm{Te}(^{4}\mathrm{n}, 2n)^{132}\mathrm{Te}$ ✘

de Boer, NP A350 (1980) 149

Volume 66B, number 4 PHYSICS LETTERS 14 February 1977

POSSIBLE EXISTENCE OF BOUND NEUTRAL NUCLEI

Claude DETRAZ

Institut de Physique Nucléaire, BP 1, 91406 Orsay, France

Two neutrons cannot form a bound nuclear system. That does not necessarily imply that several neutrons cannot constitute a bound nucleus. Unfortunately, the neutron-neutron interaction is not known so far with enough precision as to allow a reliable prediction of

VOL 38, NUM 20 PHYSICAL REVIEW LETTERS 16 MAY 1977

Search for Particle-Bound Polyneutron Systems

Anthony Turkevich, James R. Cadieux, John Warren, Thanasis Economou, Jerome La Rosa, and H. Roland Heydegger

A search for particle-bound polyneutron systems (^{6}n–^{12}n) produced in ~ 700-MeV proton interactions with uranium has yielded negative results. A radiochemical technique

Nuclear Physics **A350** (1980) 149–156 © *North-Holland Publishing Co., Amsterdam*

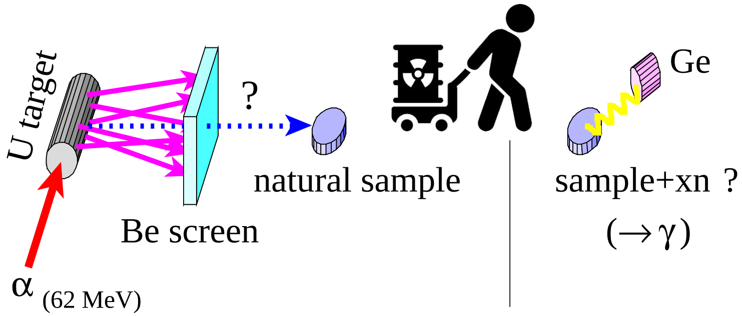
THE TETRANEUTRON REVISITED

F.W.N. DE BOER
J.J. VAN RUYVEN, A.W.B. KALSHOVEN and R. VIS
E. SUGARBAKER, C. FIELDS and C.S. ZAIDINS

It seems likely that secondary tritons produced in the (p + W) interactions, with the subsequently induced (t, p) reactions in the detection target, must account for Détraz results. Although shielding against charged fragmentation products had been applied, the number of highly energetic tritons has probably been underestimated [25].

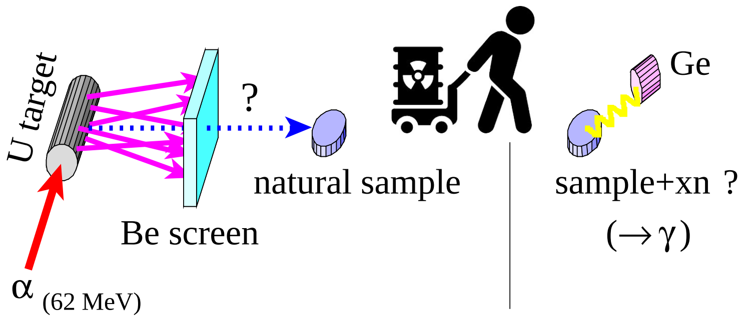
Super-heavy multineutrons ?

Kurchatov Institute



Super-heavy multineutrons ?

Kurchatov Institute



ISSN 0021-3640, JETP Letters, 2012, Vol. 96, No. 5, pp. 280–284. © Pleiades Publishing, Inc., 2012.

Possible Observation of Light Neutron Nuclei in the Alpha-Particle-Induced Fission of ^{238}U

B. G. Novatsky, E. Yu. Nikolsky, S. B. Sakuta, and D. N. Stepanov
National Research Centre Kurchatov Institute, pl. Akademika Kurchatova 1, Moscow, 123182 Russia

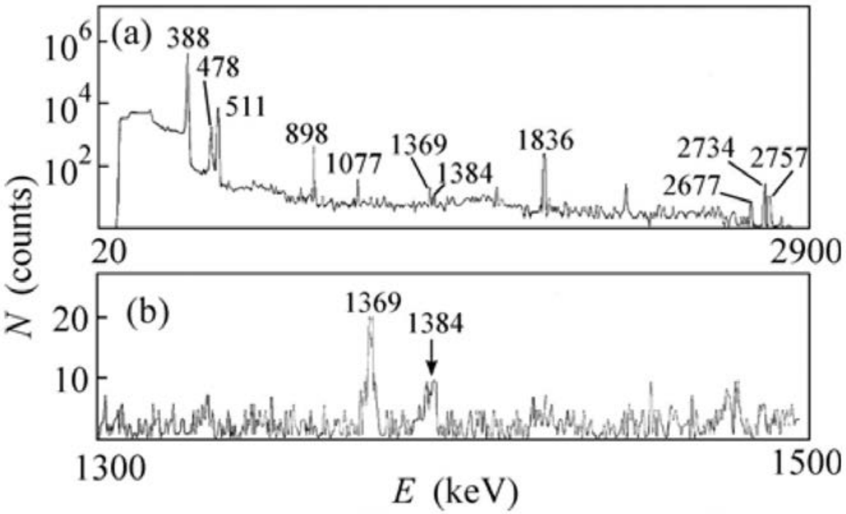
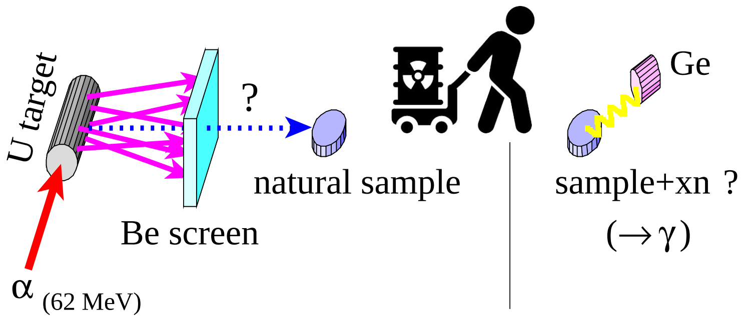


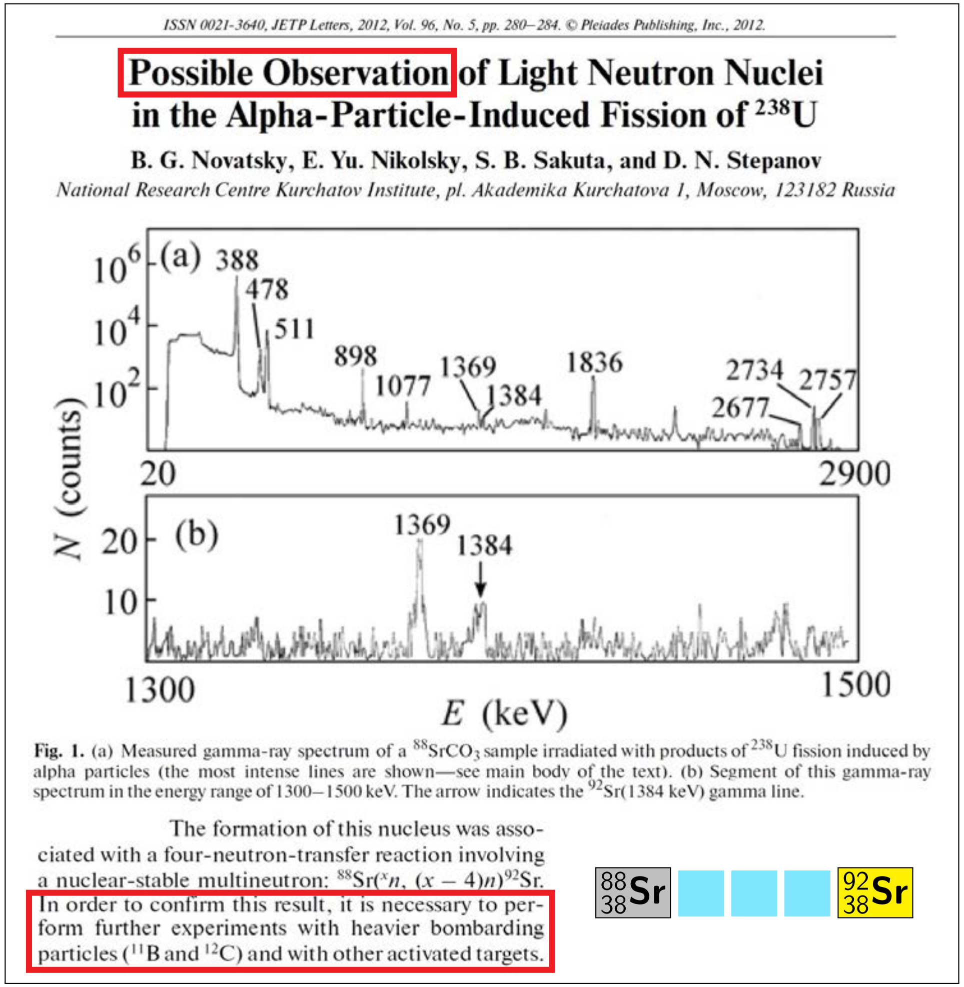
Fig. 1. (a) Measured gamma-ray spectrum of a $^{88}SrCO_3$ sample irradiated with products of ^{238}U fission induced by alpha particles (the most intense lines are shown—see main body of the text). (b) Segment of this gamma-ray spectrum in the energy range of 1300–1500 keV. The arrow indicates the ^{92}Sr(1384 keV) gamma line.

The formation of this nucleus was associated with a four-neutron-transfer reaction involving a nuclear-stable multineutron: ^{88}Sr(^{x}n, $(x-4)n$)^{92}Sr. In order to confirm this result, it is necessary to perform further experiments with heavier bombarding particles (^{11}B and ^{12}C) and with other activated targets.

$^{88}_{38}$Sr → $^{92}_{38}$Sr

Kurchatov Institute





ISSN 0021-3640, JETP Letters, 2012, Vol. 96, No. 5, pp. 280–284. © Pleiades Publishing, Inc., 2012.

Possible Observation of Light Neutron Nuclei in the Alpha-Particle-Induced Fission of ^{238}U

B. G. Novatsky, E. Yu. Nikolsky, S. B. Sakuta, and D. N. Stepanov
National Research Centre Kurchatov Institute, pl. Akademika Kurchatova 1, Moscow, 123182 Russia

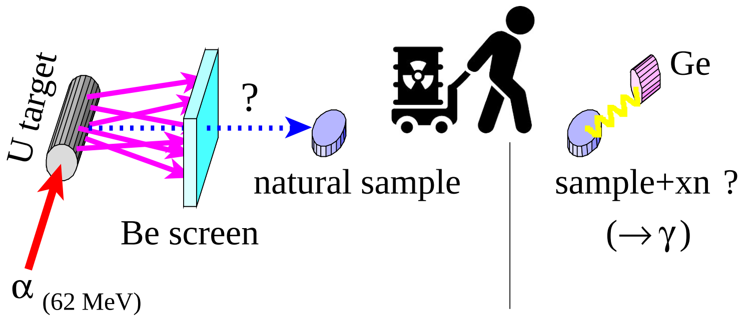
Fig. 1. (a) Measured gamma-ray spectrum of a $^{88}SrCO_3$ sample irradiated with products of ^{238}U fission induced by alpha particles (the most intense lines are shown—see main body of the text). (b) Segment of this gamma-ray spectrum in the energy range of 1300–1500 keV. The arrow indicates the ^{92}Sr(1384 keV) gamma line.

The formation of this nucleus was associated with a four-neutron-transfer reaction involving a nuclear-stable multineutron: $^{88}Sr(^{x}n, (x-4)n)^{92}Sr$. In order to confirm this result, it is necessary to perform further experiments with heavier bombarding particles (^{11}B and ^{12}C) and with other activated targets.

$^{88}_{38}Sr$ → $^{92}_{38}Sr$

Super-heavy multineutrons ?

Kurchatov Institute



ISSN 0021-3640, JETP Letters, 2012, Vol. 96, No. 5, pp. 280–284. © Pleiades Publishing, Inc., 2012.

Possible Observation of Light Neutron Nuclei in the Alpha-Particle-Induced Fission of ^{238}U

B. G. Novatsky, E. Yu. Nikolsky, S. B. Sakuta, and D. N. Stepanov
National Research Centre Kurchatov Institute, pl. Akademika Kurchatova 1, Moscow, 123182 Russia

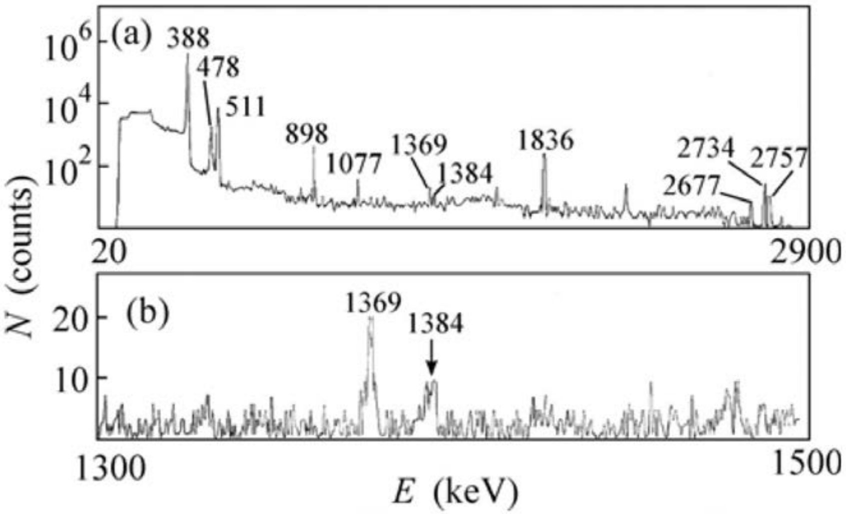


Fig. 1. (a) Measured gamma-ray spectrum of a $^{88}SrCO_3$ sample irradiated with products of ^{238}U fission induced by alpha particles (the most intense lines are shown—see main body of the text). (b) Segment of this gamma-ray spectrum in the energy range of 1300–1500 keV. The arrow indicates the ^{92}Sr(1384 keV) gamma line.

The formation of this nucleus was associated with a four-neutron-transfer reaction involving a nuclear-stable multineutron: ^{88}Sr(^{x}n, $(x-4)n$)^{92}Sr. In order to confirm this result, it is necessary to perform further experiments with heavier bombarding particles (^{11}B and ^{12}C) and with other activated targets.

$^{88}_{38}$Sr → $^{92}_{38}$Sr

ISSN 0021-3640, JETP Letters, 2013, Vol. 98, No. 11, pp. 656–660. © Pleiades Publishing, Inc., 2013.

Detection of Light Neutron Nuclei in the Alpha-Particle-Induced Fission of ^{238}U by the Activation Method with ^{27}Al

B. G. Novatsky, S. B. Sakuta*, and D. N. Stepanov
National Research Centre Kurchatov Institute, pl. Akademika Kurchatova 1, Moscow, 123182 Russia

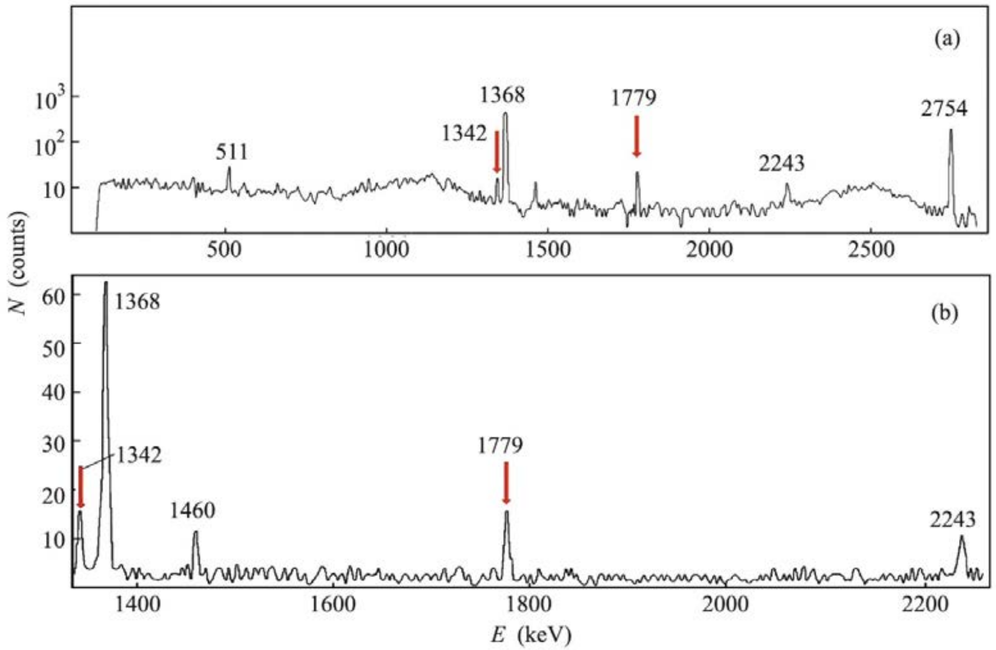


Fig. 2. (Color online) (a) Energy spectrum of gamma rays from the ^{27}Al sample that was irradiated by the products of alpha-particle-induced fission of the ^{238}U nucleus. (b) Fragment of this gamma-ray spectrum in the energy range of 1330–2250 keV. The arrows mark the 1342- and 1779-keV gamma lines from the beta decay of ^{28}Mg and ^{28}Al nuclei, respectively.

The results of two independent experiments indicate that nuclear-stable multineutrons (most likely, ^{6}n) are emitted from the alpha-particle-induced ternary fission of ^{238}U. In the future, we are going to improve the statistics of the measurements by increasing the intensity of the beam and irradiation time of sample.

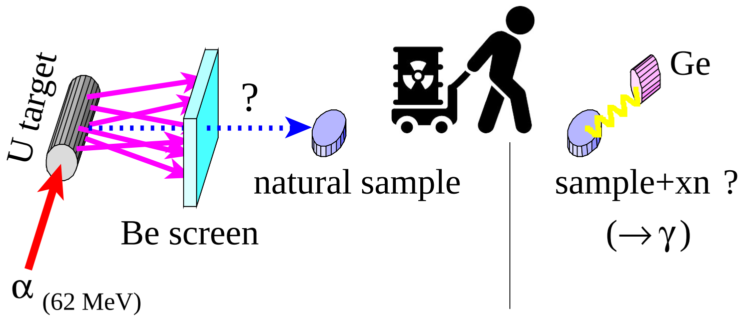
$^{27}_{13}$Al → $^{28}_{12}$Mg

Novatsky, JETPL 98-11 (2013) 656

Novatsky, JETPL 96-5 (2012) 280

Super-heavy multineutrons ?

Kurchatov Institute



ISSN 0021-3640, JETP Letters, 2012, Vol. 96, No. 5, pp. 280–284. © Pleiades Publishing, Inc., 2012.

Possible Observation of Light Neutron Nuclei in the Alpha-Particle-Induced Fission of ^{238}U

B. G. Novatsky, E. Yu. Nikolsky, S. B. Sakuta, and D. N. Stepanov
National Research Centre Kurchatov Institute, pl. Akademika Kurchatova 1, Moscow, 123182 Russia

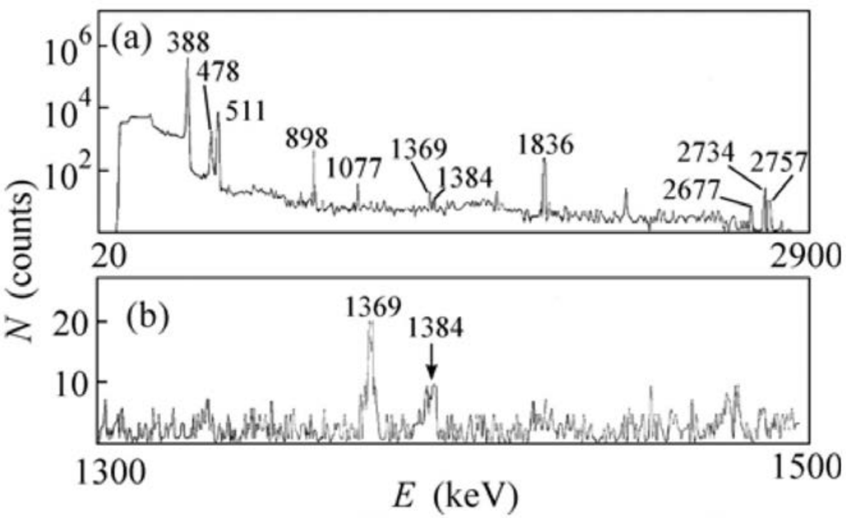


Fig. 1. (a) Measured gamma-ray spectrum of a $^{88}SrCO_3$ sample irradiated with products of ^{238}U fission induced by alpha particles (the most intense lines are shown—see main body of the text). (b) Segment of this gamma-ray spectrum in the energy range of 1300–1500 keV. The arrow indicates the ^{92}Sr(1384 keV) gamma line.

The formation of this nucleus was associated with a four-neutron-transfer reaction involving a nuclear-stable multineutron: $^{88}Sr(^{x}n, (x-4)n)^{92}Sr$. In order to confirm this result, it is necessary to perform further experiments with heavier bombarding particles (^{11}B and ^{12}C) and with other activated targets.

ISSN 0021-3640, JETP Letters, 2013, Vol. 98, No. 11, pp. 656–660. © Pleiades Publishing, Inc., 2013.

Detection of Light Neutron Nuclei in the Alpha-Particle-Induced Fission of ^{238}U by the Activation Method with ^{27}Al

B. G. Novatsky, S. B. Sakuta*, and D. N. Stepanov
National Research Centre Kurchatov Institute, pl. Akademika Kurchatova 1, Moscow, 123182 Russia

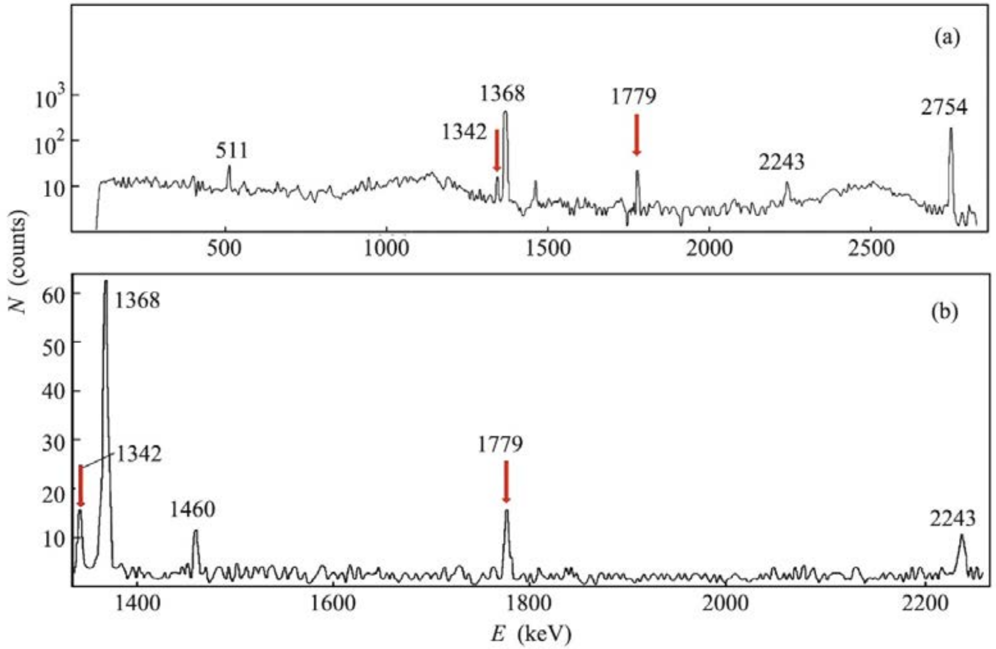
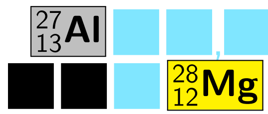


Fig. 2. (Color online) (a) Energy spectrum of gamma rays from the ^{27}Al sample that was irradiated by the products of alpha-particle-induced fission of the ^{238}U nucleus. (b) Fragment of this gamma-ray spectrum in the energy range of 1330–2250 keV. The arrows mark the 1342- and 1779-keV gamma lines from the beta decay of ^{28}Mg and ^{28}Al nuclei, respectively.

The results of two independent experiments indicate that nuclear-stable multineutrons (most likely, ^{6}n) are emitted from the alpha-particle-induced ternary fission of ^{238}U. In the future, we are going to improve the statistics of the measurements by increasing the intensity of the beam and irradiation time of sample.



Novatsky, JETPL 98-11 (2013) 656

Novatsky, JETPL 96-5 (2012) 280

Changing the charge of pion beams

$$^{3,4}\text{He}\,(\pi^-,\pi^+)\,^{3,4}n$$

(4n) Gilly, PL 19 (1965) 335

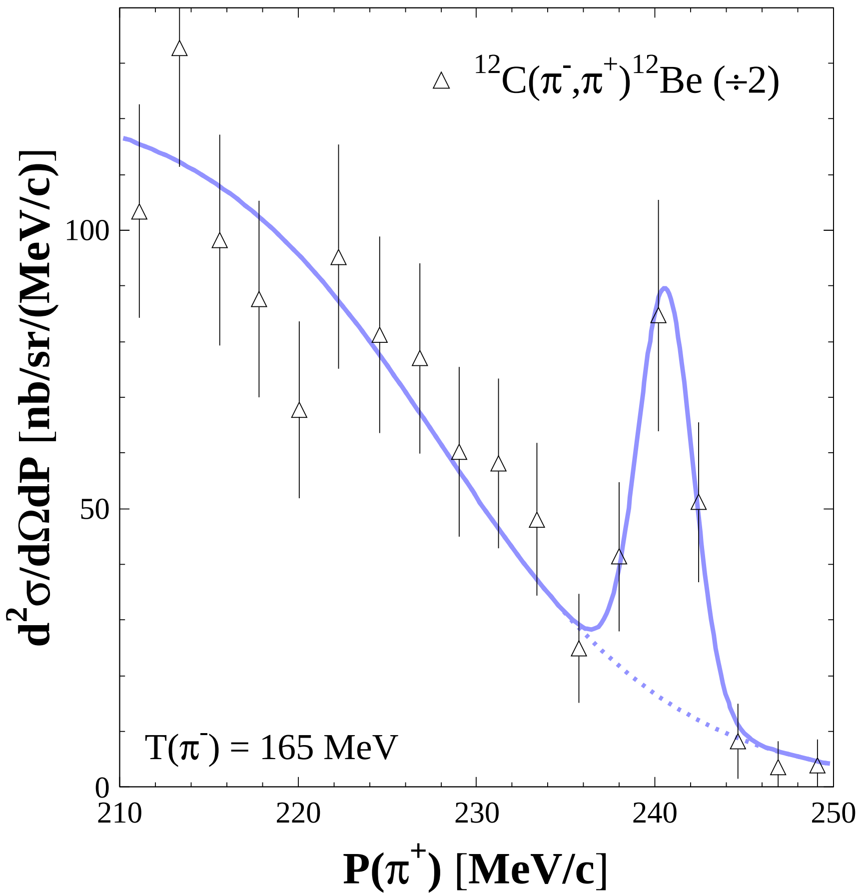
(3n) Sperinde, PL 32B (1970) 185

(3n) Sperinde, NP B78 (1974) 345

Changing the charge of pion beams

$^{3,4}\mathrm{He}\,(\pi^-, \pi^+)\, ^{3,4}n$

(4n) Gilly, PL 19 (1965) 335
(3n) Sperinde, PL 32B (1970) 185
(3n) Sperinde, NP B78 (1974) 345
(4n) Ungar, PL 144B (1984) 333 :



Changing the charge of pion beams

$^{3,4}\text{He}\,(\pi^-, \pi^+)\,^{3,4}\text{n}$

(4n) Gilly, PL 19 (1965) 335

(3n) Sperinde, PL 32B (1970) 185

(3n) Sperinde, NP B78 (1974) 345

(4n) Ungar, PL 144B (1984) 333 :

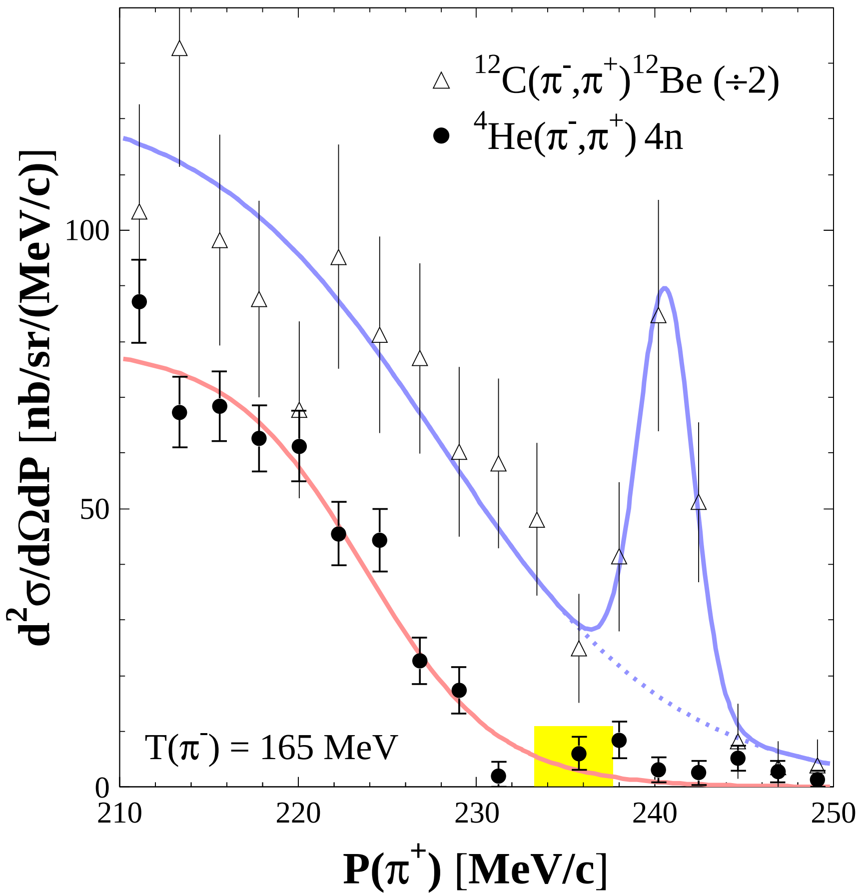
(3n) Jibuti, NP A437 (1985) 687

(3,4n) Stetz, NP A457 (1986) 669

(4n) Gorringe, PRC 40 (1989) 2390

(3n) Yuly, PRC 55 (1997) 1848

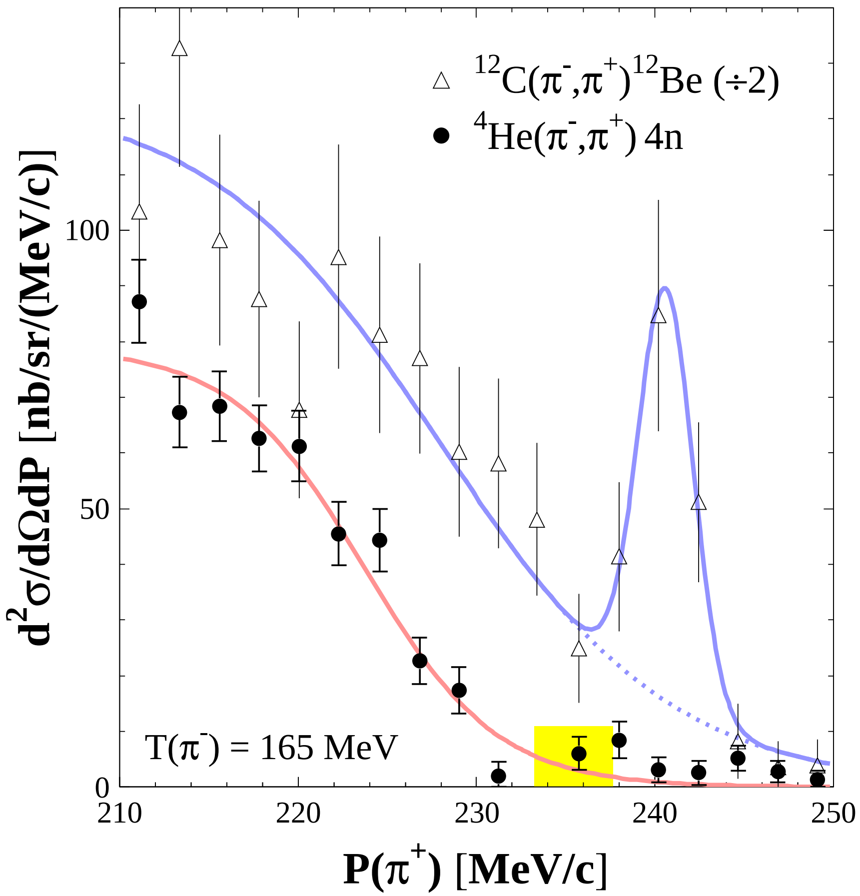
(3n) Gräter, EPJB 4 (1999) 5



Changing the charge of pion beams

$^{3,4}\mathrm{He}\,(\pi^-,\pi^+)\,^{3,4}\mathrm{n}$

(4n) Gilly, PL 19 (1965) 335
(3n) Sperinde, PL 32B (1970) 185
(3n) Sperinde, NP B78 (1974) 345
(4n) Ungar, PL 144B (1984) 333 :



(3n) Jibuti, NP A437 (1985) 687
(3,4n) Stetz, NP A457 (1986) 669
(4n) Gorringe, PRC 40 (1989) 2390
(3n) Yuly, PRC 55 (1997) 1848

(3n) Gräter, EPJB 4 (1999) 5

(4n) Chultem, NP A316 (1979) 290 :

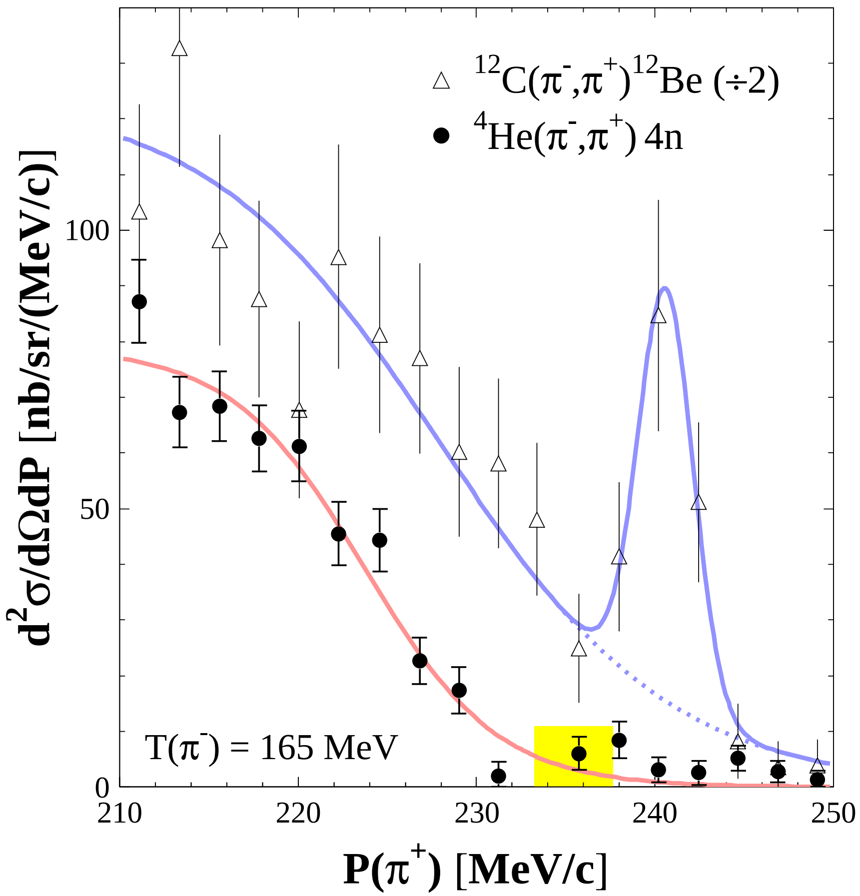
$$^{208}\mathrm{Pb}[\alpha]\,(\pi^-,\pi^+)\,^{4}\mathrm{n} \xrightarrow{(\mathrm{Pb})} {}^{212}\mathrm{Pb}$$ ✘

$$(\rightarrow {}^{212}\mathrm{Bi} \rightarrow {}^{212}\mathrm{Po})$$

Changing the charge of pion beams

^{3,4}He (π^-, π^+) ^{3,4}n

(4n) Gilly, PL 19 (1965) 335
(3n) Sperinde, PL 32B (1970) 185
(3n) Sperinde, NP B78 (1974) 345
(4n) Ungar, PL 144B (1984) 333 :



(3n) Jibuti, NP A437 (1985) 687
(3,4n) Stetz, NP A457 (1986) 669
(4n) Gorringe, PRC 40 (1989) 2390
(3n) Yuly, PRC 55 (1997) 1848

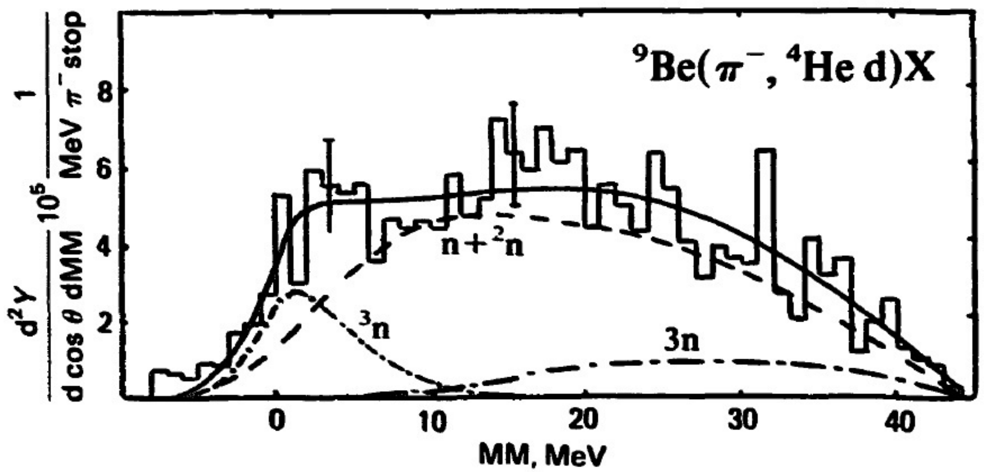
(3n) Gräter, EPJB 4 (1999) 5

(4n) Chultem, NP A316 (1979) 290 :

$$^{208}\text{Pb}[\alpha]\,(\pi^-,\pi^+)^4\text{n} \xrightarrow{(\text{Pb})} {}^{212}\text{Pb}$$ ✘

$(\rightarrow {}^{212}\text{Bi} \rightarrow {}^{212}\text{Po})$

(3n) Gornov, NP A531 (1991) 613 :



→ *"phase-space can lead to a distortion of the results"*

→ *"the rather poor experimental data"* ...

Searching for trineutrons into the light : $^3H(\pi^-, \gamma)$

VOLUME 36, NUMBER 16 PHYSICAL REVIEW LETTERS 19 APRIL 1976

Photon Spectrum in Pion Capture on Tritium*

J. A. Bistirlich, S. Cooper, K. M. Crowe, and F. T. Shively†
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
E. R. Grilly, J. P. Perroud,‡ and R. H. Sherman
Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545
H. W. Baer§
Case Western Reserve University, Cleveland, Ohio 44106
P. Truöl
Physik-Institut der Universität, Zürich, Switzerland

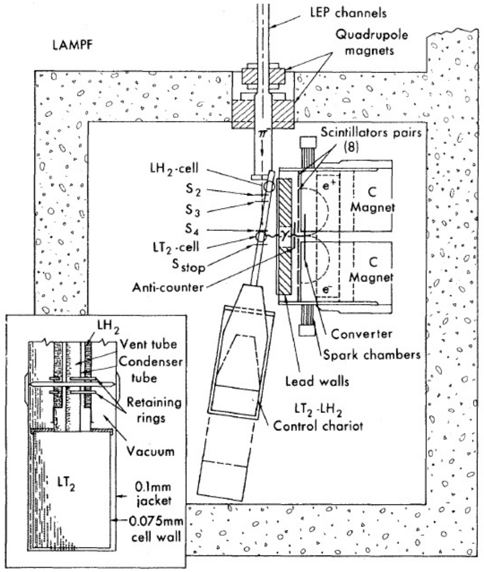


FIG. 1. The experimental setup at LAMPF showing the pair spectrometer and liquid-tritium target. The inset shows a cross section of the target cell obtained from an x-ray radiograph.

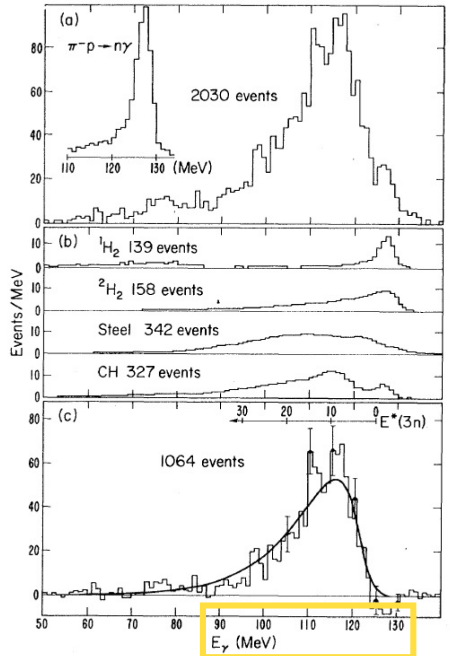


FIG. 2. (a) Raw photon spectrum obtained from the tritium target. The inset shows our resolution obtained at 129.4 MeV. (b) Background spectra for hydrogen, deuterium, steel, and CH. (c) Spectrum from reaction $\pi^- + {}^3\text{H} \to n + n + n + \gamma$ after subtraction of ^{1}H, ^{2}H, steel, and scintillator contributions. Solid curve is the theoretical spectrum of Phillips and Roig (Ref. 10) (see text), folded with acceptance and instrumental line shape and normalized to the total number of photons.

The overall fit to the data is satisfactory, although small excesses of events in the low-mass region $7 < E_x(3n) \lesssim 16$ MeV are observed. Considering the low statistics and uncertainty in background subtraction, it would be premature to regard this as evidence for a $T = \frac{3}{2}$ resonance

Searching for trineutrons into the light : $^{3}H(\pi^{-},\gamma)$

VOLUME 36, NUMBER 16 PHYSICAL REVIEW LETTERS 19 APRIL 1976

Photon Spectrum in Pion Capture on Tritium*

J. A. Bistirlich, S. Cooper, K. M. Crowe, and F. T. Shively†
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
E. R. Grilly, J. P. Perroud,‡ and R. H. Sherman
Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545
H. W. Baer§
Case Western Reserve University, Cleveland, Ohio 44106
P. Truöl
Physik-Institut der Universität, Zürich, Switzerland

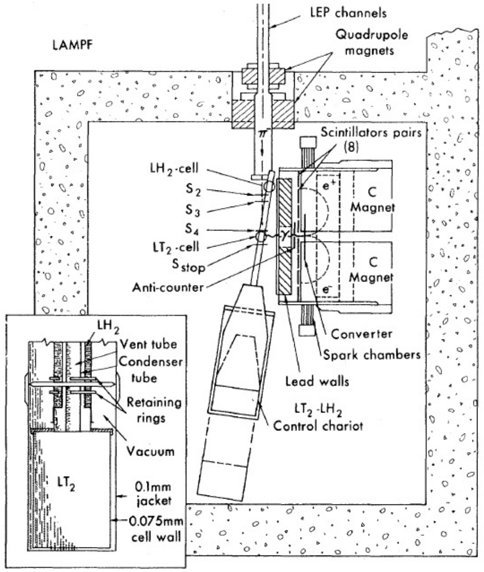


FIG. 1. The experimental setup at LAMPF showing the pair spectrometer and liquid-tritium target. The inset shows a cross section of the target cell obtained from an x-ray radiograph.

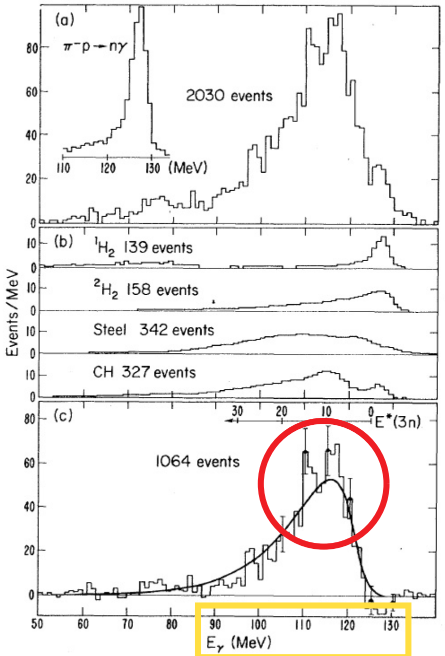


FIG. 2. (a) Raw photon spectrum obtained from the tritium target. The inset shows our resolution obtained at 129.4 MeV. (b) Background spectra for hydrogen, deuterium, steel, and CH. (c) Spectrum from reaction $\pi^- + {}^3H \to n + n + n + \gamma$ after subtraction of ^1H, ^2H, steel, and scintillator contributions. Solid curve is the theoretical spectrum of Phillips and Roig (Ref. 10) (see text), folded with acceptance and instrumental line shape and normalized to the total number of photons.

The overall fit to the data is satisfactory, although small excesses of events in the low-mass region $7 < E_x(3n) \lesssim 16$ MeV are observed. Considering the low statistics and uncertainty in background subtraction, it would be premature to regard this as evidence for a $T = \frac{3}{2}$ resonance

Searching for trineutrons into the light : $^3H(\pi^-, \gamma)$

VOLUME 36, NUMBER 16 PHYSICAL REVIEW LETTERS

Photon Spectrum in Pion Capture on Tritium*

J. A. Bistirlich, S. Cooper, K. M. Crowe, and F. T. Shively†
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94
E. R. Grilly, J. P. Perroud,‡ and R. H. Sherman
Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545
H. W. Baer§
Case Western Reserve University, Cleveland, Ohio 44106
P. Truöl
Physik-Institut der Universität, Zürich, Switzerland

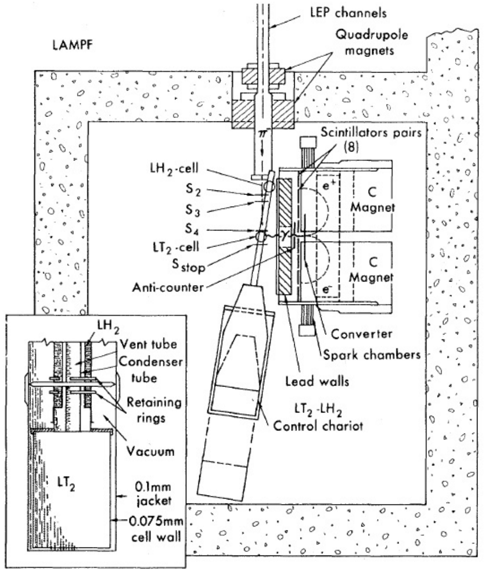
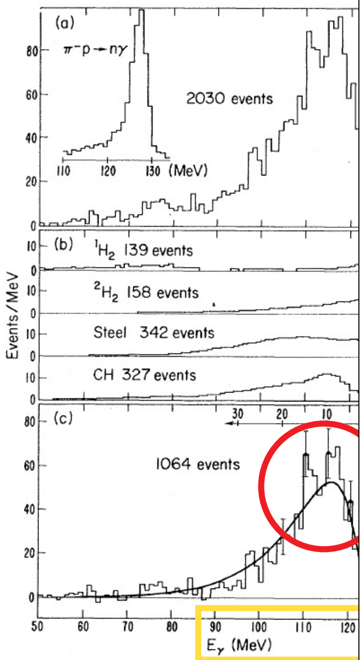


FIG. 1. The experimental setup at LAMPF showing the pair spectrometer and liquid-tritium target. The inset shows a cross section of the target cell obtained from an x-ray radiograph.



The overall fit to the data is satisfactory, although small excesses of events in the low-mass region $7 < E_x(3n) \lesssim 16$ MeV are observed. Considering the low statistics and uncertainty in background subtraction, it would be premature to regard this as evidence for a $T = \frac{3}{2}$ resonance

FIG. 2. (a) Raw photon spectrum ob tritium target. The inset shows our r tained at 129.4 MeV. (b) Background gen, deuterium, steel, and CH. (c) Sp action $\pi^- + {}^3H \to n + n + n + \gamma$ after subtra steel, and scintillator contributions. the theoretical spectrum of Phillips ar (see text), folded with acceptance and shape and normalized to the total numl

Nuclear Physics **A343** (1980) 347 – 355; © *North-Holland Publishing Co., Amsterdam*

UPPER LIMITS FOR BOUND STATES AND RESONANCE BEHAVIOR IN THE TRINEUTRON SYSTEM

J. P. MILLER †, J. A. BISTIRLICH, K. M. CROWE, S. S. ROSENBLUM, P. C. ROWE and F. T. SHIVELY
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720, USA
E. R. GRILLY, E. C. KERR, J. NOVAK and R. H. SHERMAN
Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545, USA
H. BRÄNDLE ††
Physics Department, University of California, Los Angeles, California 90024, USA
G. STRASSNER ††† and P. TRUÖL
Physik-Institut der Universität Zürich, CH-8001 Zürich, Switzerland

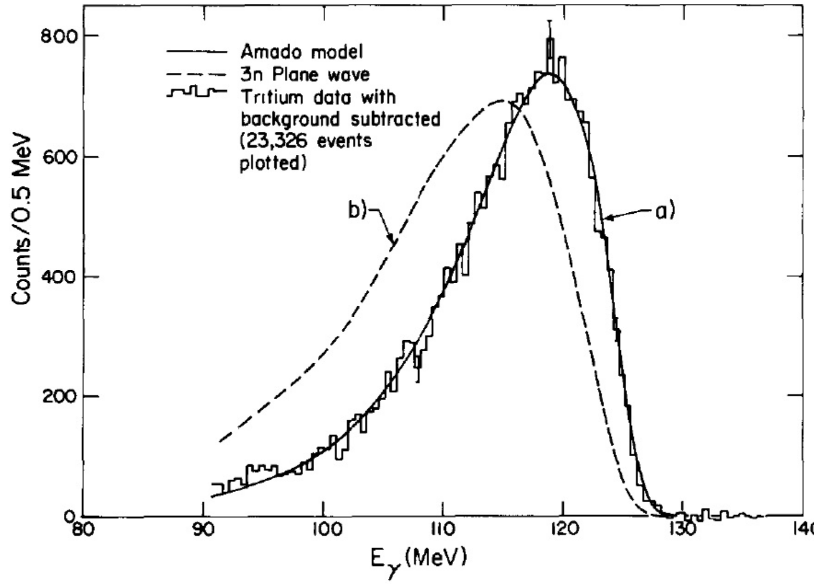


Fig. 4. Measured tritium spectrum with background subtracted. Curve a, Amado model and curve b, plane wave for 3n final state, from refs. [3,21])

In conclusion, we have performed an experiment expected to be highly sensitive to the presence of 3n structure near threshold and see no evidence for it, other than a very pronounced shift to low 3n energy which can be explained in terms of the simple s-wave pairwise interaction between neutrons in the final state.

Searching for trineutrons into the light: $^3H(\pi^-, \gamma)$

VOLUME 36, NUMBER 16 PHYSICAL REVIEW LETTERS

Photon Spectrum in Pion Capture on Tritium*

J. A. Bistirlich, S. Cooper, K. M. Crowe, and F. T. Shively†
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94
E. R. Grilly, J. P. Perroud,‡ and R. H. Sherman
Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545
H. W. Baer§
Case Western Reserve University, Cleveland, Ohio 44106
P. Truöl
Physik-Institut der Universität, Zürich, Switzerland

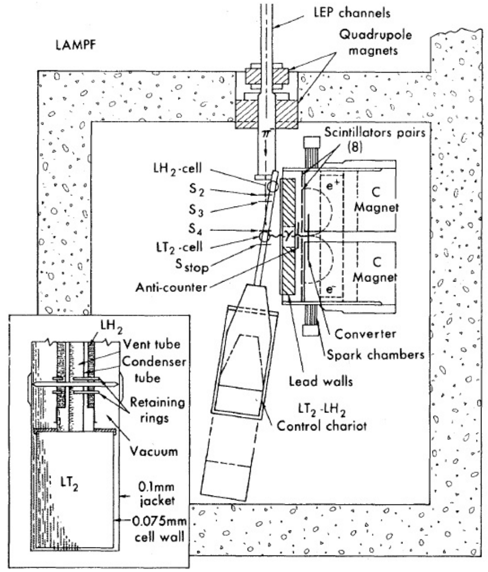


FIG. 1. The experimental setup at LAMPF showing the pair spectrometer and liquid-tritium target. The inset shows a cross section of the target cell obtained from an x-ray radiograph.

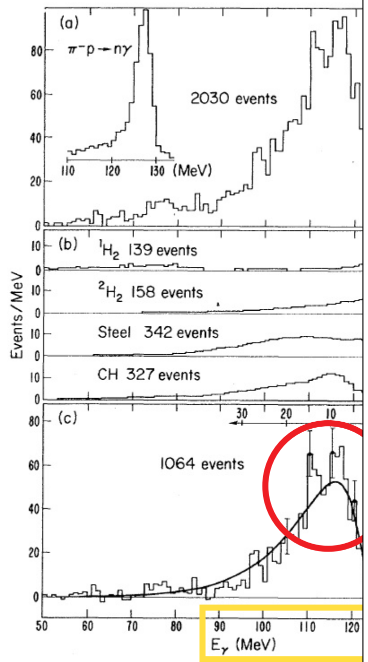


FIG. 2. (a) Raw photon spectrum ob tritium target. The inset shows our r tained at 129.4 MeV. (b) Background gen, deuterium, steel, and CH. (c) Sp action $\pi^- + {}^3H \to n + n + n + \gamma$ after subtra steel, and scintillator contributions. the theoretical spectrum of Phillips an (see text), folded with acceptance and shape and normalized to the total num

The overall fit to the data is satisfactory, although small excesses of events in the low-mass region $7 < E_x(3n) \lesssim 16$ MeV are observed. Considering the low statistics and uncertainty in background subtraction, it would be premature to regard this as evidence for a $T = \frac{3}{2}$ resonance

Nuclear Physics **A343** (1980) 347–355; © *North-Holland Publishing Co., Amsterdam*

UPPER LIMITS FOR BOUND STATES AND RESONANCE BEHAVIOR IN THE TRINEUTRON SYSTEM

J. P. MILLER †, J. A. BISTIRLICH, K. M. CROWE, S. S. ROSENBLUM, P. C. ROWE and F. T. SHIVELY
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720, USA
E. R. GRILLY, E. C. KERR, J. NOVAK and R. H. SHERMAN
Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545, USA
H. BRÄNDLE ††
Physics Department, University of California, Los Angeles, California 90024, USA
G. STRASSNER ††† and P. TRUÖL
Physik-Institut der Universität Zürich, CH-8001 Zürich, Switzerland

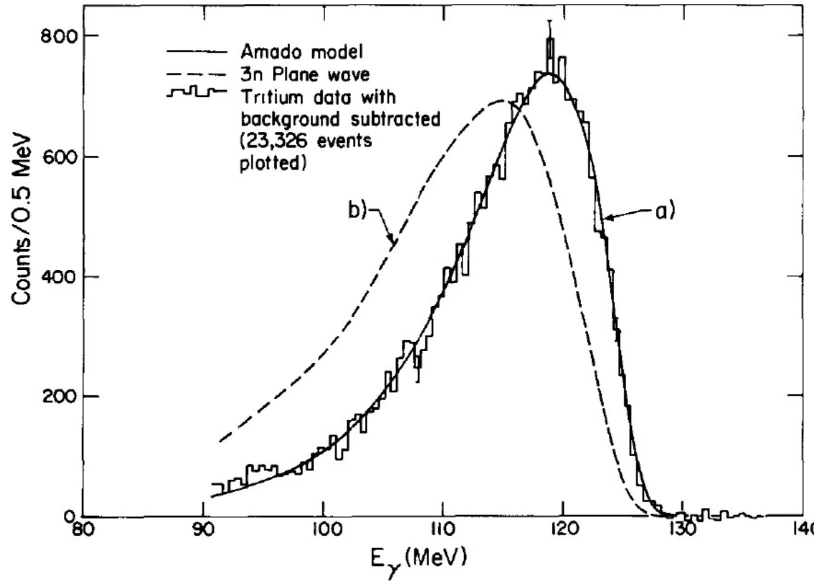


Fig. 4. Measured tritium spectrum with background subtracted. Curve a, Amado model and curve b, plane wave for 3n final state, from refs. [3,21])

In conclusion, we have performed an experiment expected to be highly sensitive to the presence of 3n structure near threshold and see no evidence for it, other than a very pronounced shift to low 3n energy which can be explained in terms of the simple s-wave pairwise interaction between neutrons in the final state.

Transfer : exploring beam/target combinations

Ajdačić, PRL 14 (1965) 444 : $^3\mathrm{H}(n,p)^3\mathrm{n}$ (✔)

Thornton, PRL 17 (1966) 701 : $^3\mathrm{H}(n,p)^3\mathrm{n}$ ✘

Ohlsen, PR 176 (1968) 1163 : $^3\mathrm{H}(t,{}^3\mathrm{He})3\mathrm{n}$ (✔)

→ very poor data

→ some unclear "enhancements" ...

Transfer : exploring beam/target combinations

Ajdačić, PRL 14 (1965) 444 : ^{3}H$(n,p)^3$n (✔)

Thornton, PRL 17 (1966) 701 : ^{3}H$(n,p)^3$n ✘

Ohlsen, PR 176 (1968) 1163 : ^{3}H$(t,^3$He$)$3n (✔)

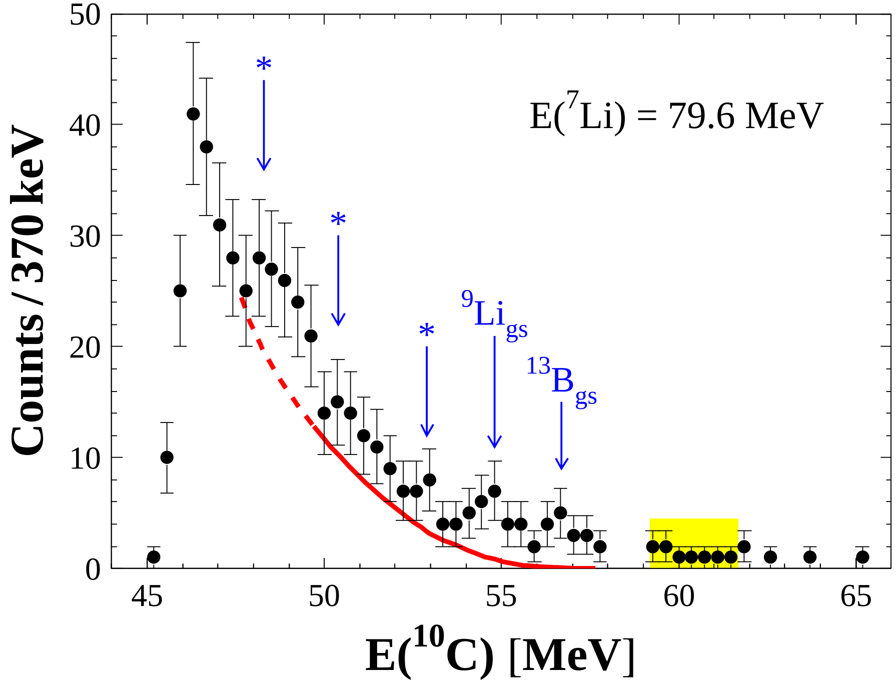
→ very poor data

→ some unclear "enhancements" ...

Cerny, PL 53B (1974) 247 :

^{7}Li$(^7$Li$,^{11}$C$)^3$n ✘

^{7}Li$(^7$Li$,^{10}$C$)^4$n ✘



Transfer : exploring beam/target combinations

Ajdačić, PRL 14 (1965) 444 : ^{3}H$(n,p)^{3}$n (✔)

Thornton, PRL 17 (1966) 701 : ^{3}H$(n,p)^{3}$n ✘

Ohlsen, PR 176 (1968) 1163 : ^{3}H$(t,^{3}$He$)$3n (✔)

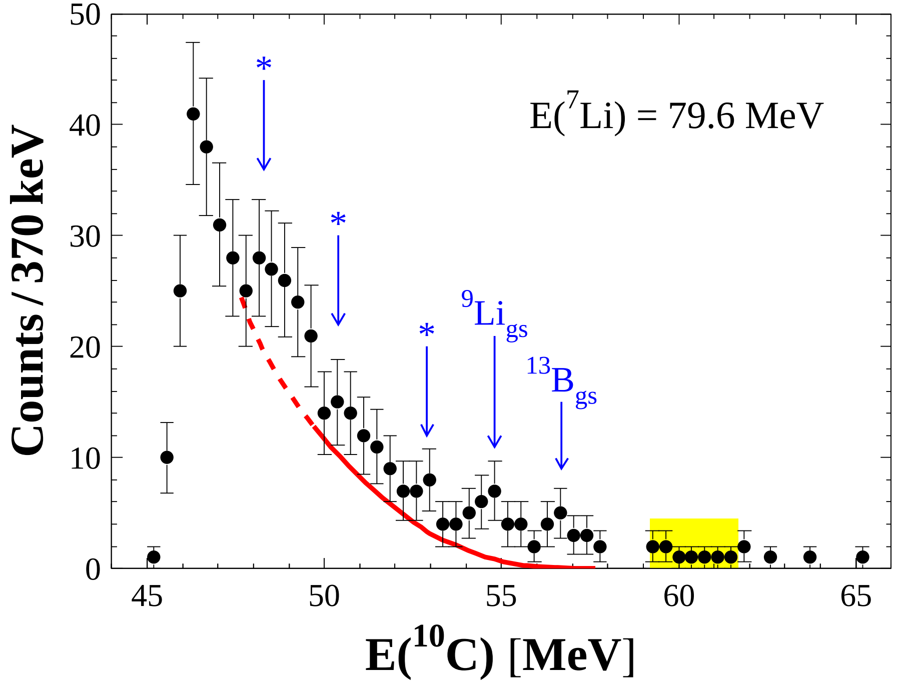
→ very poor data

→ some unclear "enhancements" ...

Cerny, PL 53B (1974) 247 :

^{7}Li(^{7}Li,^{11}C)^{3}n ✘

^{7}Li(^{7}Li,^{10}C)^{4}n ✘



Belozyorov, NP A477 (1988) 131 :

^{7}Li(^{11}B,^{15}O)3n ✘ ^{7}Li(^{9}Be,^{12}N)4n ✘

^{7}Li(^{11}B,^{14}O)4n ✘ ^{9}Be(^{9}Be,^{14}O)4n ✘

Ajdačić, PRL 14 (1965) 444 : ^{3}H$(n,p)^{3}$n (✔)

Thornton, PRL 17 (1966) 701 : ^{3}H$(n,p)^{3}$n ✘

Ohlsen, PR 176 (1968) 1163 : ^{3}H$(t,^{3}$He$)$3n (✔)

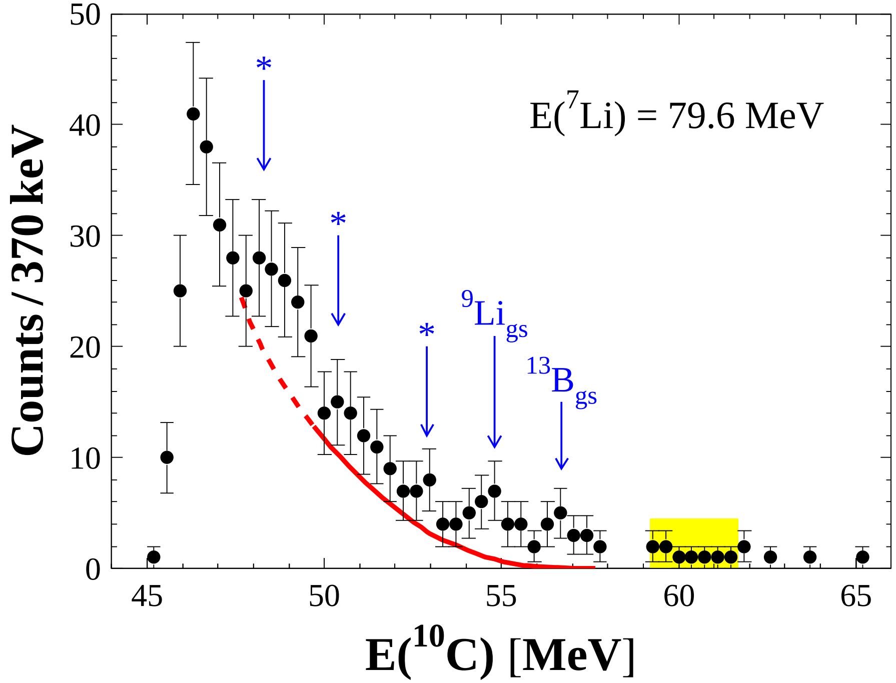
→ very poor data

→ some unclear "enhancements" ...

Cerny, PL 53B (1974) 247 :

^{7}Li(^{7}Li,^{11}C)^{3}n ✘

^{7}Li(^{7}Li,^{10}C)^{4}n ✘



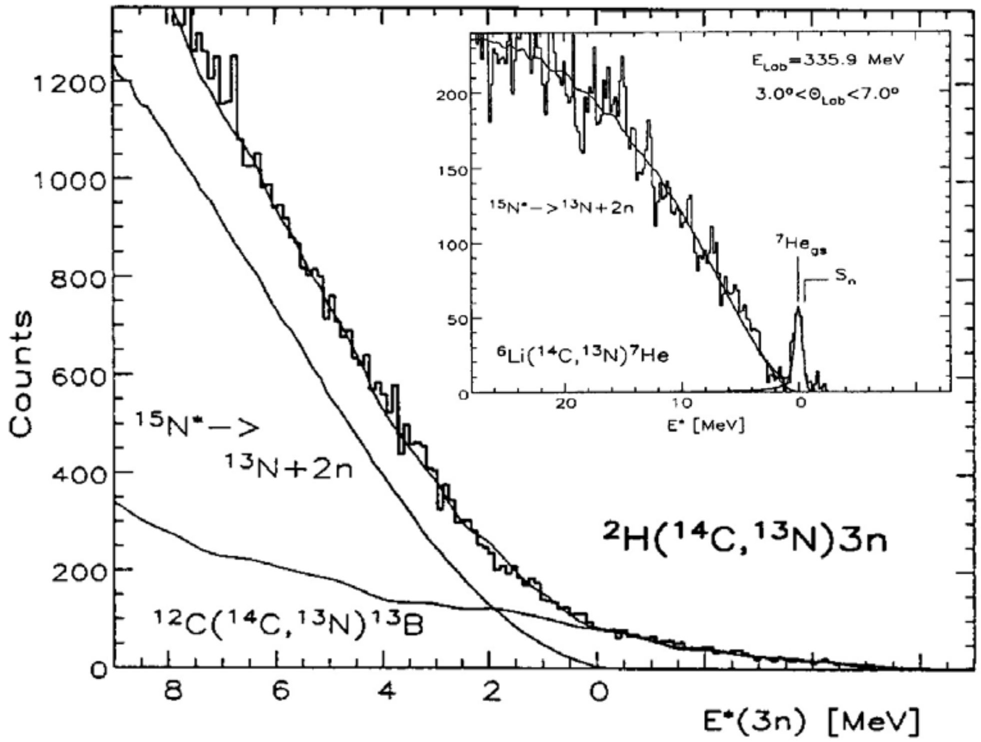
Belozyorov, NP A477 (1988) 131 :

^{7}Li(^{11}B,^{15}O)3n ✘ ^{7}Li(^{9}Be,^{12}N)4n ✘

^{7}Li(^{11}B,^{14}O)4n ✘ ^{9}Be(^{9}Be,^{14}O)4n ✘

Bohlen, NP A583 (1995) 775 :

[^{6}Li$_2$O/CD$_2$](^{14}C,^{13}N) ≡ −● +●●



Transfer : exploring beam/target combinations

Ajdačić, PRL 14 (1965) 444 : ^{3}H$(n,p)^3$n (✔)

Thornton, PRL 17 (1966) 701 : ^{3}H$(n,p)^3$n ✘

Ohlsen, PR 176 (1968) 1163 : ^{3}H$(t,^3$He$)$3n (✔)

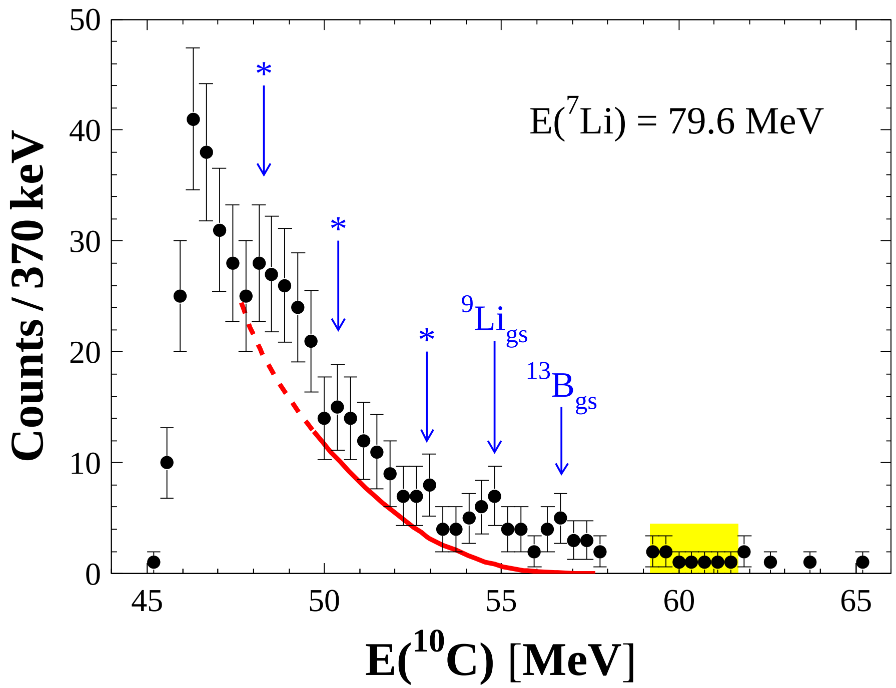
→ very poor data

→ some unclear "enhancements" ...

Cerny, PL 53B (1974) 247 :

^{7}Li(^{7}Li,^{11}C)^{3}n ✘

^{7}Li(^{7}Li,^{10}C)^{4}n ✘



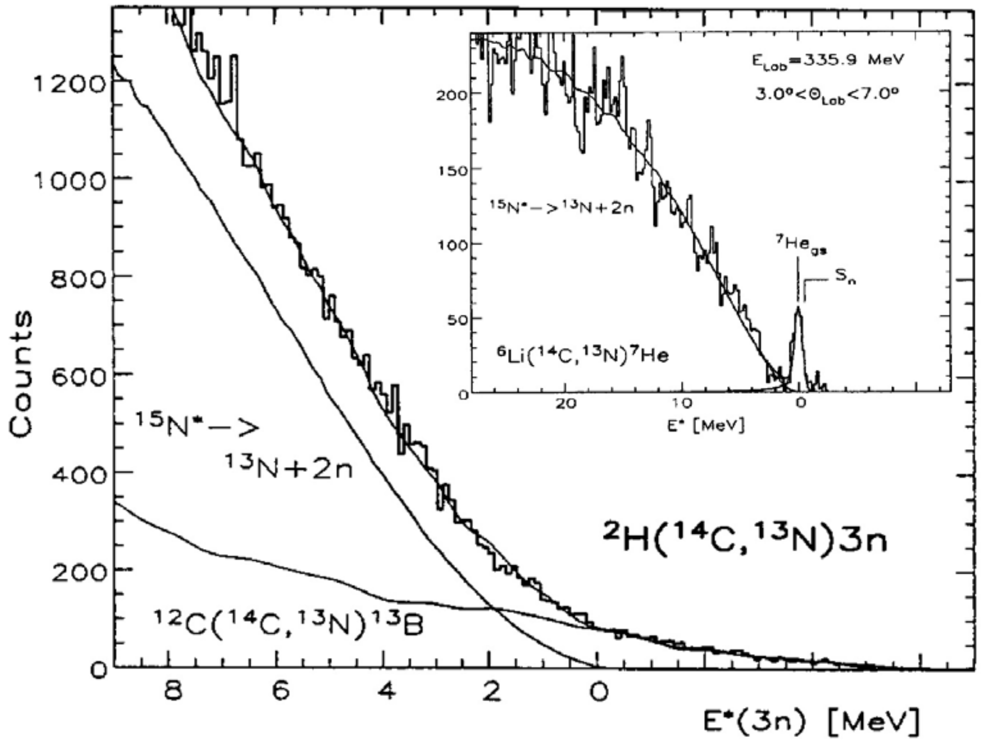
Belozyorov, NP A477 (1988) 131 :

^{7}Li(^{11}B,^{15}O)3n ✘ ^{7}Li(^{9}Be,^{12}N)4n ✘

^{7}Li(^{11}B,^{14}O)4n ✘ ^{9}Be(^{9}Be,^{14}O)4n ✘

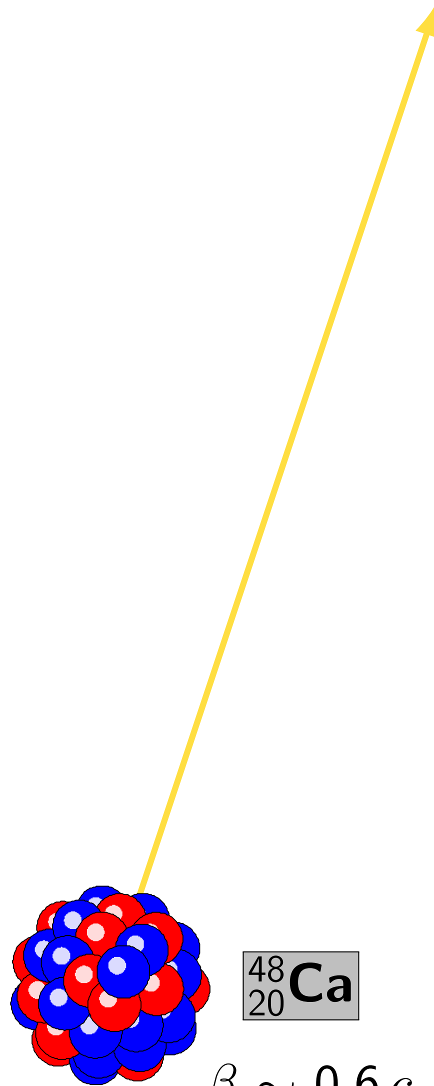
Bohlen, NP A583 (1995) 775 :

[^{6}Li$_2$O/CD$_2$](^{14}C,^{13}N) ≡ − ● + ●●



Aleksandrov, JETPL 81-2 (2005) 43 : confirms Cerny's work

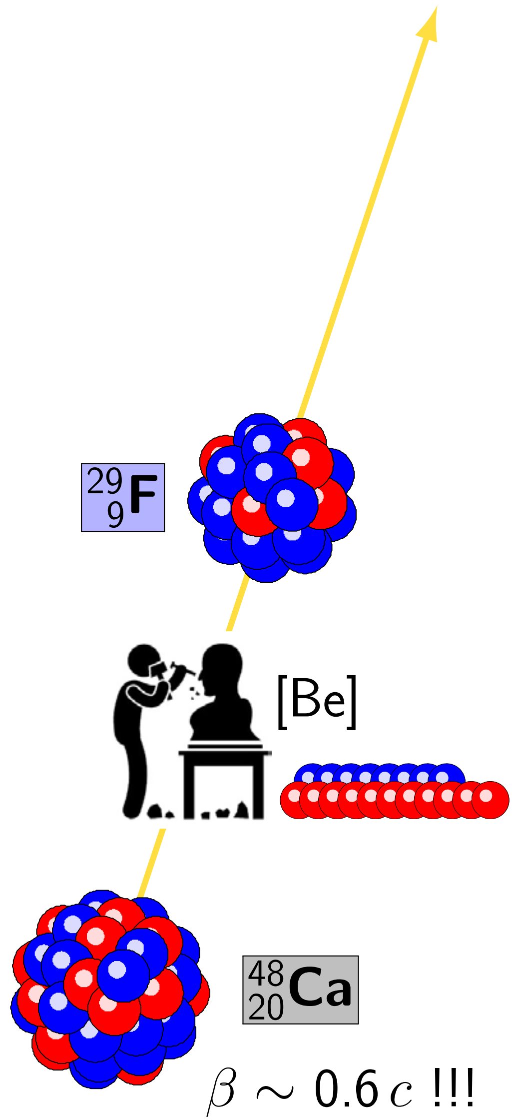
Sculpting exotic beams (SAMURAI21)



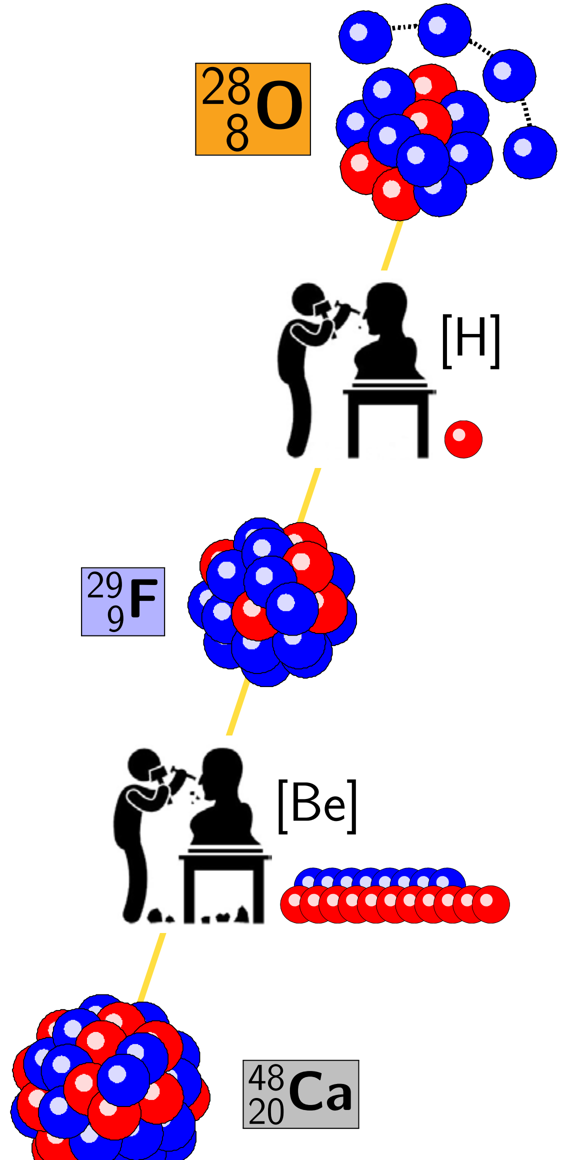
$^{48}_{20}$Ca

$\beta \sim 0.6\,c$!!!

Sculpting exotic beams (SAMURAI21)

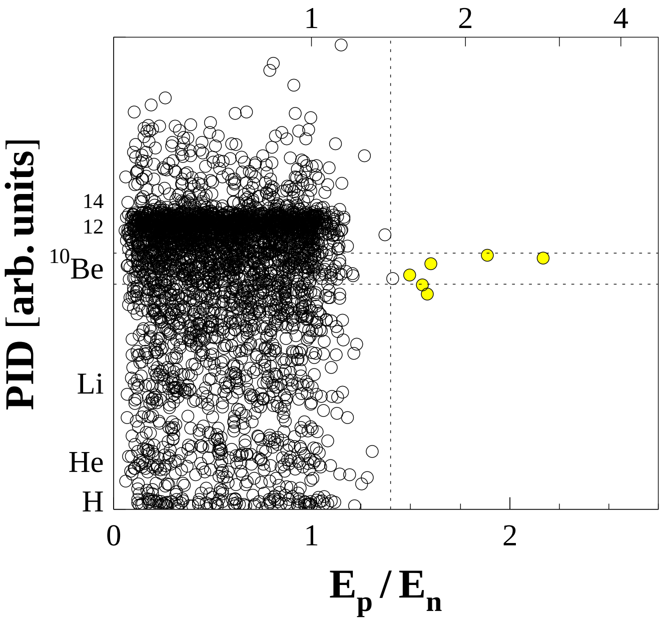


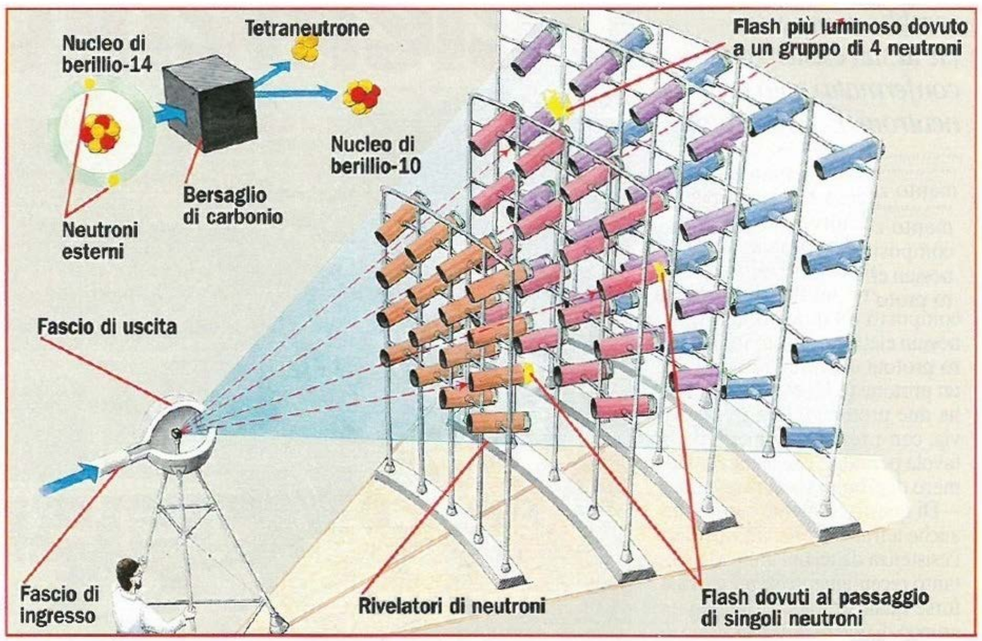

RI BEAM FACTORY 01
RRC RIKEN RING CYCLOTRON
(理研リングサイクロトロン)
第1のリングサイクロトロン。RIビームファクトリーのサイクロトロンの中では一番の古株。
重さ 2,300t
直径 12.6m
RIビームファクトリー全体図
RIビームファクトリーではさまざまな実験装置を使って、原子核の構造と反応を研究しておるのじゃ。
ビーム発射
SAMURAI
反応を調べる
大きさをはかる
SCRIT
地下1階
GARIS
RILAC
ゼロ度スペクトロメータ
形を調べる
光速の4%
数値は地点通過時のビーム速度を表しています。
AVFサイクロトロン
RILAC2
回して調べる
稀少RIリング
重さをはかる
地下2階
叩いて調べる
SHARAQ
光速の16%
光速の70%
光速の47%
SLOWRI
止まれ
止めて調べる
BigRIPS
原子核を壊す
ここには「ビームダンプ」という装置があって、重イオンビームからRIビームに変わるところなんだよ。
RI BEAM FACTORY 04
SRC SUPERCONDUCTING RING CYCLOTRON
(超伝導リングサイクロトロン)
第4のリングサイクロトロンで最終加速。6基の超伝導電磁石を持つ史上最強のリングサイクロトロン。
重さ 8,300t
直径 18.5m


$^{28}_{8}$O
[H]
$^{29}_{9}$F
[Be]
$^{48}_{20}$Ca

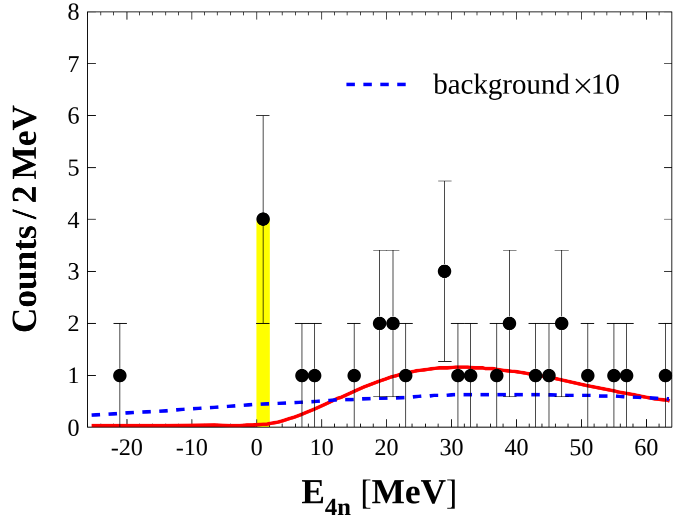
$\beta \sim 0.6\,c$!!!

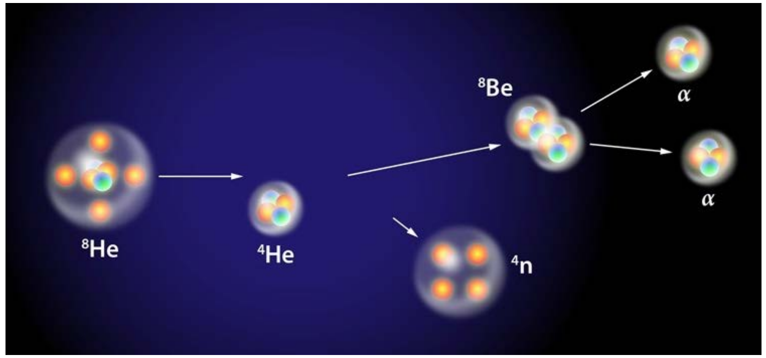
- $^{14}\mathrm{Be} \xrightarrow{(C)} {}^{10}\mathrm{Be} + {}^{4}\mathbf{n}$:





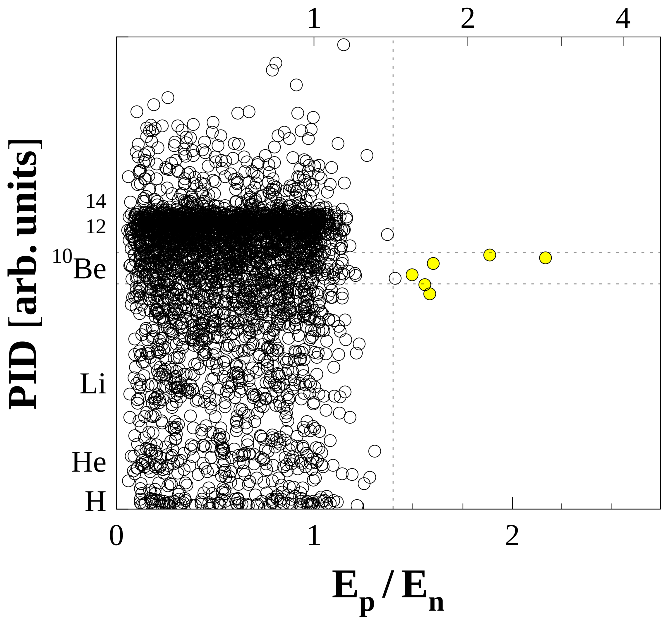
- $^{4}\mathrm{He}\,(^{8}\mathrm{He}, {}^{8}\mathrm{Be})\, {}^{4}\mathbf{n}$:

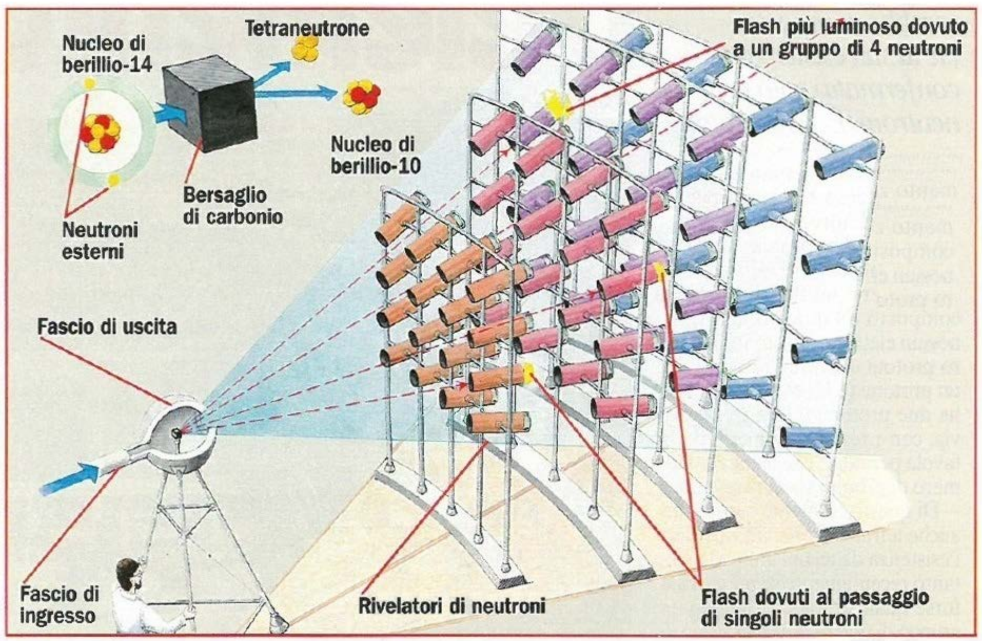




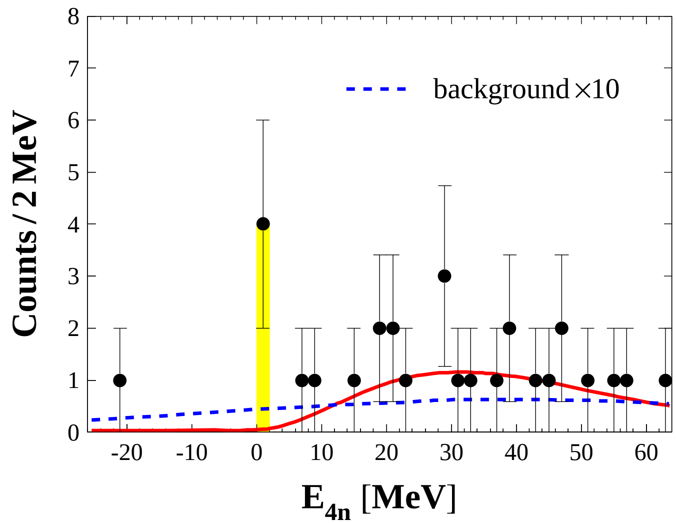
XXI century signals : GANIL & RIKEN

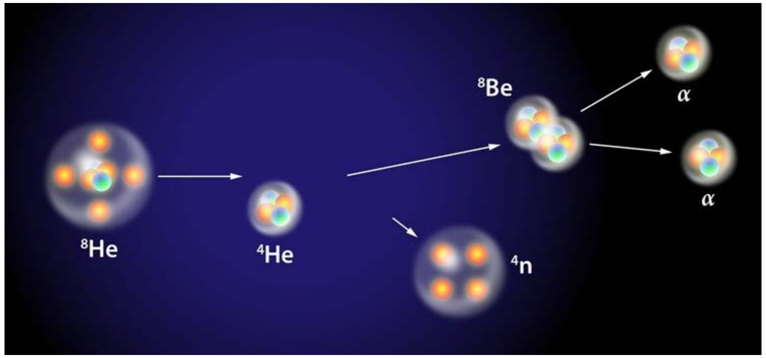
- $^{14}\text{Be} \xrightarrow{(C)} {}^{10}\text{Be} + \mathbf{{}^4n}$:





- $^4\text{He}\,(^8\text{He}, {}^8\text{Be})\,\mathbf{{}^4n}$:





Kisamori, PRL 116 (2016) 052501 → E(4n) = 0.8±1.3 MeV

FMM, PRC 65 (2002) 044006
FMM, arXiv nucl-ex/0504009
} E(4n) ∈ [−1, +2] MeV

Theory : another hard & interesting quest

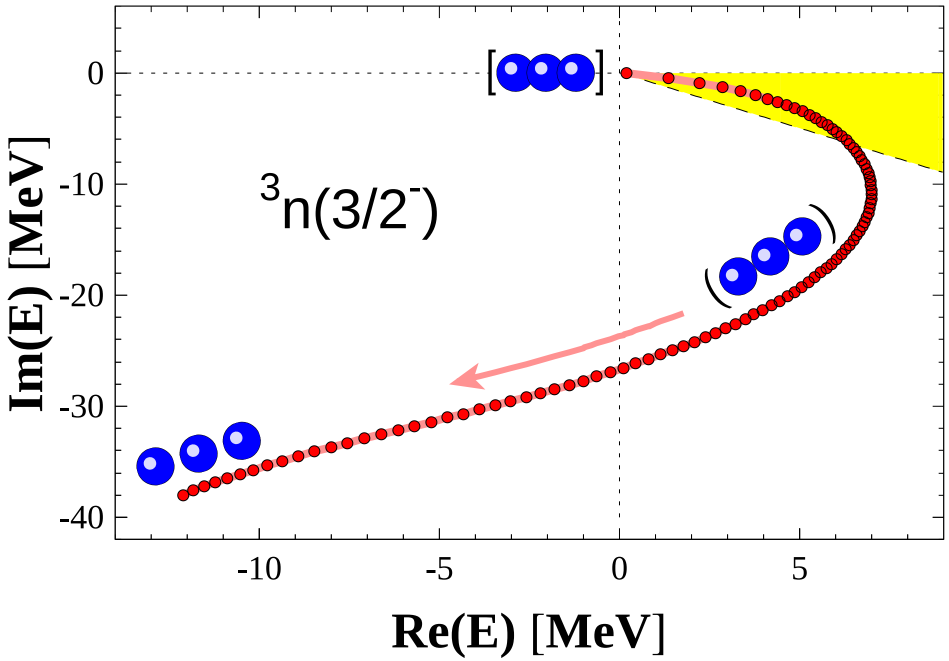
- ‘Exact’ calculations are categorical !

Glöckle, PRC 18 (1978) 564 : $V_{nn} \times 4.2$

Offermann, NPA 318 (1979) 138 : $V_{nn} \times 3.7$ (+P-waves)

Witała, PRC 60 (1999) 024002 : avoid ^{2}n with $V_{nn}(^{1}S_{0}) \times 1$

Hemmdan, PRC 66 (2002) 054001 :



“3n resonances close to the physical region will not exist”

Theory : another hard & interesting quest

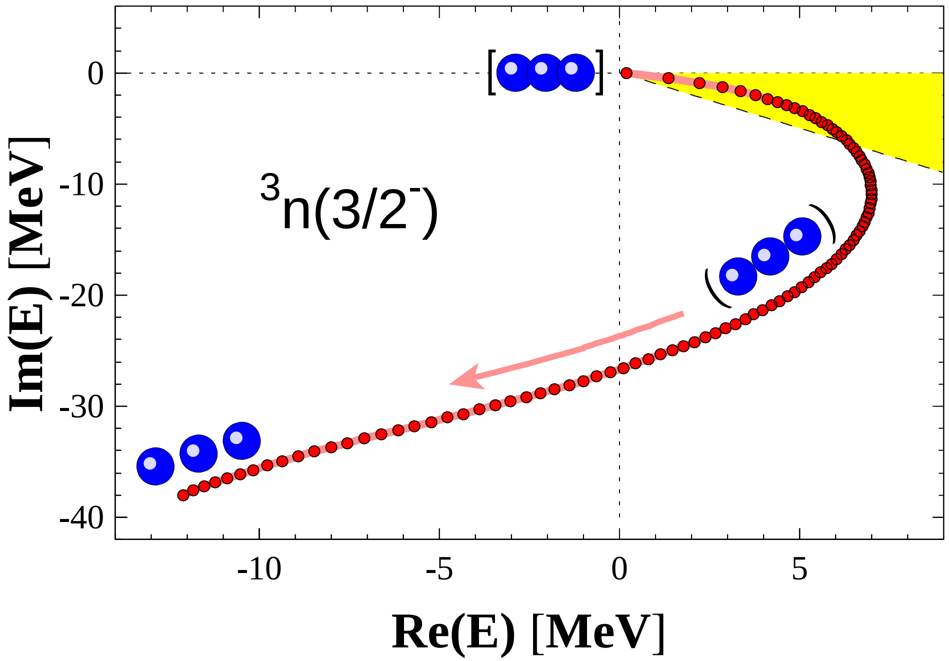
- ‘Exact’ calculations are categorical !

Glöckle, PRC 18 (1978) 564 : $V_{nn}\times 4.2$

Offermann, NPA 318 (1979) 138 : $V_{nn}\times 3.7$ (+P-waves)

Witała, PRC 60 (1999) 024002 : avoid ^{2}n with $V_{nn}(^{1}S_{0})\times 1$

Hemmdan, PRC 66 (2002) 054001 :



“3n resonances close to the physical region will not exist”

(3n) Lazauskas, PRC 71 (2005) 044004 : 3NF ✘

(4n) Lazauskas, PRC 72 (2005) 034003 : 4NF ✘

(3,4n) Hiyama, PRC 93 (2016) 044004 : 3NF(T=3/2) ✘ !

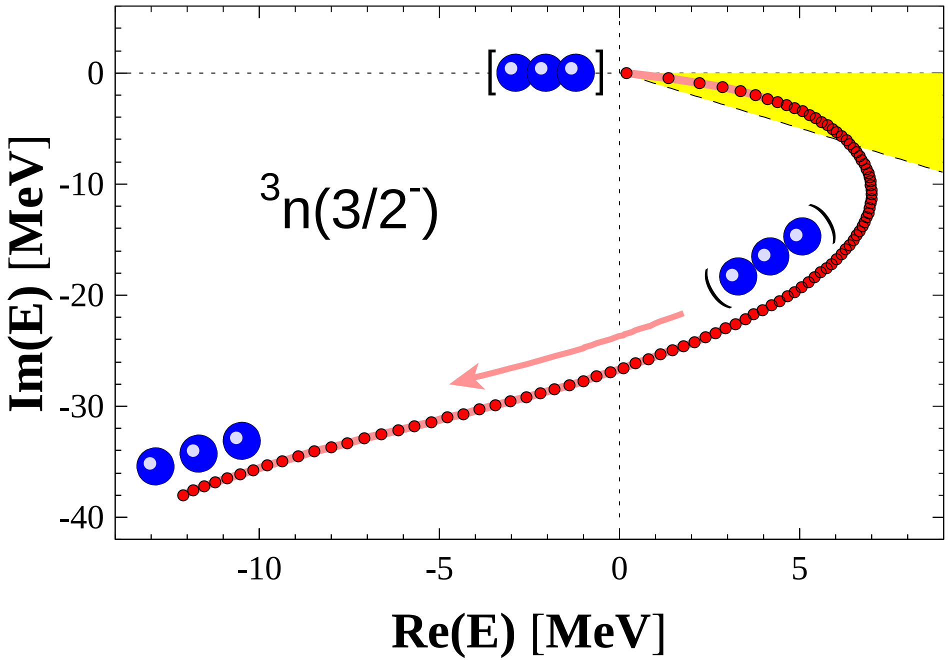
- ‘Exact’ calculations are categorical !

Glöckle, PRC 18 (1978) 564 : $V_{nn}\times 4.2$

Offermann, NPA 318 (1979) 138 : $V_{nn}\times 3.7$ (+P-waves)

Witała, PRC 60 (1999) 024002 : avoid ^{2}n with $V_{nn}(^1S_0)\times 1$

Hemmdan, PRC 66 (2002) 054001 :



“3n resonances close to the physical region will not exist”

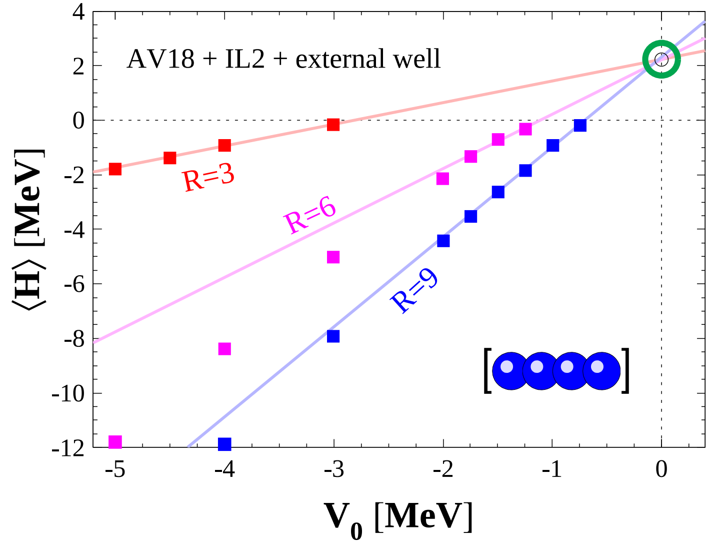
(3n) Lazauskas, PRC 71 (2005) 044004 : 3NF ✘

(4n) Lazauskas, PRC 72 (2005) 034003 : 4NF ✘

(3,4n) Hiyama, PRC 93 (2016) 044004 : 3NF(T=3/2) ✘ !

- Many-body approximations, not so much ...

Pieper, PRL 90 (2003), 252501 :



“the resonance, if it exists at all, must be very broad”

Shirokov, PRL 117 (2016) 182502
Gandolfi, PRL 118 (2017) 232501
Fossez, PRL 119 (2017) 032501
Li, PRC 100 (2019) 054313

} 3n/4n ✔ ?

Theory : another hard & interesting quest

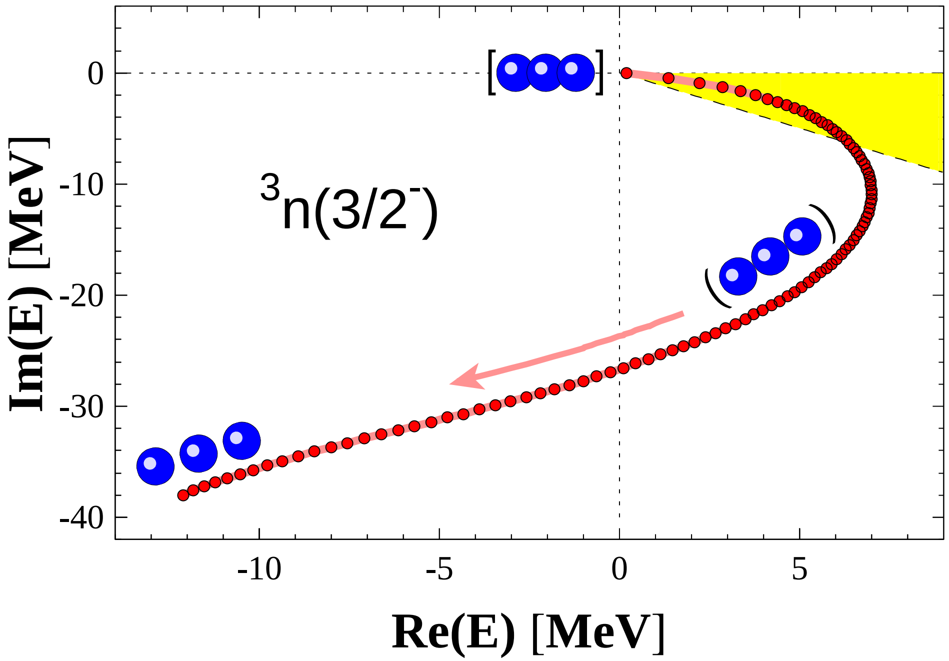
▶ 'Exact' calculations are categorical !

Glöckle, PRC 18 (1978) 564 : $V_{nn}\times 4.2$

Offermann, NPA 318 (1979) 138 : $V_{nn}\times 3.7$ (+P-waves)

Witała, PRC 60 (1999) 024002 : avoid ^{2}n with $V_{nn}(^1S_0)\times 1$

Hemmdan, PRC 66 (2002) 054001 :



"3n resonances close to the physical region will not exist"

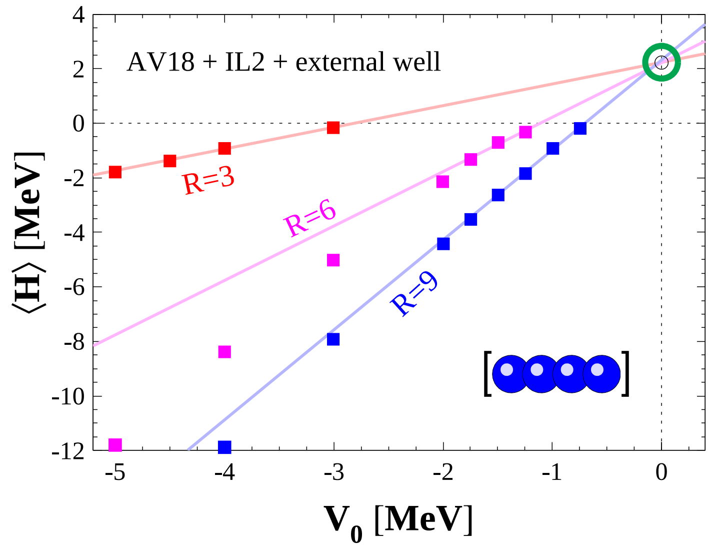
(3n) Lazauskas, PRC 71 (2005) 044004 : 3NF ✘

(4n) Lazauskas, PRC 72 (2005) 034003 : 4NF ✘

(3,4n) Hiyama, PRC 93 (2016) 044004 : 3NF(T=3/2) ✘ !

▶ Many-body approximations, not so much …

Pieper, PRL 90 (2003), 252501 :

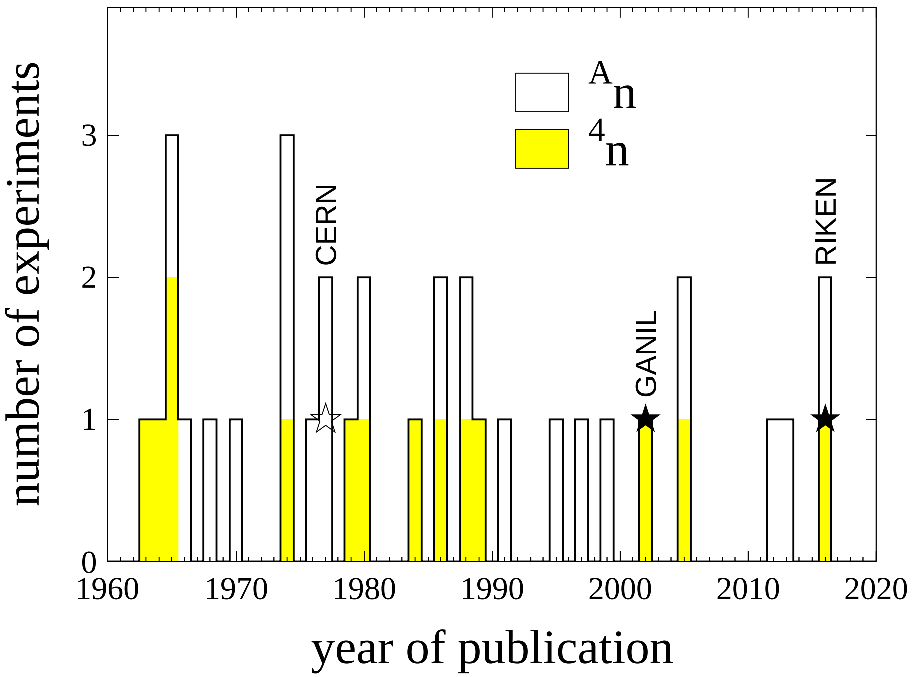


"the resonance, if it exists at all, must be very broad"

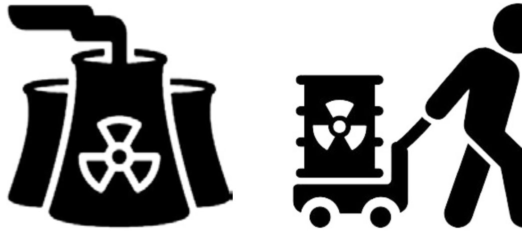
Shirokov, PRL 117 (2016) 182502
Gandolfi, PRL 118 (2017) 232501
Fossez, PRL 119 (2017) 032501
Li, PRC 100 (2019) 054313
} 3n/4n ✔ ?

Deltuva, PRL 123 (2019) 069201
Deltuva, PRC 100 (2019) 044002
Ishikawa, PRC 102 (2020) 034002
} 3n/4n ✘ !!! (trap/evolution/scaling)

Deltuva, PLB 782 (2018) 238
Higgins, PRL 125 (2020) 052501
} QM enhancements …

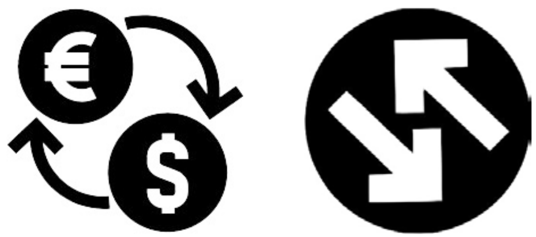


- 34 works published !
  - 14 exclusively for tetraneutron
  - 3 positive signals !
    - → 1 strong but refuted
    - → 2 weak but uncontested (yet)



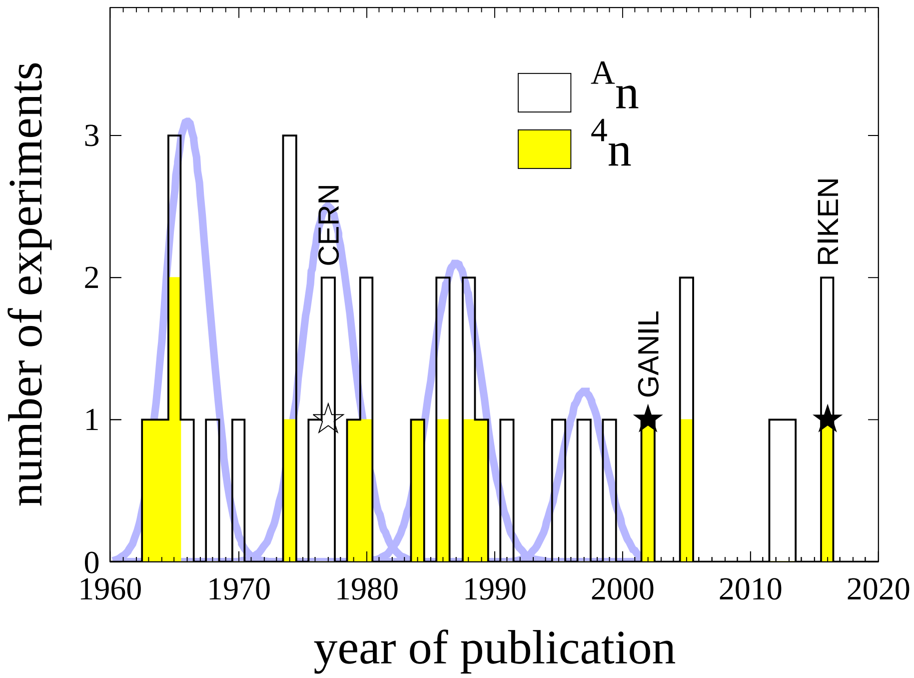
Détraz, PL 66B (1977) 333

FMM, PRC 65 (2002) 044006



Kisamori, PRL 116 (2016) 052501

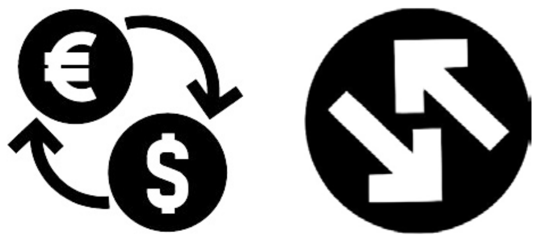
Sixty years of multineutron quest



- 34 works published !
  - 14 exclusively for tetraneutron
  - 3 positive signals !
    - → 1 strong but refuted
    - → 2 weak but uncontested (yet)
  - recurring pattern in XX century :
    - → decreasing number of experiments
    - → new increase in 2020s ?

Détraz, PL 66B (1977) 333

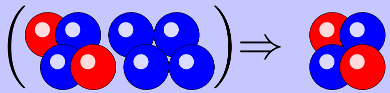
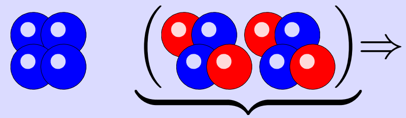
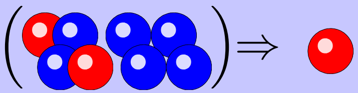
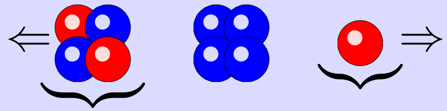
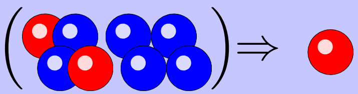
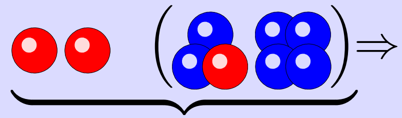
FMM, PRC 65 (2002) 044006



Kisamori, PRL 116 (2016) 052501

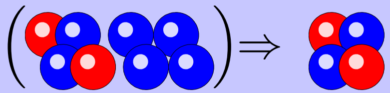
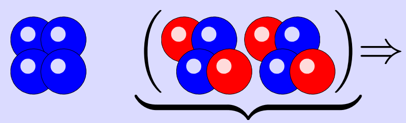
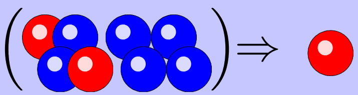
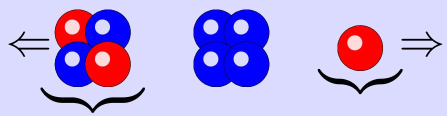
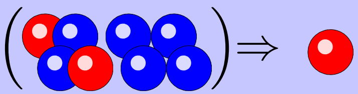
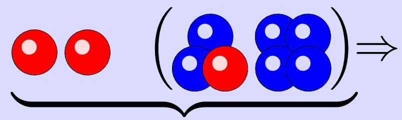
Tetraneutron context @ RIKEN

- Three experiments : same beam (^{8}**He**) & energy (150–200 MeV/N) ?

reaction	initial state	final state	σ	results
('16) ^{4}He (^{8}He, $\alpha\alpha$) ^{4}**n** Shimoura, NP1512-SHARAQ10			nb	$N_{evt} \sim 10$ s ^{4}n : E, Γ
('17) ^{8}He (p,pα) ^{4}**n** Paschalis, NP1406-SAMURAI19			μb	$N_{evt} \sim 1000$ s ^{4}n : E, Γ
('17) ^{8}He (p,2p) {^{3}**H**+^{4}**n**} FMM/Yang, NP1512-SAMURAI34			**mb**	$N_{evt} \sim$ **10,000** s ^{4}n & ^{7}H : E, Γ, $\boldsymbol{\Omega}$

Tetraneutron context @ RIKEN

- Three experiments : same beam (^{8}**He**) & energy (150–200 MeV/N) ?

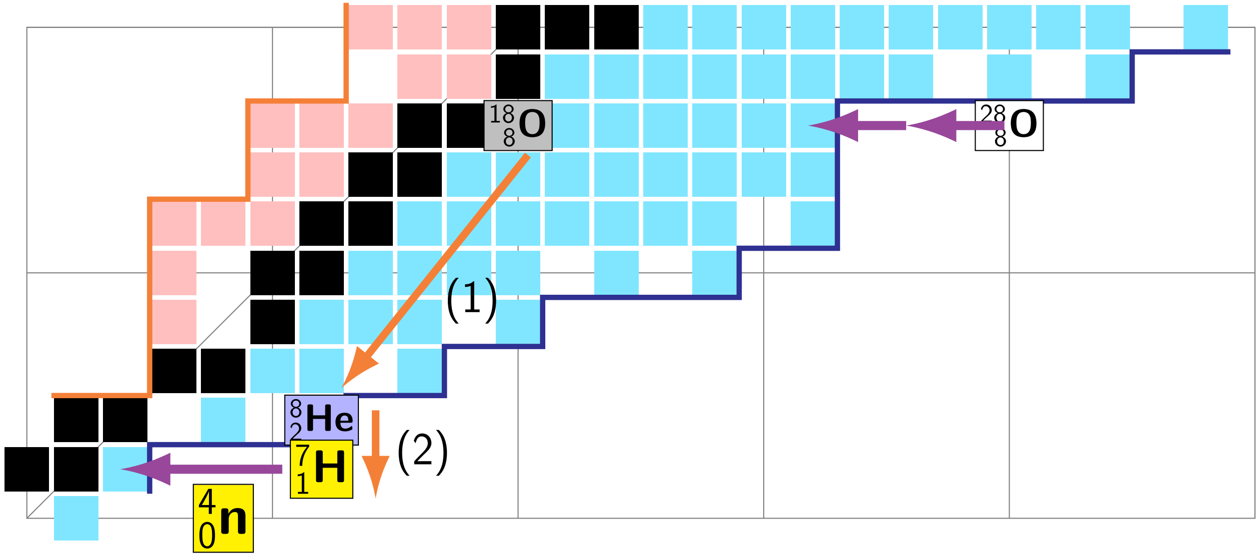
reaction	initial state	final state	σ	results
('16) ^{4}He $(^8$He$, \alpha\alpha)$ ^{4}**n** Shimoura, NP1512-SHARAQ10			nb	$N_{evt} \sim 10$ s ^{4}n : E, Γ
('17) ^{8}He (p,pα) ^{4}**n** Paschalis, NP1406-SAMURAI19			μb	$N_{evt} \sim 1000$ s ^{4}n : E, Γ
('17) ^{8}He (p,2p) $\{^3$**H**$+^4$**n**$\}$ FMM/Yang, NP1512-SAMURAI34			**mb**	$N_{evt} \sim$ **10,000** s ^{4}n & ^{7}H : E, Γ, Ω

$\rightarrow$ a very 'simple' formula :

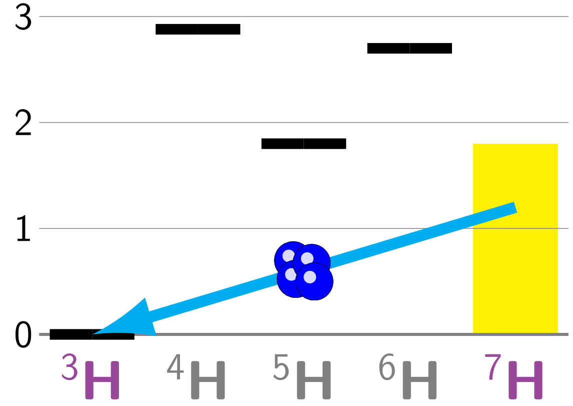
$$\mathbf{N_{evt}} \propto I \times \sigma \times \rho \times \varepsilon$$

- beam **intensity**
- reaction **cross-section**
- number of **target** nuclei
- detection **efficiency**

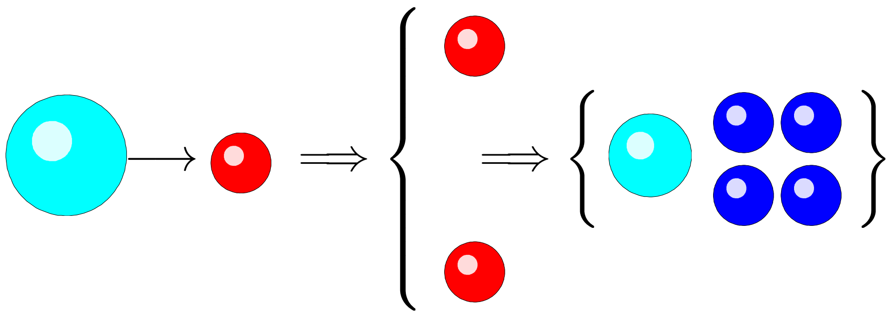
Hydrogen 7 & Tetraneutron ‘emission’ ?



- N = 6 $(\nu p_{3/2})^4$ sub-shell closure ?

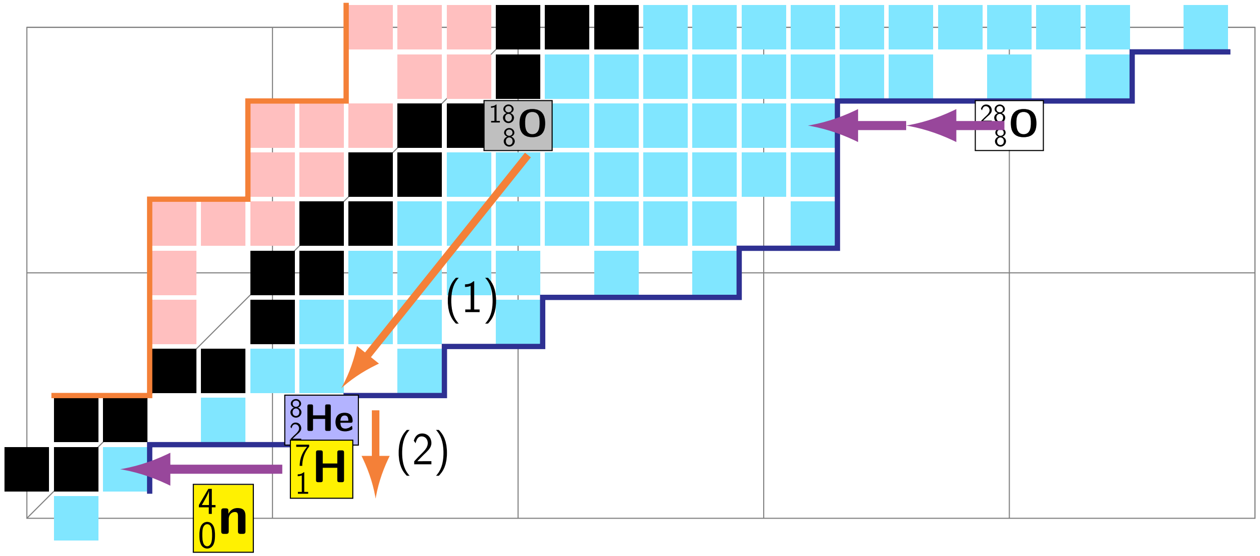


▸ ^{8}He (p,2p) ^{7}H @ 150 MeV/N :

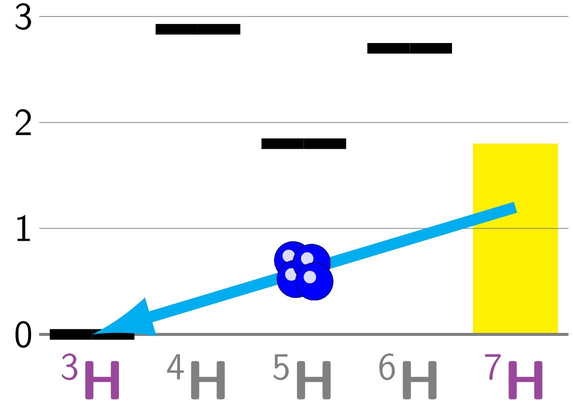


→ 7-body final state !

Hydrogen 7 & Tetraneutron 'emission' ?

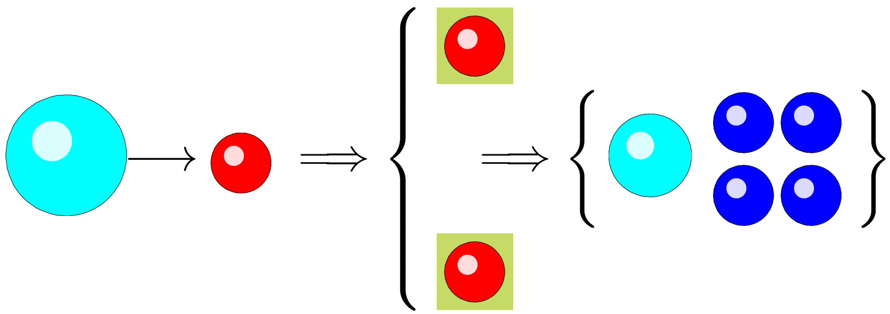


- $N = 6\ (\nu p_{3/2})^4$ sub-shell closure ?



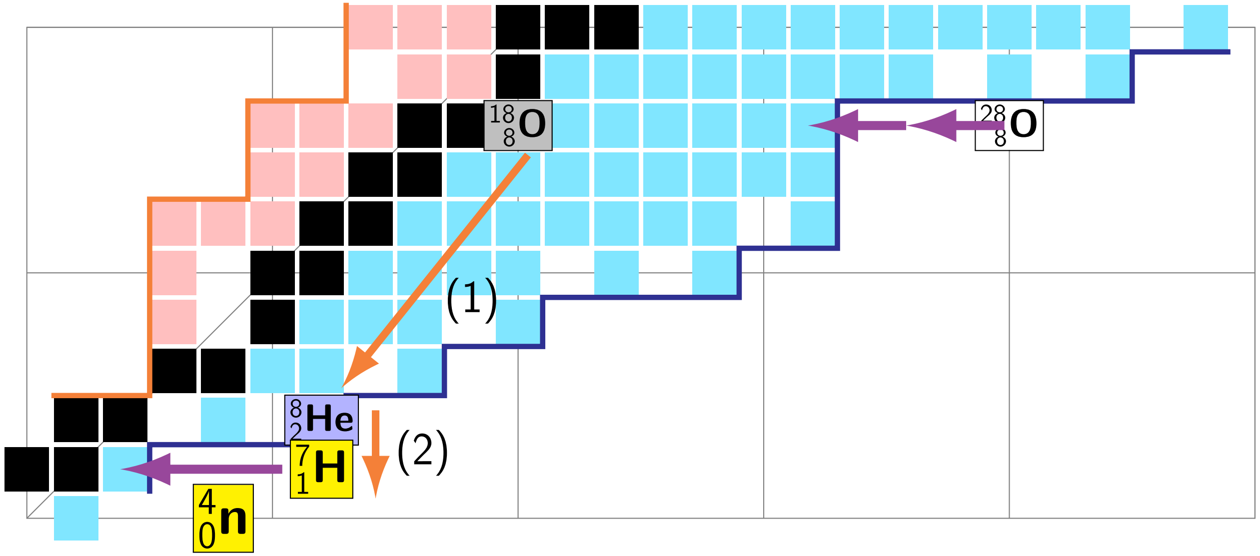
- an array of arrays :
  - → **MINOS** liquid H target
  - → **DALI** NaI crystals

▶ ^{8}He (p,2p) ^{7}H @ 150 MeV/N :

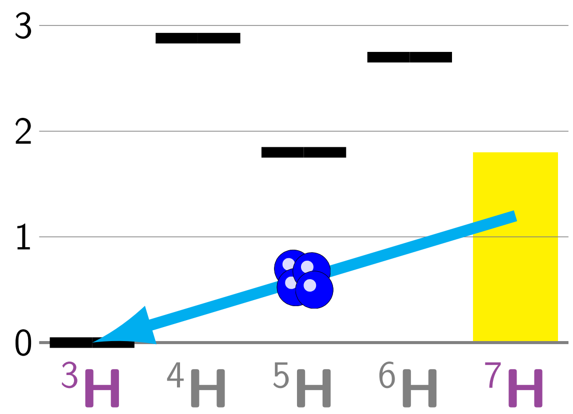


→ 7-body final state !

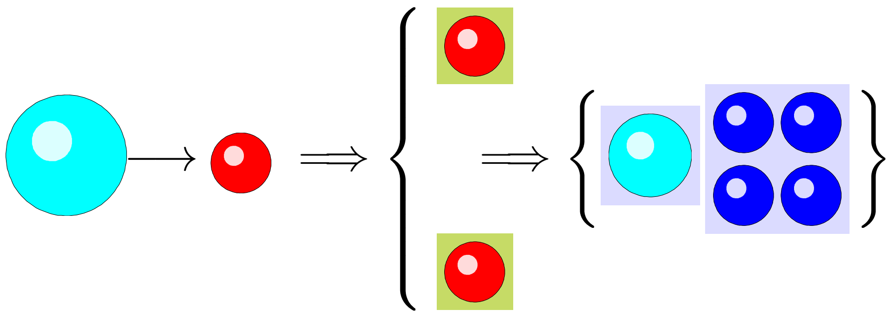
→ FWHM ∼ few MeV



- N = 6 $(\nu p_{3/2})^4$ sub-shell closure ?



▶ ^{8}He (p,2p) ^{7}H @ 150 MeV/N :



→ 7-body final state !

→ FWHM ∼ few MeV → 100 keV !

- an array of arrays :

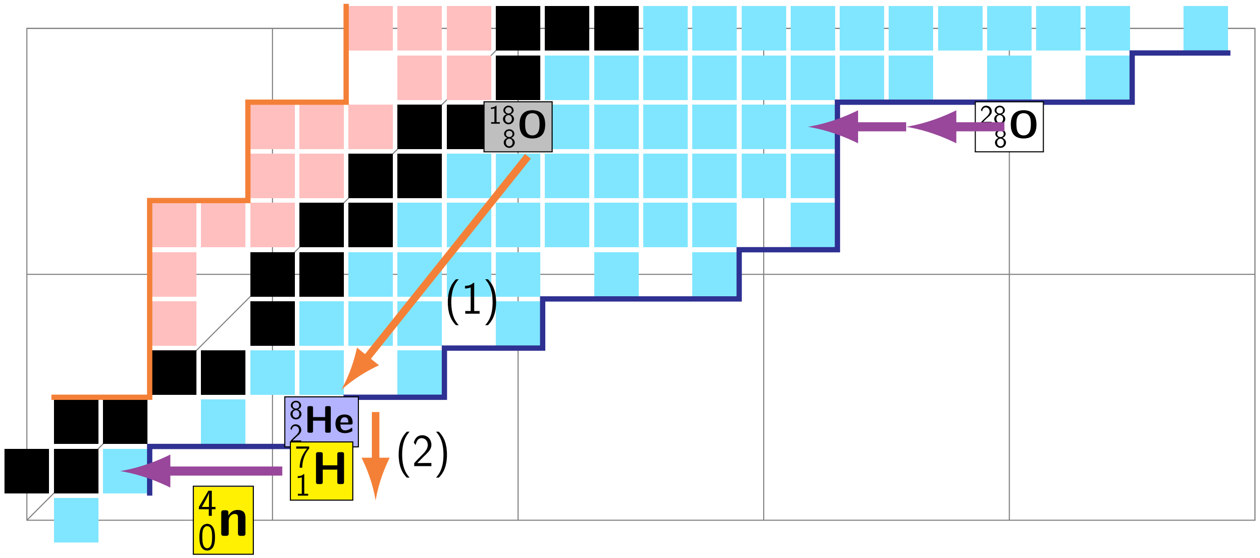
→ **MINOS** liquid H target

→ **DALI** NaI crystals

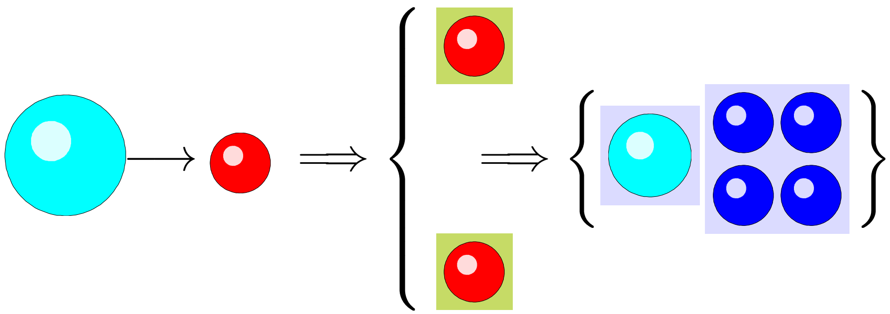
→ **SAMURAI** spectrometer

→ **NEBULA + NeuLAND**

Hydrogen 7 & Tetraneutron 'emission' ?



► ^{8}He (p,2p) ^{7}H @ 150 MeV/N :

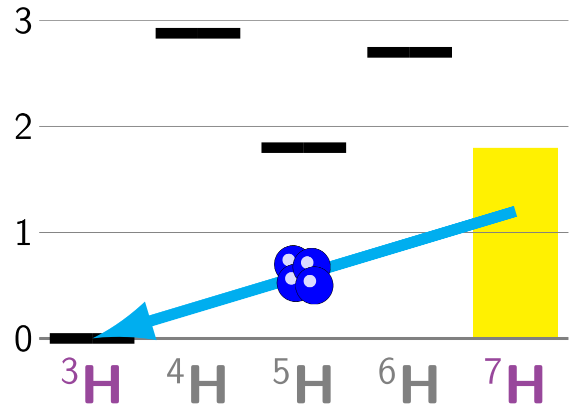


→ 7-body final state !

→ FWHM ∼ few MeV → 100 keV !

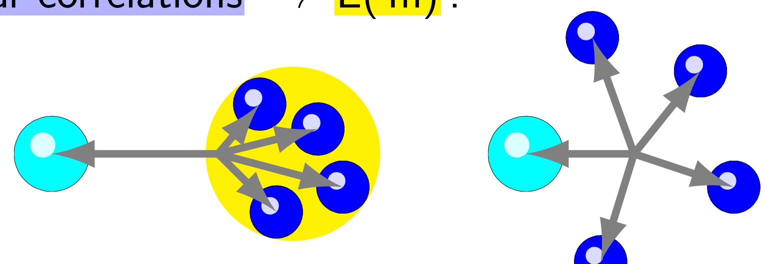
→ (2p+t+3n) ∼ 150 keV

- N = 6 $(\nu p_{3/2})^4$ sub-shell closure ?



- an array of arrays :
  - → **MINOS** liquid H target
  - → **DALI** NaI crystals
  - → **SAMURAI** spectrometer
  - → **NEBULA + NeuLAND**

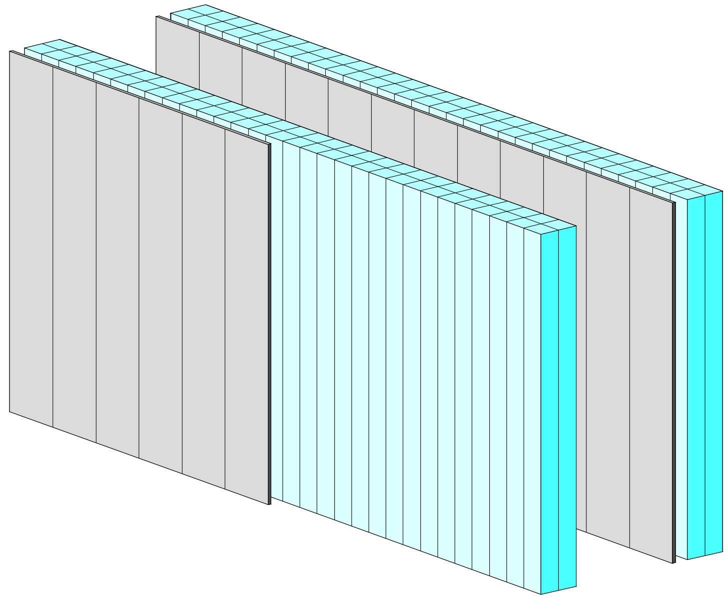
- angular correlations → E(4n) !

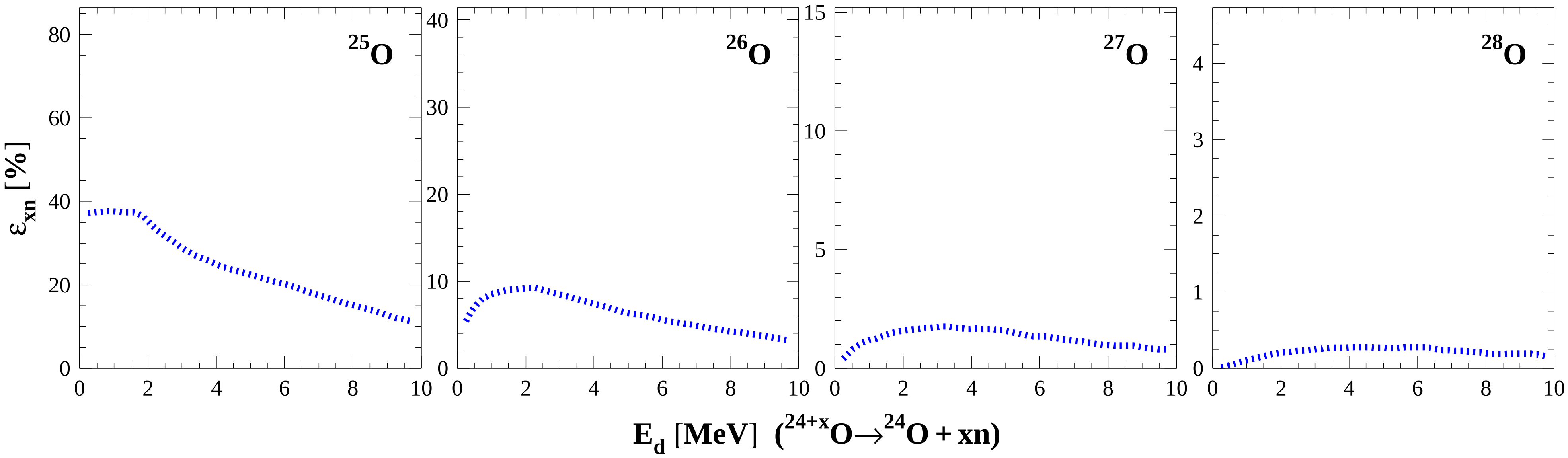


(2-body PS) (5-body PS)

Multineutron detector arrays

- EXPAND project (French ANR):
  - expand NEBULA multi-n capabilities !
    - → France: LPC, IRFU, IPNO
    - → Japan: TITech, RIKEN



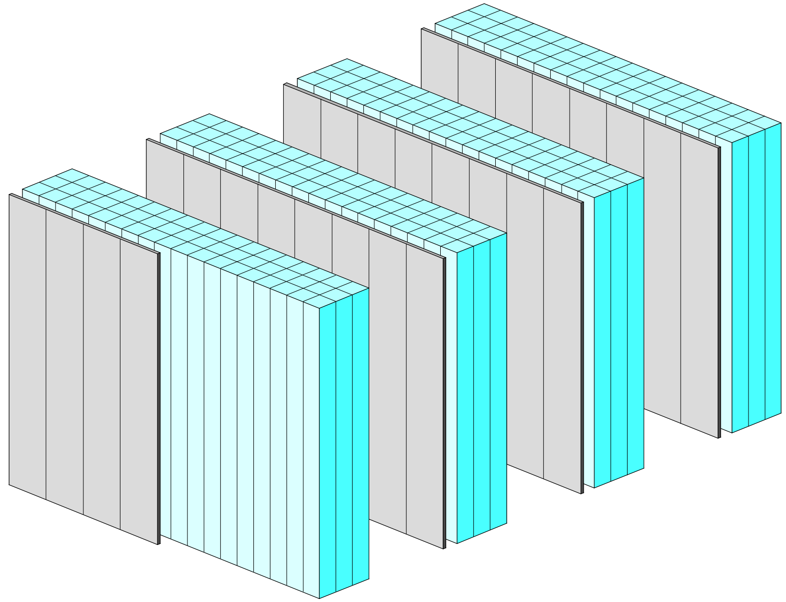


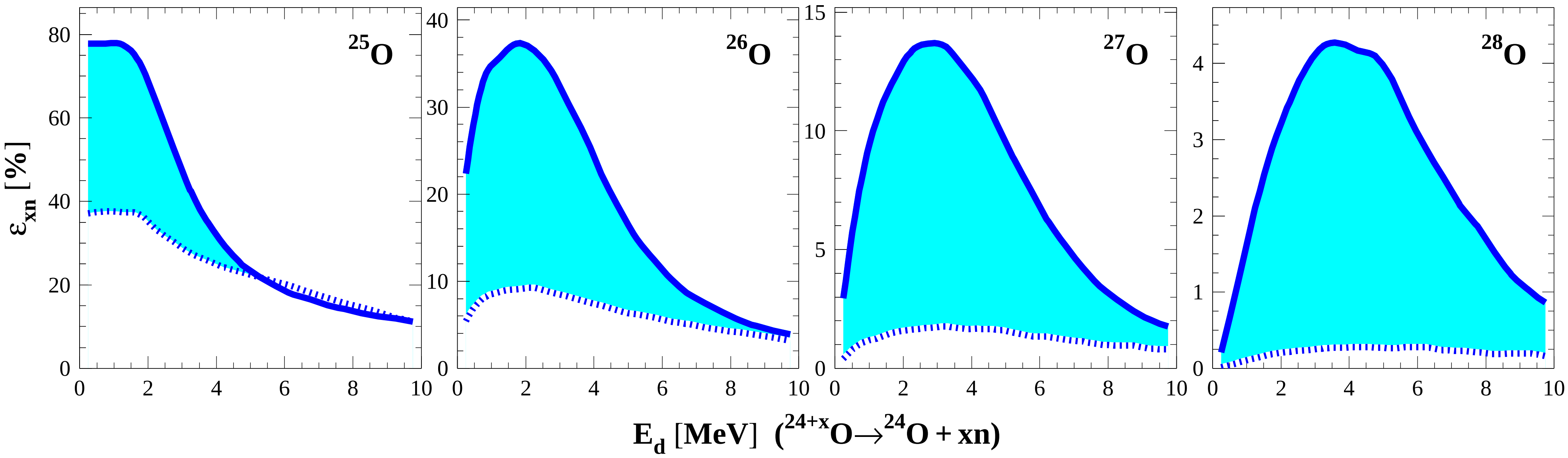
($\varepsilon_{xn} < \varepsilon_n^x$ due to neutron cross-talk) FMM, NIM A 450 (2000) 109

Multineutron detector arrays

- EXPAND project (French ANR) :
  - expand NEBULA multi-n capabilities !
    - → France : LPC, IRFU, IPNO
    - → Japan : TITech, RIKEN
    - → +90 bars : Comm. & Day-1 2021
    - → suggested configuration :

      ⟹ ε(4n) enhanced $\sim \times 16$!



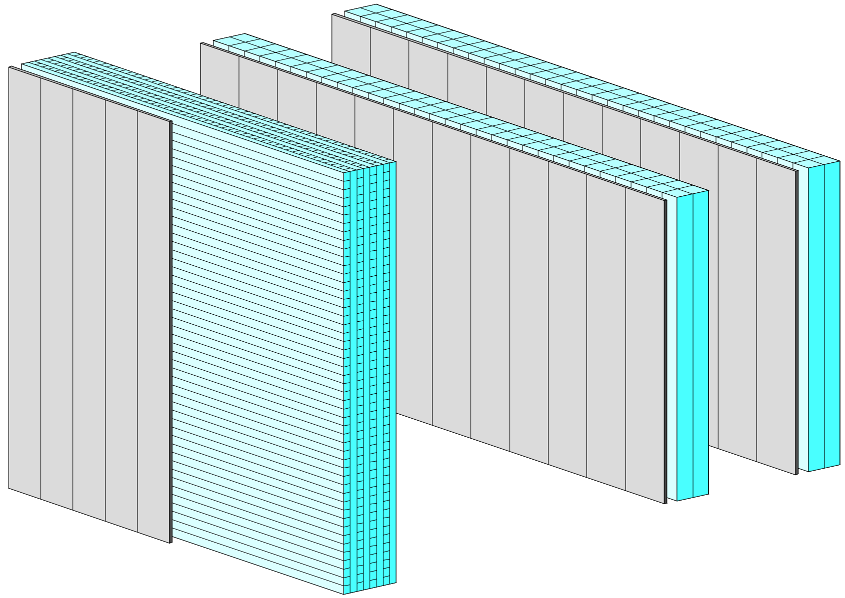


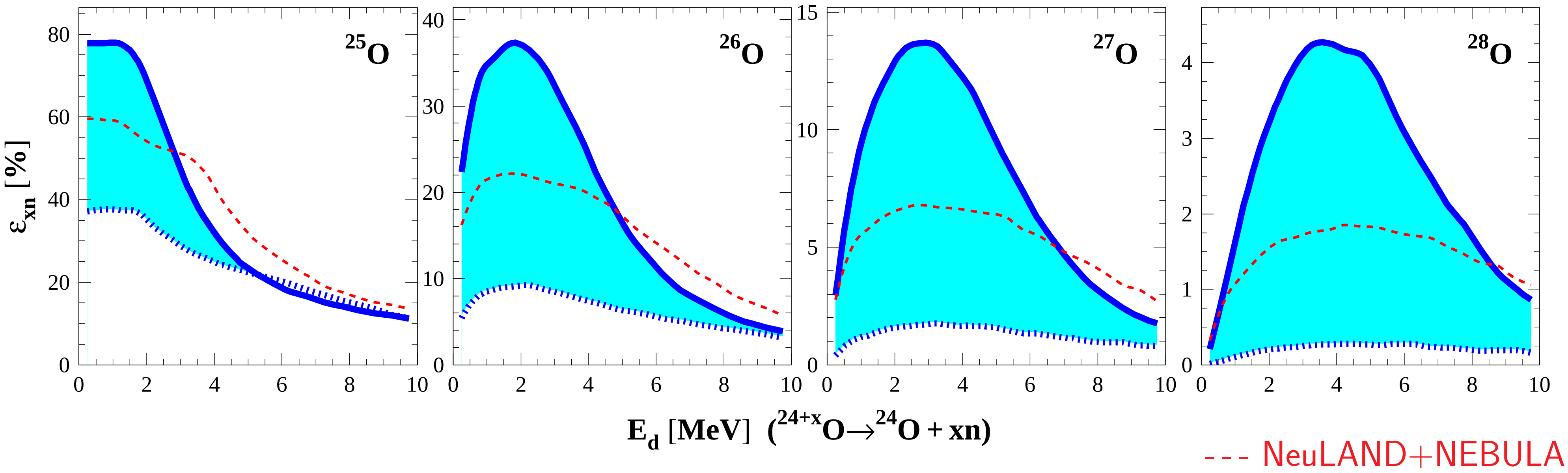
($\varepsilon_{xn} < \varepsilon_n^x$ due to neutron cross-talk) FMM, NIM A 450 (2000) 109

Multineutron detector arrays

- EXPAND project (French ANR) :
  - expand NEBULA multi-n capabilities !
    - → France : LPC, IRFU, IPNO
    - → Japan : TITech, RIKEN
    - → +90 bars : Comm. & Day-1 2021
    - → suggested configuration :

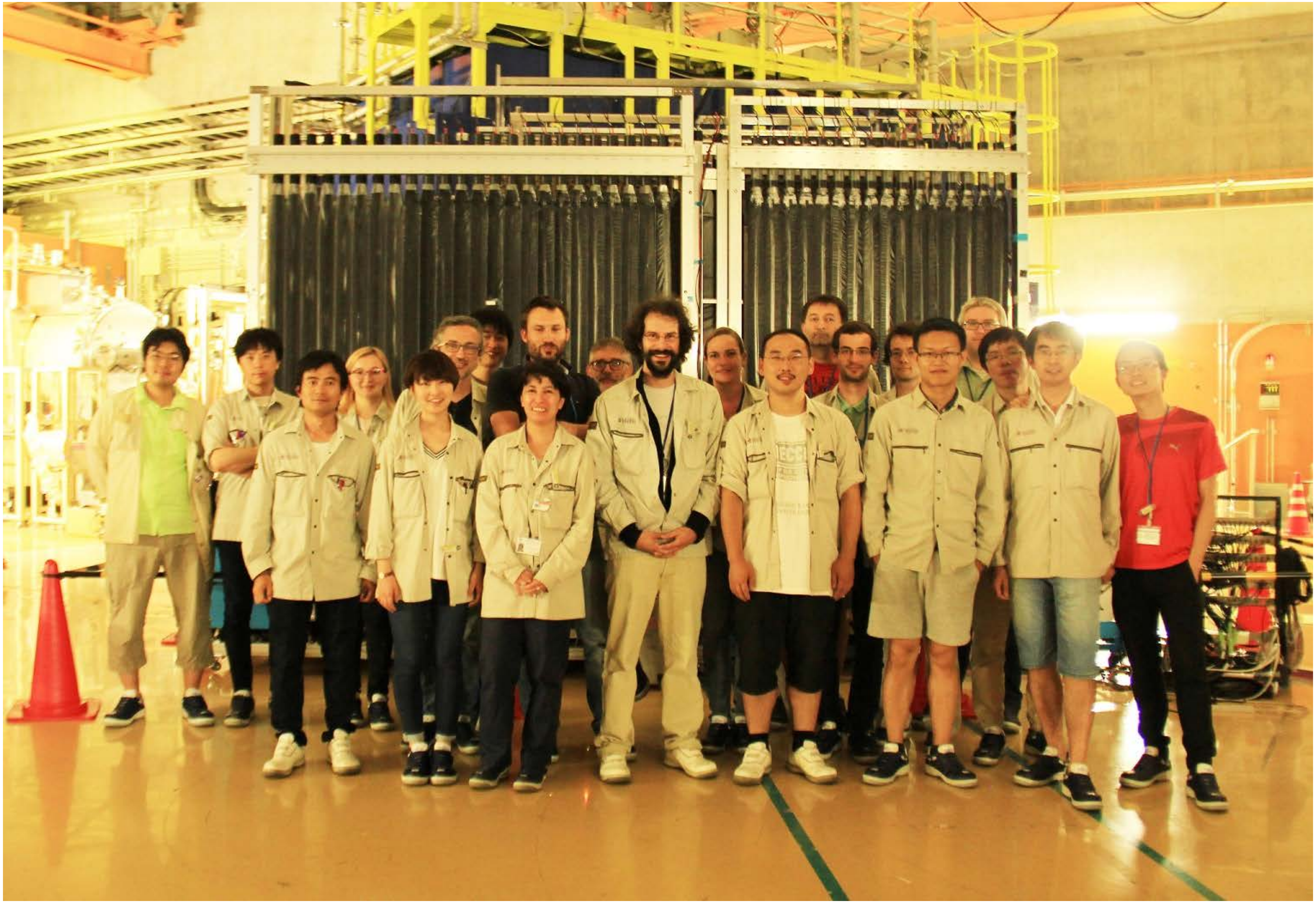
      ⇨ ε(4n) enhanced $\sim \times 16$!





($\varepsilon_{xn} < \varepsilon_n^x$ due to neutron cross-talk) FMM, NIM A 450 (2000) 109

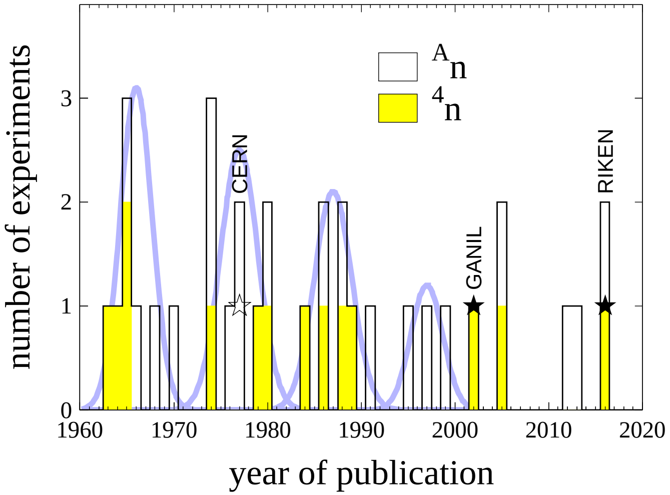
SAMURAI S34 collaboration (part)



RIKEN : SAMURAI (& MINOS-DALI-NeuLAND/NEBULA)

Game over or game on ?

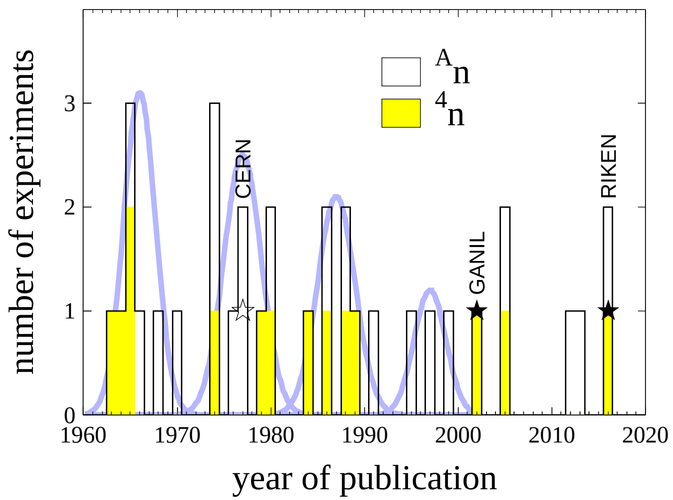
Schiffer (1963) *"As in most experiments of this sort, however, a negative result cannot be regarded as conclusive"*



- An extraordinary series of experiments !
  - very fascinating ideas
  - some very precise results (3n)
  - few 4n signals, still weak

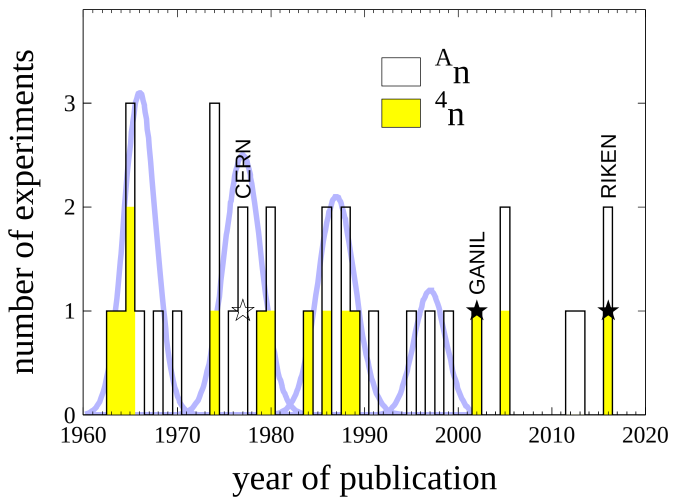
Game over or game on ?

Schiffer (1963) *"As in most experiments of this sort, however, a negative result cannot be regarded as conclusive"*



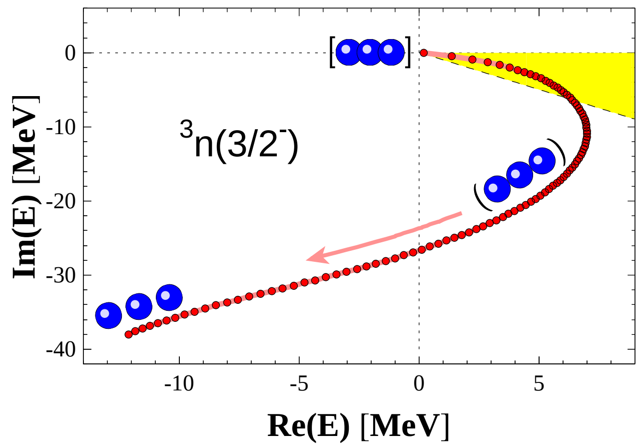
- An extraordinary series of experiments !
  - very fascinating ideas
  - some very precise results (3n)
  - few 4n signals, still weak :
    - → confirm or refute them ...
    - → 4n states or "enhancements" ?
  - 2020s harvest looks good !
    - → high statistics & resolution
    - → first 6n experiments (^{10}He decay) ...

Schiffer (1963) *"As in most experiments of this sort, however, a negative result cannot be regarded as conclusive"*



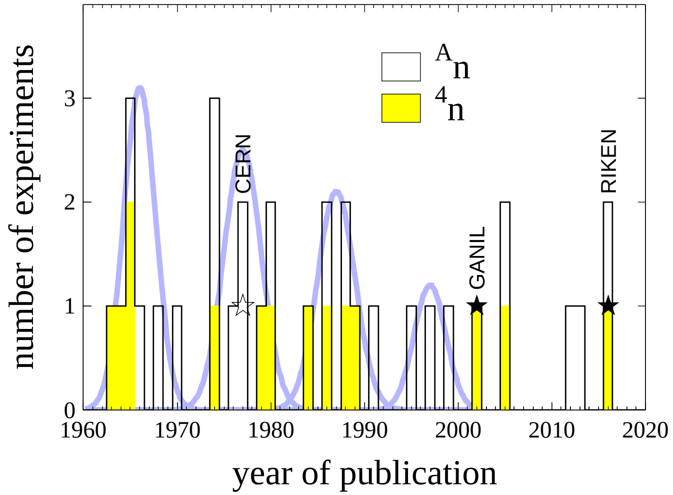
- ▶ An extraordinary series of experiments !
  - very fascinating ideas
  - some very precise results (3n)
  - few 4n signals, still weak :
    - → confirm or refute them …
    - → 4n states or "enhancements" ?
  - 2020s harvest looks good !
    - → high statistics & resolution
    - → first 6n experiments (^{10}He decay) …

- ▶ Some theoretical certainties :
  - all exact calculations categorical :
    - → signals cannot be assigned to 4n "states" !
  - many-body approx. claim 3/4n resonances …
  - consensus : independently of $V_{nn(n)}$!
    - → trap & global scaling : thresholds
    - → extrapolation of states into continuum



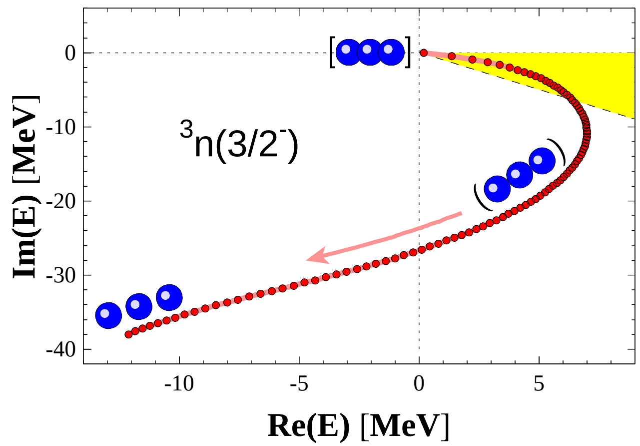
Game over or game on ?

Schiffer (1963) *"As in most experiments of this sort, however, a negative result cannot be regarded as conclusive"*



- ▶ An extraordinary series of experiments !
  - very fascinating ideas
  - some very precise results (3n)
  - few 4n signals, still weak :
    - → confirm or refute them ...
    - → 4n states or "enhancements" ?
  - 2020s harvest looks good !
    - → high statistics & resolution
    - → first 6n experiments (^{10}He decay) ...

- ▶ Some theoretical certainties :
  - all exact calculations categorical :
    - → signals cannot be assigned to 4n "states" !
  - many-body approx. claim 3/4n resonances ...
  - consensus : independently of $V_{nn(n)}$!
    - → trap & global scaling : thresholds
    - → extrapolation of states into continuum



- ▶ Some theoretical hopes ?
  - firm experimental results !
  - QM "enhancements" ?
  - evolution of 6,8,10n ...