



Experimental aspects of nuclear resonances

J. Gibelin

LPC Caen, ENSICAEN, Université de Caen, CNRS/IN2P3, Caen, France
7th September 2021



UNIVERSITÉ
CAEN
NORMANDIE



Normandie Université

- 1 Basics of nuclear physics experiments
- 2 Illustration of resonance production, on the ^{21}C two body unbound nucleus
- 3 Three body resonance: the unbound ^{16}Be case
- 4 The tetra-neutron, a 4 body resonance

Basics of nuclear physics experiments

Wave function

Observables

Theory vs experiments in nuclear physics

Wave function ✗

Observables

Theory vs experiments in nuclear physics

Wave function ✗

$|\text{Wave function}|^2$

Observables

Theory vs experiments in nuclear physics

Wave function ✗

$|\text{Wave function}|^2$ ✗

Observables

Theory vs experiments in nuclear physics

Wave function ✗

$|\text{Wave function}|^2$ ✗

Cross section, decay probability, etc

Observables

Theory vs experiments in nuclear physics

Wave function ✗

$|\text{Wave function}|^2$ ✗

Cross section, decay probability, etc ✓

Observables

Theory vs experiments in nuclear physics

Wave function ✗

$|\text{Wave function}|^2$ ✗

Cross section, decay probability, etc ✓

Pole zero matrix

Observables

Theory vs experiments in nuclear physics

Wave function ✗

$|\text{Wave function}|^2$ ✗

Cross section, decay probability, etc ✓

Pole zero matrix ✗

Observables

Theory vs experiments in nuclear physics

Wave function ✗

$|\text{Wave function}|^2$ ✗

Cross section, decay probability, etc ✓

Pole zero matrix ✗


Designing an experiment

How to get these from our fundamental experimental observables?

Observables

Experimental, fundamental


Direct

Count particles and nuclei  \Rightarrow cross section(s)

Observables

Experimental, fundamental

Direct

Count particles and nuclei  \Rightarrow cross section(s)

Detect part. position(s) (interaction position of or w/in detector)
 \Rightarrow distance(s) angle(s)

Observables

Experimental, fundamental

Direct

Count particles and nuclei  \Rightarrow cross section(s)

Detect part. position(s) (interaction position of or w/in detector)
 \Rightarrow distance(s) angle(s)

Deposited (kinetic) energy (not necessarily total!)

Observables

Experimental, fundamental

Direct

Count particles and nuclei ~~||||~~ \Rightarrow cross section(s)

Detect part. position(s) (interaction position of or w/in detector)
 \Rightarrow distance(s) angle(s)


Deposited (kinetic) energy (not necessarily total!)

Time difference (w/ respect to a ref.)

Observables

Experimental, fundamental

Direct

Count particles and nuclei  \Rightarrow cross section(s)

Detect part. position(s) (interaction position of or w/in detector)
 \Rightarrow distance(s) angle(s)

Deposited (kinetic) energy (not necessarily total!)


Time difference (w/ respect to a ref.)

Indirect

Observables

Experimental, fundamental

Direct

Count particles and nuclei  \Rightarrow cross section(s)

Detect part. position(s) (interaction position of or w/in detector)
 \Rightarrow distance(s) angle(s)

Deposited (kinetic) energy (not necessarily total!)

Time difference (w/ respect to a ref.)

Indirect

Mass

Observables

Experimental, fundamental

Direct

Count particles and nuclei ~~||||~~ \Rightarrow cross section(s)

Detect part. position(s) (interaction position of or w/in detector)
 \Rightarrow distance(s) angle(s)

Deposited (kinetic) energy (not necessarily total!)

Time difference (w/ respect to a ref.)

Indirect

Mass



Observables

Experimental, fundamental

Direct

Count particles and nuclei ~~||||~~ \Rightarrow cross section(s)

Detect part. position(s) (interaction position of or w/in detector)
 \Rightarrow distance(s) angle(s)

Deposited (kinetic) energy (not necessarily total!)

Time difference (w/ respect to a ref.)

Indirect

Mass

Kinetic energy

Observables

Experimental, fundamental

Direct

Count particles and nuclei ~~||||~~ |||| \Rightarrow cross section(s)

Detect part. position(s) (interaction position of or w/in detector)
 \Rightarrow distance(s) angle(s)

Deposited (kinetic) energy (not necessarily total!)

Time difference (w/ respect to a ref.)

Indirect

Mass

Kinetic energy

Momentum

Observables

Experimental, fundamental

Direct

Count particles and nuclei ~~||||~~ \Rightarrow cross section(s)

Detect part. position(s) (interaction position of or w/in detector)
 \Rightarrow distance(s) angle(s)

Deposited (kinetic) energy (not necessarily total!)

Time difference (w/ respect to a ref.)

Indirect

Mass

Kinetic energy

Momentum

Observables

Experimental, fundamental

Direct

Count particles and nuclei ~~||||~~ \Rightarrow cross section(s)

Detect part. position(s) (interaction position of or w/in detector)
 \Rightarrow distance(s) angle(s)

Deposited (kinetic) energy (not necessarily total!)

Time difference (w/ respect to a ref.)

Indirect

Mass

Kinetic energy

Momentum

Q-value

Observables

Experimental, fundamental

Direct

Count particles and nuclei  \Rightarrow cross section(s)

Detect part. position(s) (interaction position of or w/in detector)
 \Rightarrow distance(s) angle(s)

Deposited (kinetic) energy (not necessarily total!)

Time difference (w/ respect to a ref.)

Indirect

Mass

Kinetic energy

Momentum

Q-value



Observables

Experimental, fundamental

Direct

Count particles and nuclei ~~||||~~ \Rightarrow cross section(s)

Detect part. position(s) (interaction position of or w/in detector)
 \Rightarrow distance(s) angle(s)

Deposited (kinetic) energy (not necessarily total!)

Time difference (w/ respect to a ref.)

Indirect

Mass

Kinetic energy

Momentum

Q-value

Angular distribution

Observables

Experimental, fundamental

Direct

Count particles and nuclei ~~||||~~ \Rightarrow cross section(s)

Detect part. position(s) (interaction position of or w/in detector)
 \Rightarrow distance(s) angle(s)

Deposited (kinetic) energy (not necessarily total!)

Time difference (w/ respect to a ref.)

Indirect

Mass

Kinetic energy

Momentum

Q-value

Angular distribution

Observables

Experimental, fundamental

Direct

Count particles and nuclei ~~||||~~ \Rightarrow cross section(s)

Detect part. position(s) (interaction position of or w/in detector)
 \Rightarrow distance(s) angle(s)

Deposited (kinetic) energy (not necessarily total!)

Time difference (w/ respect to a ref.)

Indirect

Mass

Kinetic energy

Momentum

Q-value

Angular distribution

etc

Charged particles

electrons

muons

protons, nuclei

...

Electromagnetic interaction (usually *via* electrons of the material)

⇒ direct observation

Charged particles

electrons

muons

protons, nuclei

...

Electromagnetic interaction (usually *via* electrons of the material)

⇒ direct observation

Neutral particles

gamma

neutrons

...

Observables

Particles

Charged particles

electrons

muons

protons, nuclei

...

Electromagnetic interaction (usually *via* electrons of the material)

⇒ direct observation

Neutral particles

gamma

neutrons

...

Observables

Particles

Charged particles

electrons

muons

protons, nuclei

...

Electromagnetic interaction (usually *via* electrons of the material)

⇒ direct observation

Neutral particles

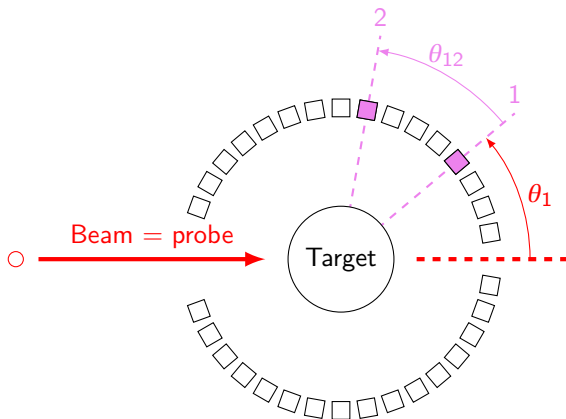
gamma

neutrons

...

Direct vs reverse kinematics

Direct kinematics



Light (probe) against heavy
CM \sim Laboratory

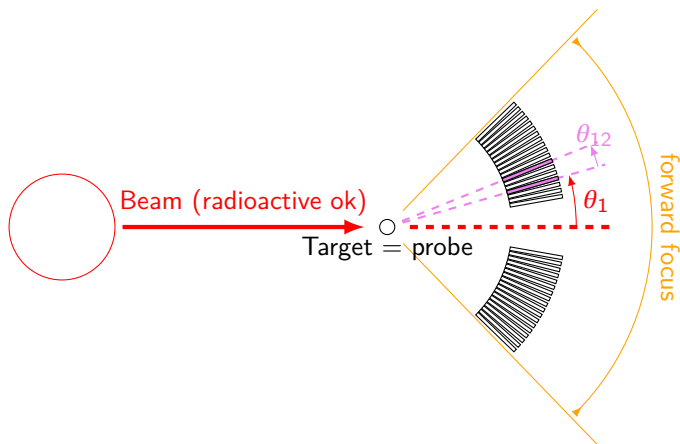
Target must be (almost)
stable!

Direct vs reverse kinematics

Reverse kinematics

Heavy against light (probe)

⇒ boost forward



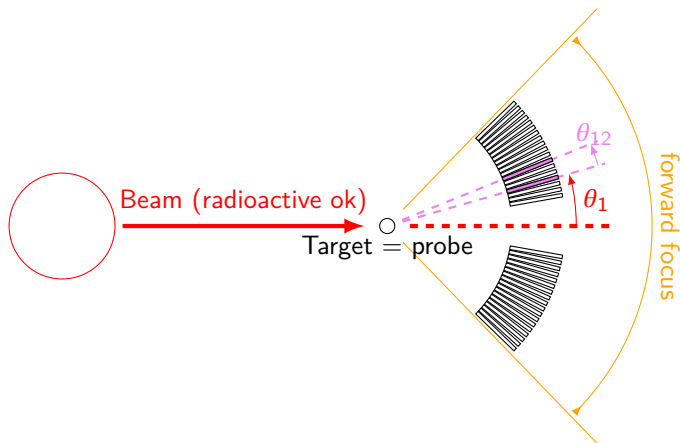
Direct vs reverse kinematics

Reverse kinematics

Heavy against light (probe)

⇒ boost forward

⇒ reduced detection area (smaller detectors)



Direct vs reverse kinematics

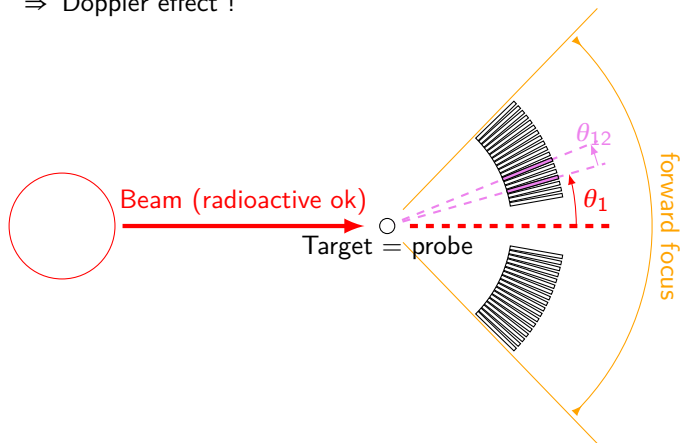
Reverse kinematics

Heavy against light (probe)

⇒ boost forward

⇒ reduced detection area (smaller detectors)

⇒ Doppler effect !



Direct vs reverse kinematics

Reverse kinematics

Heavy against light (probe)

⇒ boost forward

⇒ reduced detection area (smaller detectors)

⇒ Doppler effect !

...

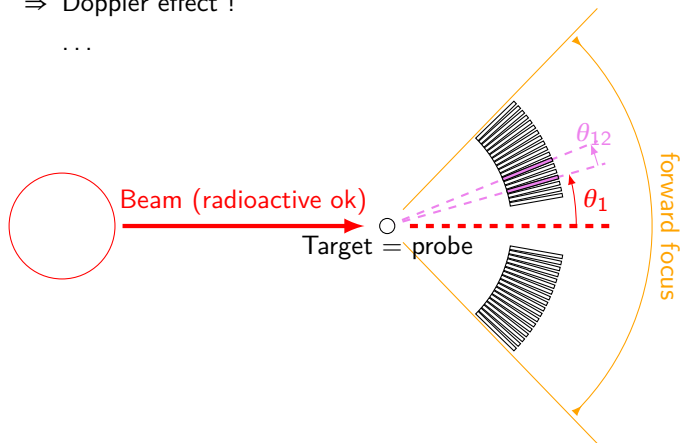
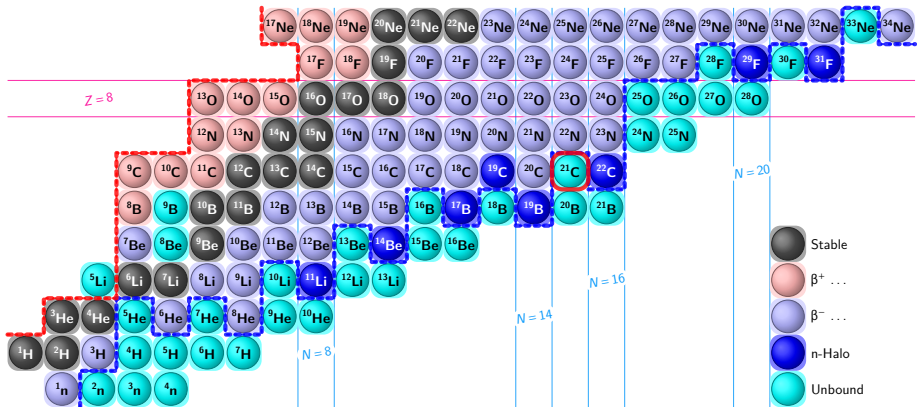
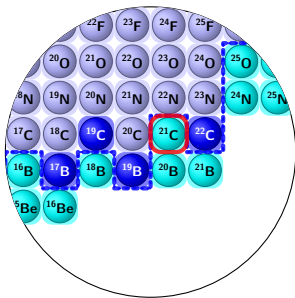


Illustration of resonance production, on the ^{21}C two body
unbound nucleus

How to produce resonances (neutron drip-line case)



How to produce resonances (neutron drip-line case)



Case study: $^{21}\text{C} \equiv ^{20}\text{C} + n$

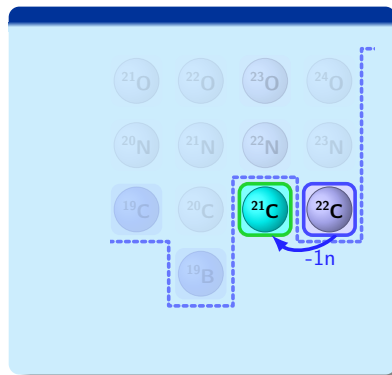


Strategies

Example : Study of unbound ^{21}C

^{22}C : 1-neutron knockout to (core+ n)

halo "hole" state



Strategies

Example : Study of unbound ^{21}C

^{22}C : 1-neutron knockout to (core+ n)

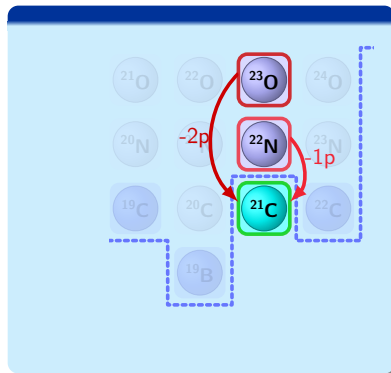
halo "hole" state



^{22}N : 1-proton K.O. to (core+ n)

^{23}O : 2-proton K.O. to (core+ n)

$v_{\text{final}} \approx v_{\text{initial}}$



Strategies

Example : Study of unbound ^{21}C

^{22}C : 1-neutron knockout to (core+ n)

halo "hole" state



^{22}N : 1-proton K.O. to (core+ n)

^{23}O : 2-proton K.O. to (core+ n)

$v_{\text{final}} \approx v_{\text{initial}}$



^{21}N : Charge exchange

Selectivity, parity change. . .



Strategies

Example : Study of unbound ^{21}C

^{22}C : 1-neutron knockout to (core+ n)

halo “hole” state



^{22}N : 1-proton K.O. to (core+ n)

^{23}O : 2-proton K.O. to (core+ n)

$v_{\text{final}} \approx v_{\text{initial}}$

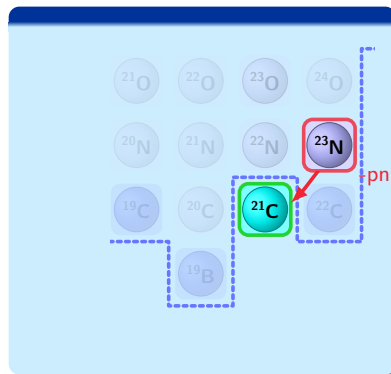


^{21}N : Charge exchange

Selectivity, parity change. . .

^{23}N : Multiple neutron removal

Non selective



Strategies

Example : Study of unbound ^{21}C

^{22}C : 1-neutron knockout to (core+ n)

halo “hole” state



^{22}N : 1-proton K.O. to (core+ n)

^{23}O : 2-proton K.O. to (core+ n)

$v_{\text{final}} \approx v_{\text{initial}}$



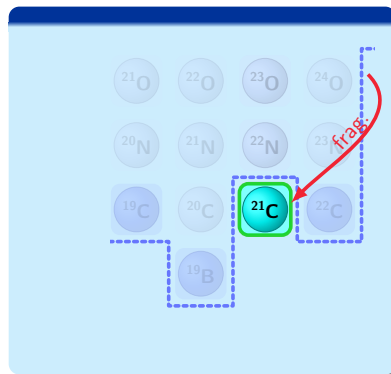
^{21}N : Charge exchange

Selectivity, parity change. . .

^{23}N : Multiple neutron removal

$A > 21, Z > 6$: “Fragmentation”

Non selective



Strategies

Example : Study of unbound ^{21}C

^{22}C : 1-neutron knockout to (core+ n)

halo “hole” state



^{22}N : 1-proton K.O. to (core+ n)

^{23}O : 2-proton K.O. to (core+ n)

$v_{\text{final}} \approx v_{\text{initial}}$



^{21}N : Charge exchange

Selectivity, parity change. . .

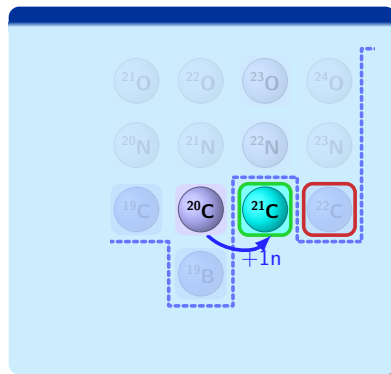
^{23}N : Multiple neutron removal

$A > 21, Z > 6$: “Fragmentation”

Non selective

^{20}C : Transfer reaction (here d, p)

Neutron shells probe



Strategies

Example : Study of unbound ^{21}C

^{22}C : 1-neutron knockout to (core+ n)

halo “hole” state



^{22}N : 1-proton K.O. to (core+ n)

^{23}O : 2-proton K.O. to (core+ n)

$v_{\text{final}} \approx v_{\text{initial}}$



^{21}N : Charge exchange

Selectivity, parity change. . .

^{23}N : Multiple neutron removal

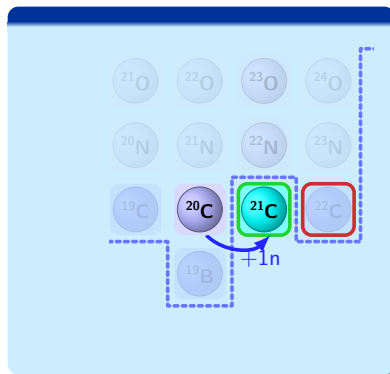
$A > 21, Z > 6$: “Fragmentation”

Non selective

^{20}C : Transfer reaction (here d, p)

Neutron shells probe

...



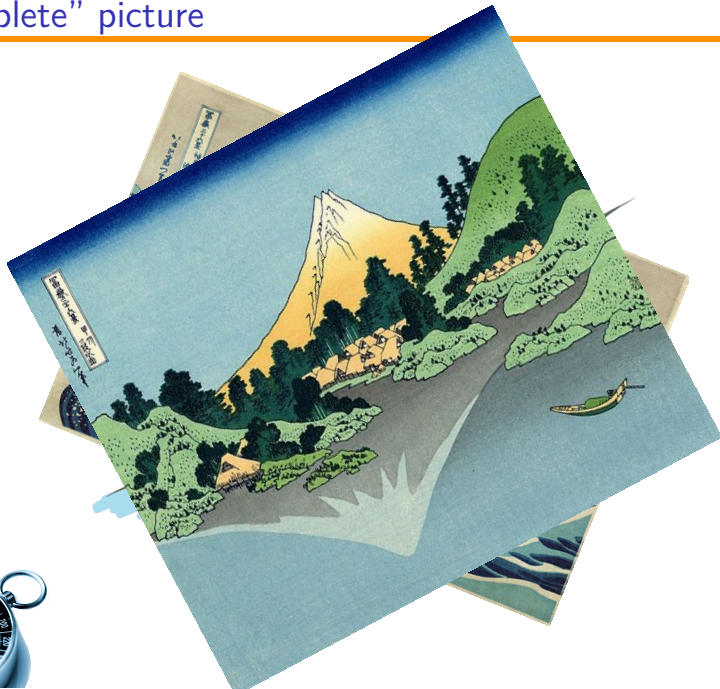
“Complete” picture



“Complete” picture



“Complete” picture



“Complete” picture



“Complete” picture



“Complete” picture



“Complete” picture



“Complete” picture



“Complete” picture



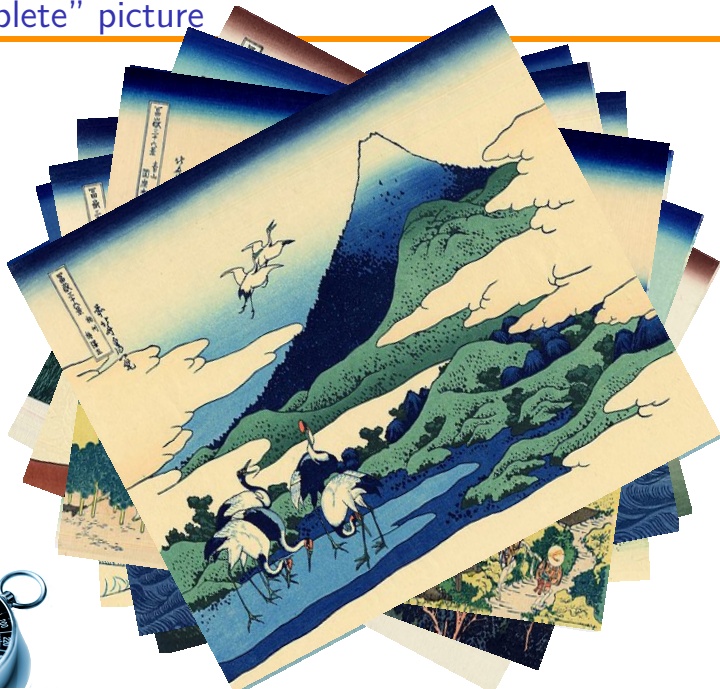
“Complete” picture



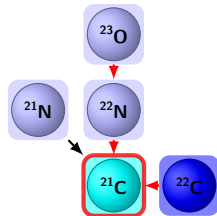
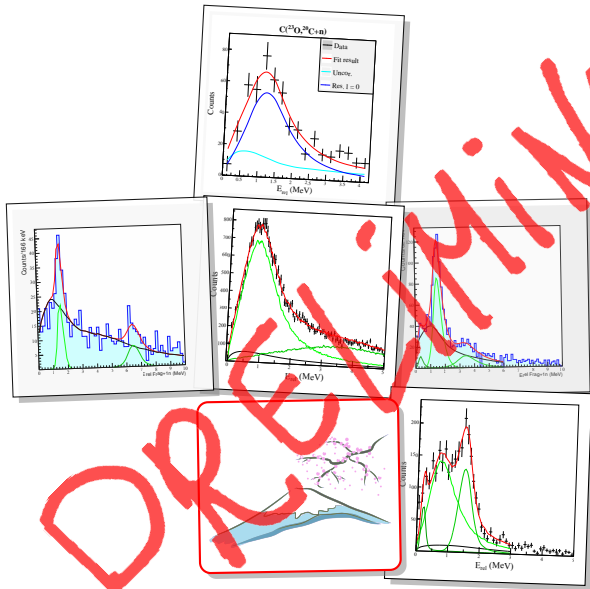
“Complete” picture



“Complete” picture

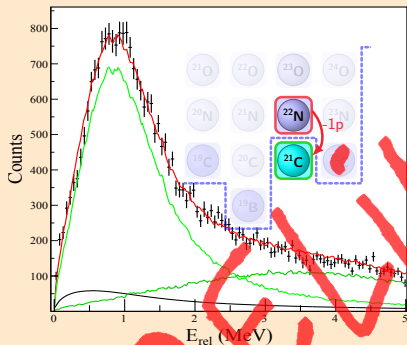


^{21}C "Complete" picture

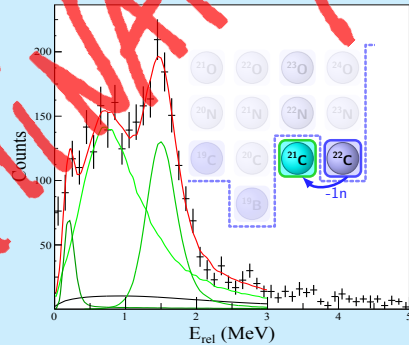


^{21}C : main channels (S. Leblond's PhD)

p -K.O.



n -K.O.



points: data

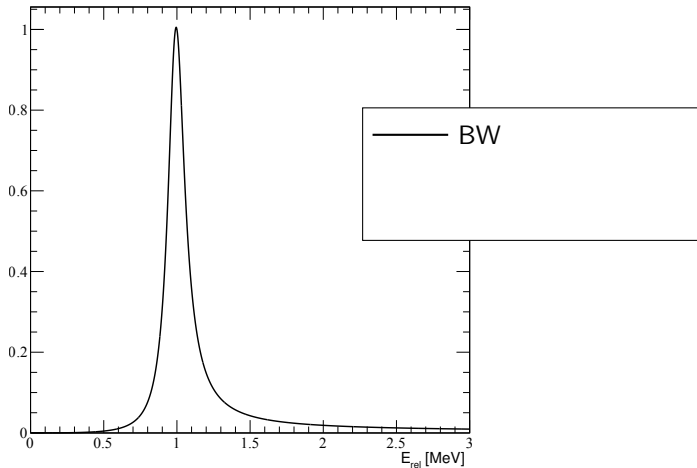
black line: non correlated background

green lines: resonant states \equiv energy dependent width BW convoluted w/
experimental response function

Compare experimental spectra & theoretical distribution

(Response matrix method)

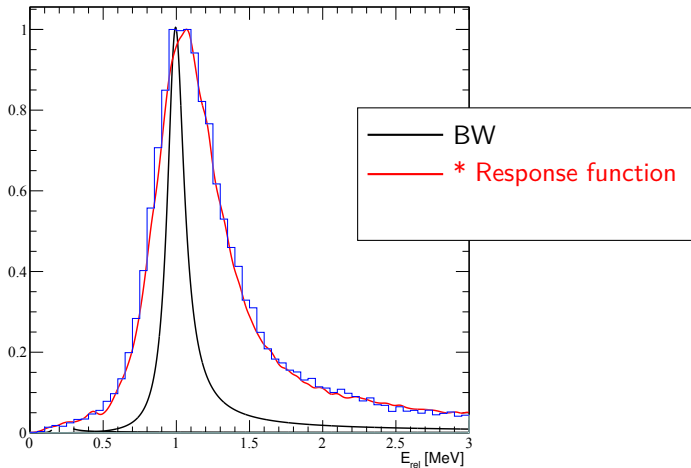
In principle theory can not **directly** be compared to experimental spectra



Compare experimental spectra & theoretical distribution

(Response matrix method)

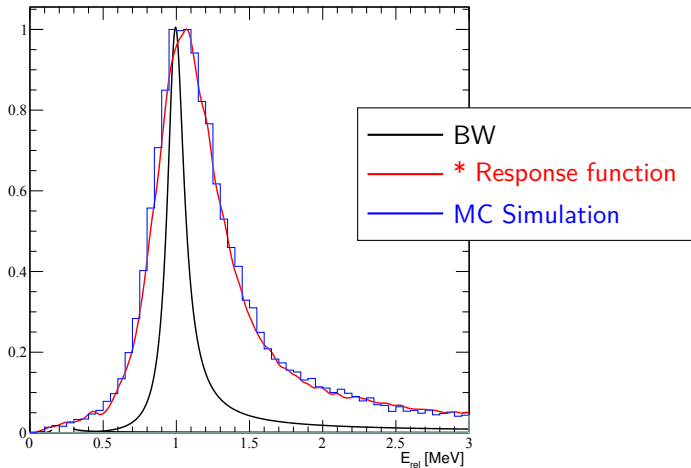
In principle theory can not **directly** be compared to experimental spectra



Compare experimental spectra & theoretical distribution

(Response matrix method)

In principle theory can not **directly** be compared to experimental spectra



Compare experimental spectra & theoretical distribution

(Response matrix method)

$$\underbrace{f_{\text{exp.}}(E_r)}_{\text{Experimental distribution}} = (\underbrace{f}_{\text{Resonances...}} * \underbrace{\mathcal{R}}_{\text{Response function}})(E_r) = \int_0^\infty f(\epsilon) \mathcal{R}(E_r - \epsilon) d\epsilon$$

Experimental distribution

Resonances...

Response function

Compare experimental spectra & theoretical distribution

(Response matrix method)

$$\underbrace{f_{\text{exp.}}(E_r)}_{\text{Experimental distribution}} = (\underbrace{f}_{\text{Resonances...}} * \underbrace{\mathcal{R}}_{\text{Response function}})(E_r) = \int_0^\infty f(\epsilon) \mathcal{R}(E_r - \epsilon) d\epsilon$$

Experimental distribution

Resonances...

Response function

Discrete values \Rightarrow matrix elements

$$f_{\text{exp.}}(e_j) = \sum_i f(e_i) m_{ij}$$

Compare experimental spectra & theoretical distribution

(Response matrix method)

$$\underbrace{f_{\text{exp.}}(E_r)}_{\text{Experimental distribution}} = (\underbrace{f}_{\text{Resonances...}} * \underbrace{\mathcal{R}}_{\text{Response function}})(E_r) = \int_0^\infty f(\epsilon) \mathcal{R}(E_r - \epsilon) d\epsilon$$

Resonances...

Experimental distribution

Response function

Discrete values \Rightarrow matrix elements (interpolation)

$$f_{\text{exp.}}(e_j) = \sum_i f(e_i) m_{ij} = \sum_i f(e_i) \left[m_{ij} + (m_{i(j+1)} - m_{ij}) \frac{E_r - e_{ij}}{e_{i(j+1)} - e_{ij}} \right]$$

w/ $j: e_j \leq E_r \leq e_{j+1}$

Compare experimental spectra & theoretical distribution

(Response matrix method)

Procedure

Simulate + analyze the experimental response for uniformly distributed energies of resonances E_r^{in}

Fill a 2D histogram/matrix for the pair (E_r^{in}, E_r^{out})

Normalize the matrix

Compare experimental spectra & theoretical distribution

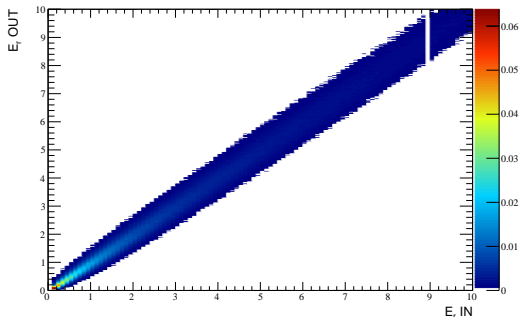
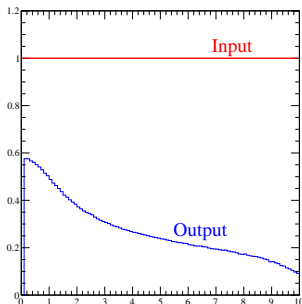
(Response matrix method)

Procedure

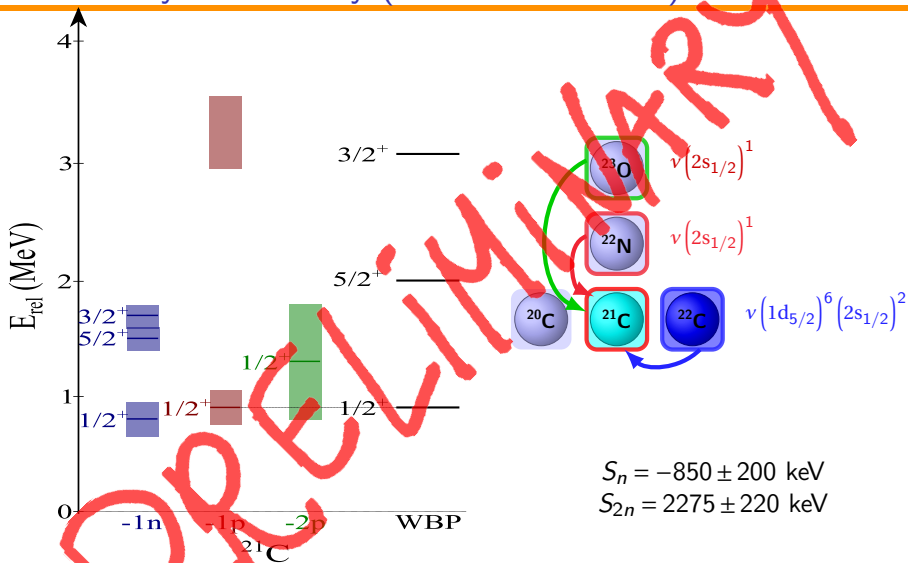
Simulate + analyze the experimental response for uniformly distributed energies of resonances E_r^{in}

Fill a 2D histogram/matrix for the pair (E_r^{in}, E_r^{out})

Normalize the matrix



^{21}C : Analysis summary (S. Leblond's PhD)



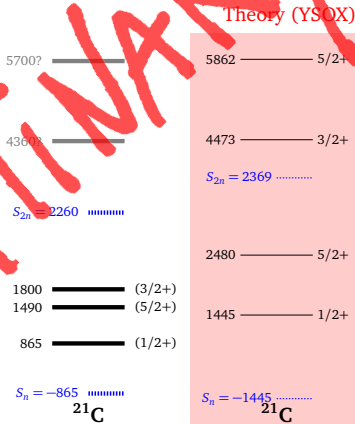
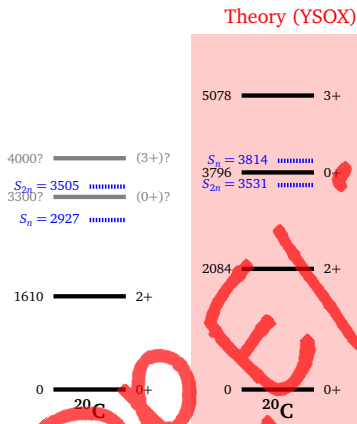
$$S_n = -850 \pm 200 \text{ keV}$$

$$S_{2n} = 2275 \pm 220 \text{ keV}$$

SM calculations:

Kobayashi, PRC 86 (2012) 054604

²¹C: Analysis techniques



Theory: Yuan PRC85(2012)064324 + J. Bonnard Priv. Comm.

^{21}C : Analysis summary (ext'd)

Occupation factors & decay probabilities

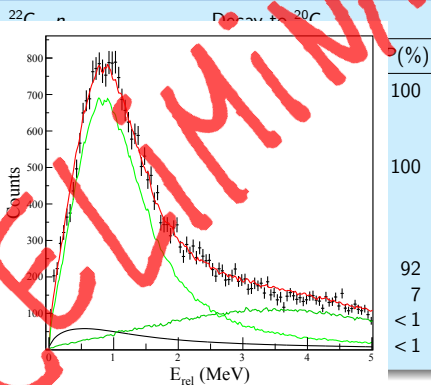
^{21}C		$^{22}\text{N}-p$	$^{22}\text{C}-n$	Decay to ^{20}C				
E_x	J^π	$\sim \langle ^{21}\text{C} ^{22}\text{N} \rangle$	$\sim \langle ^{21}\text{C} ^{22}\text{C} \rangle$	E_x	nlj	$\sim \langle ^{21}\text{C} ^{20}\text{C} \rangle$	Γ	$P(\%)$
gs	$1/2^+$	0.8	1.5	gs	$2s_{1/2}$	0.3	5.0	100
				2.1	$1d_{3/2}$	0.1		
					$1d_{5/2}$	1.3		
1.0	$5/2^+$	0.1	4.6	gs	$1d_{5/2}$	0.2	0.2	100
				2.1	$2s_{1/2}$	0.4		
					$1d_{3/2}$	~ 0		
					$1d_{5/2}$	0.4		
3.0	$3/2^+$	~ 0	0.2	gs	$1d_{3/2}$	0.7	0.3	92
				2.1	$2s_{1/2}$	~ 0	2.4	7
					$1d_{3/2}$	0.1	~ 0	< 1
					$1d_{5/2}$	0.2	~ 0	< 1

Theory: Yuan PRC85(2012)064324 + J. Bonnard Priv. Comm.

^{21}C : Analysis summary (ext'd)

Occupation factors & decay probabilities

^{21}C	$^{22}\text{N}-p$	
E_x	J^π	$\sim \langle ^{21}\text{C} ^{22}\text{N} \rangle$
gs	$1/2^+$	0.8
1.0	$5/2^+$	0.1
3.0	$3/2^+$	~ 0

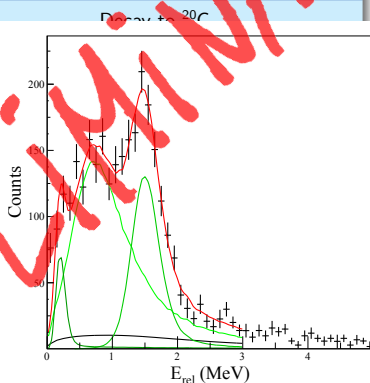


Theory: Yuan PRC85(2012)064324 + J. Bonnard Priv. Comm.

^{21}C : Analysis summary (ext'd)

Occupation factors & decay probabilities

^{21}C		$^{22}\text{N}-p$	$^{22}\text{C}-n$
E_x	J^π	$\sim \langle ^{21}\text{C} ^{22}\text{N} \rangle$	$\sim \langle ^{21}\text{C} ^{22}\text{C} \rangle$
gs	$1/2^+$	0.8	1.5
1.0	$5/2^+$	0.1	4.6
3.0	$3/2^+$	~ 0	0.2



Theory: Yuan PRC85(2012)064324 + J. Bonnard Priv. Comm.

^{21}C : Analysis summary (ext'd)

Occupation factors & decay probabilities

^{21}C		$^{22}\text{N} - p$	$^{22}\text{C} - n$	Decay to ^{20}C				
E_x	J^π	$\sim \langle ^{21}\text{C} ^{22}\text{N} \rangle$	$\sim \langle ^{21}\text{C} ^{22}\text{C} \rangle$	E_x	nlj	$\sim \langle ^{21}\text{C} ^{20}\text{C} \rangle$	Γ	$P(\%)$
gs	$1/2^+$	0.8	1.5	gs	$2s_{1/2}$	0.3	5.0	100
				2.1	$1d_{3/2}$	0.1		
					$1d_{5/2}$	1.3		
1.0	$5/2^+$	0.1	4.6	gs	$1d_{5/2}$	0.2	0.2	100
3.0	$3/2^+$	~ 0	0.2					

Theory: Yuan PRC85(2012)064324 + J. Bonnard Priv. Comm.

^{21}C : Analysis summary (ext'd)

Occupation factors & decay probabilities

^{21}C		$^{22}\text{N} - p$	$^{22}\text{C} - n$	Decay to ^{20}C				
E_x	J^π	$\sim \langle ^{21}\text{C} ^{22}\text{N} \rangle$	$\sim \langle ^{21}\text{C} ^{22}\text{C} \rangle$	E_x	nlj	$\sim \langle ^{21}\text{C} ^{20}\text{C} \rangle$	Γ	$P(\%)$
gs	$1/2^+$	0.8	1.5	gs	$2s_{1/2}$	0.3	5.0	100
				2.1	$1d_{3/2}$	0.1		
					$1d_{5/2}$	1.3		
1.0	$5/2^+$	0.1	4.6	gs	$1d_{5/2}$	0.2	0.2	100
				2.1	$2s_{1/2}$	0.4		
					$1d_{3/2}$	~ 0		
					$1d_{5/2}$	0.4		
3.0	$3/2^+$	~ 0	0.2	gs	$1d_{3/2}$	0.7	0.3	92

$^{20}\text{C}^*?$
(r)

Theory: Yuan PRC85(2012)064324 + J. Bonnard Priv. Comm.

^{21}C : Analysis summary (ext'd)

Occupation factors & decay probabilities

^{21}C		$^{22}\text{N} - p$	$^{22}\text{C} - n$	Decay to ^{20}C				
E_x	J^π	$\sim \langle ^{21}\text{C} ^{22}\text{N} \rangle$	$\sim \langle ^{21}\text{C} ^{22}\text{C} \rangle$	E_x	nlj	$\sim \langle ^{21}\text{C} ^{20}\text{C} \rangle$	Γ	$P(\%)$
gs	$1/2^+$	0.8	1.5	gs	$2s_{1/2}$	0.3	5.0	100
				2.1	$1d_{3/2}$	0.1		
1.0	$5/2^+$	0.1	4.6		$1d_{5/2}$	1.3	0.2	100
				gs	$1d_{5/2}$	0.2		
				2.1	$2s_{1/2}$	0.4		
					$1d_{3/2}$	~ 0		
					$1d_{5/2}$	0.4		
3.0	$3/2^+$	~ 0	0.2	gs	$1d_{3/2}$	0.7	0.3	92
				2.1	$2s_{1/2}$	~ 0	2.4	7
					$1d_{3/2}$	0.1	~ 0	< 1
					$1d_{5/2}$	0.2	~ 0	< 1

$^{20}\text{C}^*?$
(r)

Theory: Yuan PRC85(2012)064324 + J. Bonnard Priv. Comm.

^{21}C : Analysis summary (ext'd)

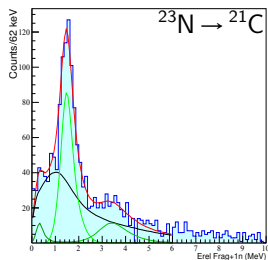
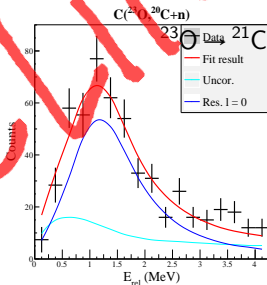
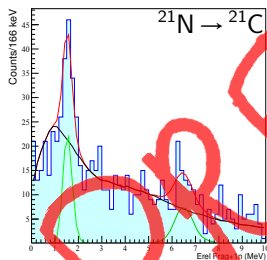
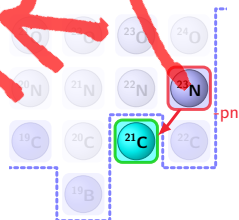
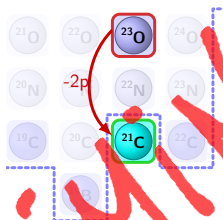
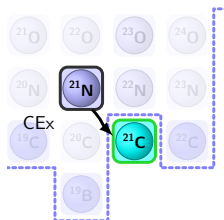
Occupation factors & decay probabilities

^{21}C		$^{22}\text{N} - p$	$^{22}\text{C} - n$	Decay to ^{20}C				
E_x	J^π	$\sim \langle ^{21}\text{C} ^{22}\text{N} \rangle$	$\sim \langle ^{21}\text{C} ^{22}\text{C} \rangle$	E_x	nlj	$\sim \langle ^{21}\text{C} ^{20}\text{C} \rangle$	Γ	$P(\%)$
gs	$1/2^+$	0.8	1.5	gs	$2s_{1/2}$	0.3	5.0	100
				2.1	$1d_{3/2}$	0.1		
1.0	$5/2^+$	0.1	4.6		$1d_{5/2}$	1.3	0.2	100
				gs	$1d_{5/2}$	0.2		
				2.1	$2s_{1/2}$	0.4		
					$1d_{3/2}$	~ 0		
					$1d_{5/2}$	0.4		
3.0	$3/2^+$	~ 0	0.2	gs	$1d_{3/2}$	0.7	0.3	92
				2.1	$2s_{1/2}$	~ 0	2.4	7
					$1d_{3/2}$	0.1	~ 0	< 1
					$1d_{5/2}$	0.2	~ 0	< 1

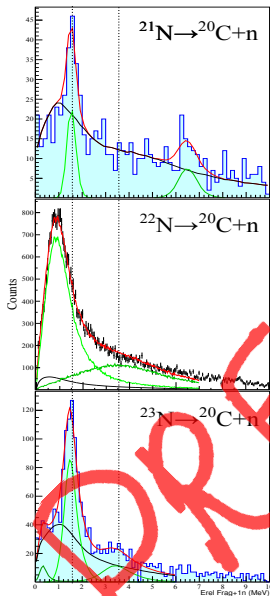
$^{20}\text{C}^*?$
(r)

Theory: Yuan PRC85(2012)064324 + J. Bonnard Priv. Comm.

^{21}C : some other channels



^{21}C : some other channels



Comments

Charge exchange & $-(np)$: $E_r \approx 1.5$ MeV
($-p$) & $-(np)$: E_r above 3 MeV (multiple states ?)

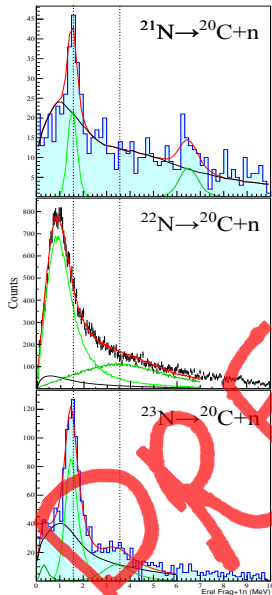
Charge exchange : $E_r \approx 6.5$ MeV

^{21}C : some other channels

Comments

Charge exchange & $-(np)$: $E_r \approx 1.5$ MeV
($-p$) & $-(np)$: E_r above 3 MeV (multiple states ?)

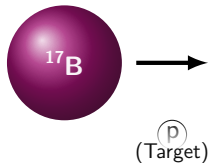
Charge exchange : $E_r \approx 6.5$ MeV



Three body resonance: the unbound ^{16}Be case

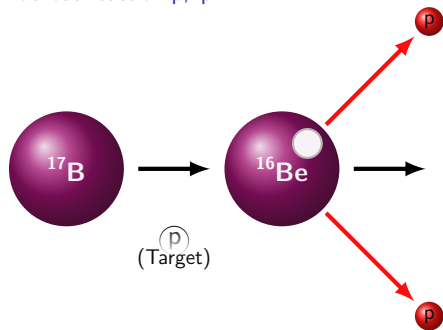
Techniques example

Knockout reaction p,2p



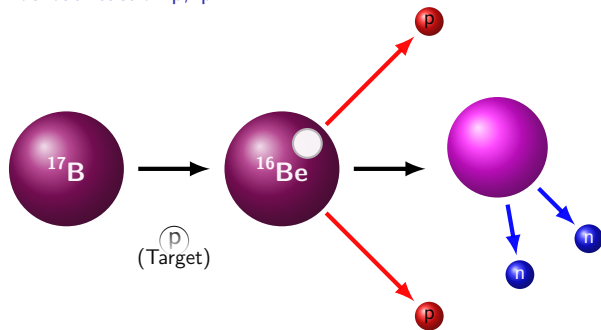
Techniques example

Knockout reaction p,2p



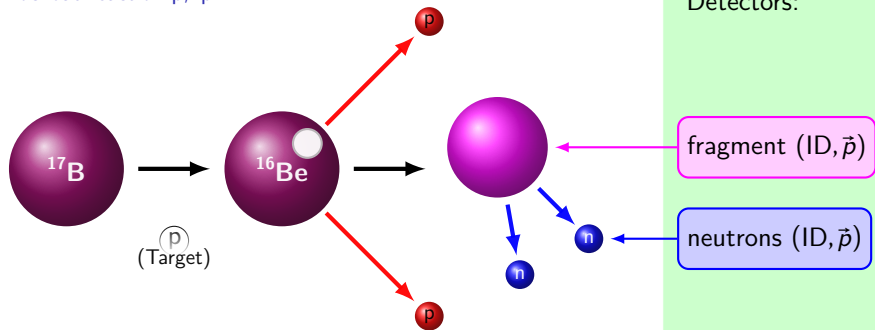
Techniques example

Knockout reaction p,2p



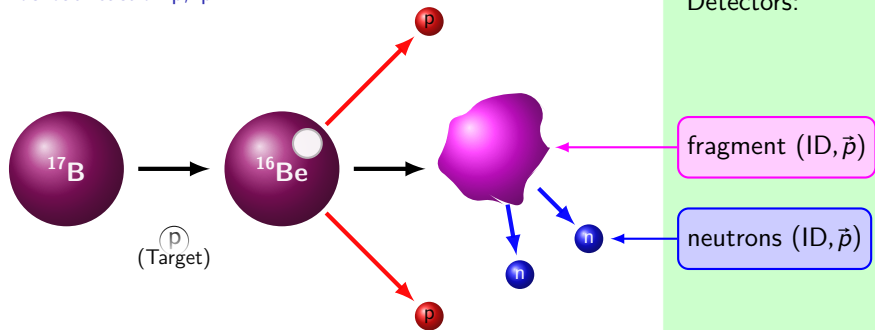
Techniques example

Knockout reaction p,2p



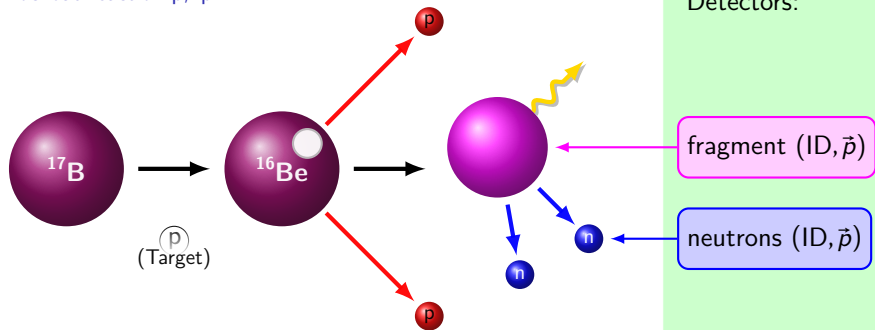
Techniques example

Knockout reaction p,2p



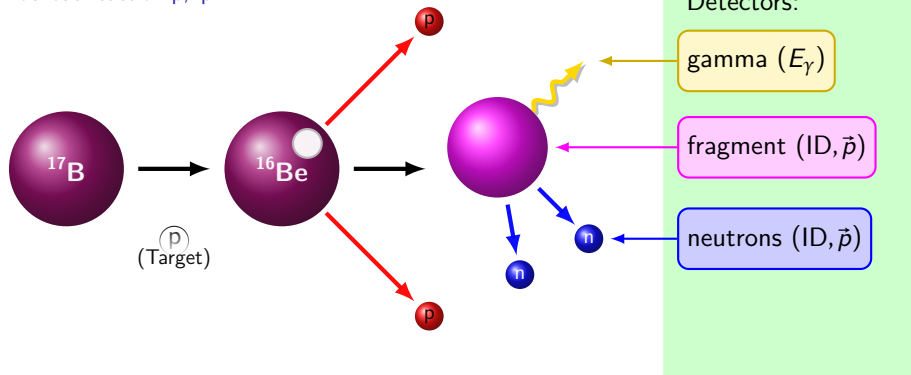
Techniques example

Knockout reaction p,2p



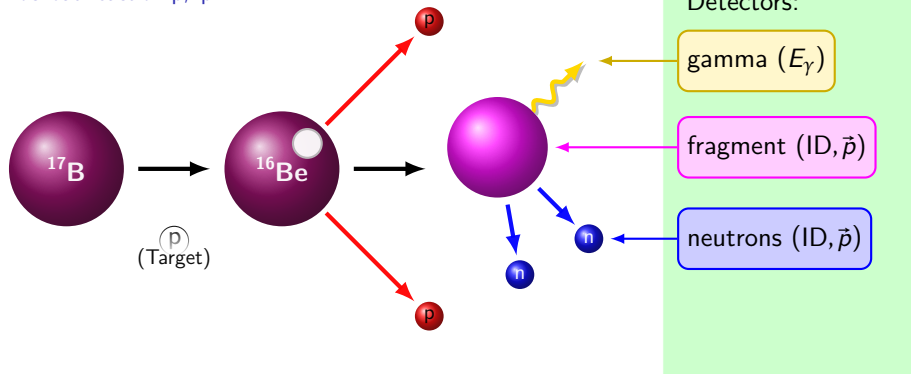
Techniques example

Knockout reaction p,2p



Techniques example

Knockout reaction p,2p



Invariant Mass :

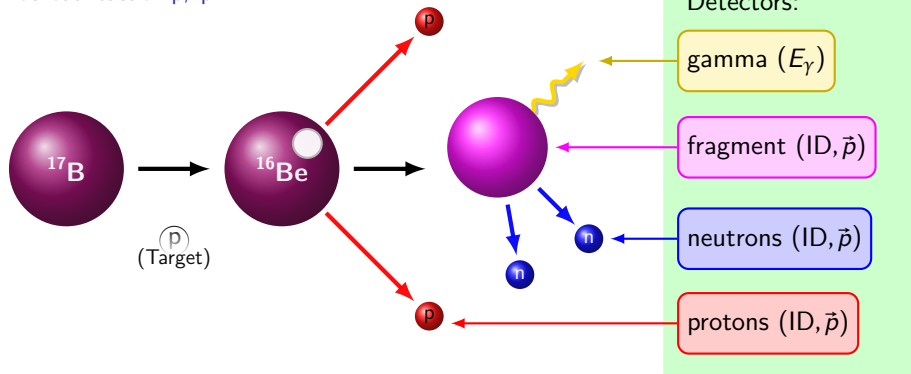
$$M^2 = (E_f + E_{n_1} + E_{n_2})^2 - (\vec{p}_f + \vec{p}_{n_1} + \vec{p}_{n_2})^2$$

$$\text{or } M = m_f + E_\gamma + 2m_n + \underbrace{E_r}_{\text{Relative energy: fragment, neutron, neutron}}$$

Relative energy: fragment, neutron, neutron

Techniques example

Knockout reaction $p, 2p$



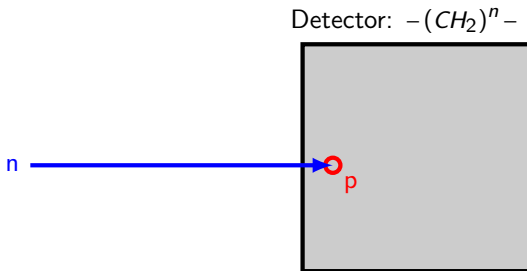
Missing Mass :

"Two" body kinematics: $(\vec{p}_{p'} \ \& \ \vec{p}_p) \Rightarrow m_{^{16}\text{Be}}^{(*)}$

$$\vec{p}_{^{17}\text{B}} = \vec{p}_p + \vec{p}_{p'} + \vec{p}_{^{16}\text{Be}} \quad \text{and} \quad T_{^{17}\text{B}} + m_{^{17}\text{B}} = T_p + T_{p'} + 2m_p + T_{^{16}\text{Be}} + m_{^{16}\text{Be}}^{(*)}$$

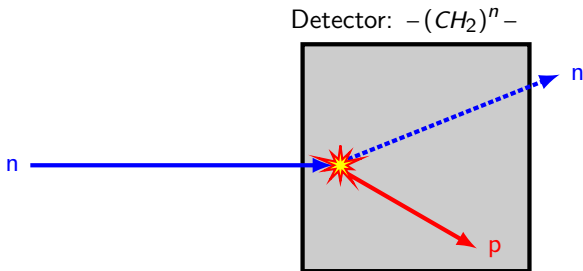
Neutron detection

Neutron: neutral \Rightarrow EM-interaction , only strong
Must interact first w/ another particle (ex: proton)
Then proton, charged, interacts



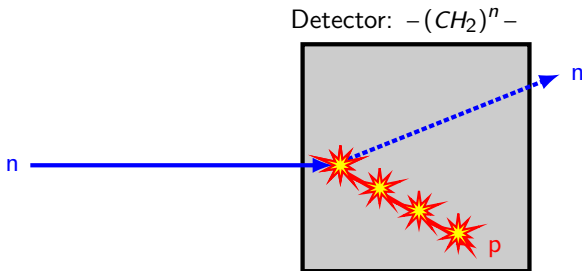
Neutron detection

Neutron: neutral \Rightarrow EM-interaction , only strong
Must interact first w/ another particle (ex: proton)
Then proton, charged, interacts



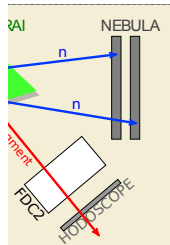
Neutron detection

Neutron: neutral \Rightarrow EM-interaction , only strong
Must interact first w/ another particle (ex: proton)
Then proton, charged, interacts



Neutron detection

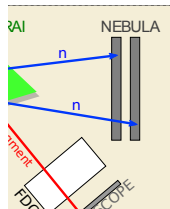
Cross-talk rejection



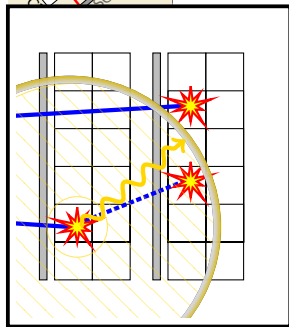
e

Neutron detection

Cross-talk rejection

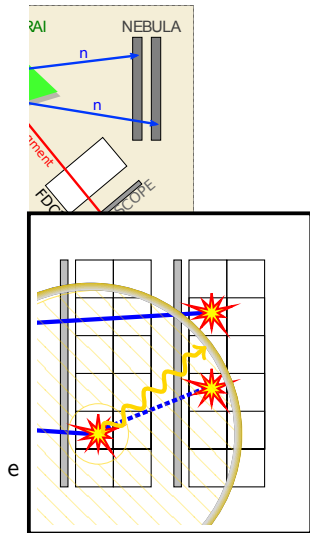


e

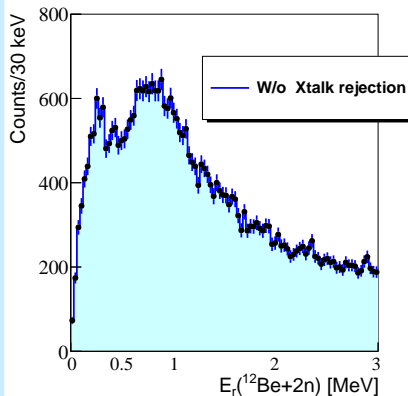


Neutron detection

Cross-talk rejection

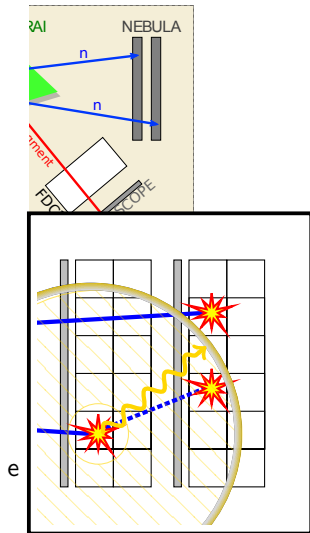


Proof of principle: $^{14}\text{Be} \rightarrow ^{12}\text{Be} + 2n$

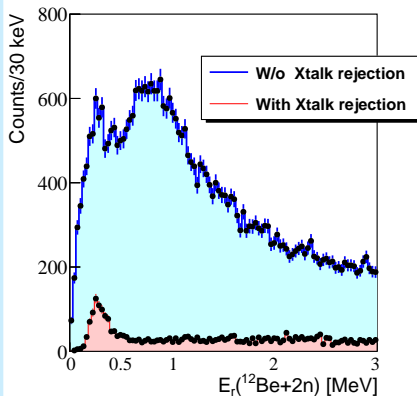


Neutron detection

Cross-talk rejection

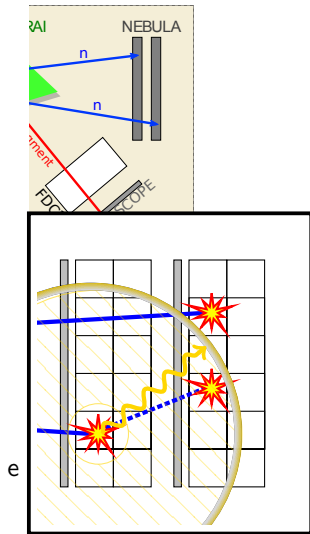


Proof of principle: $^{14}\text{Be} \rightarrow ^{12}\text{Be} + 2n$

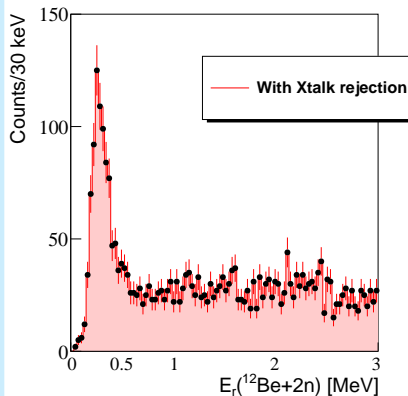


Neutron detection

Cross-talk rejection

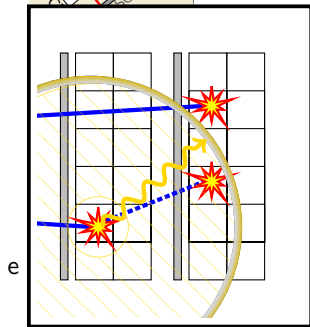
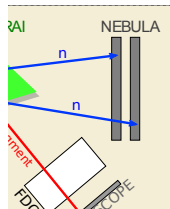


Proof of principle: $^{14}\text{Be} \rightarrow ^{12}\text{Be} + 2n$

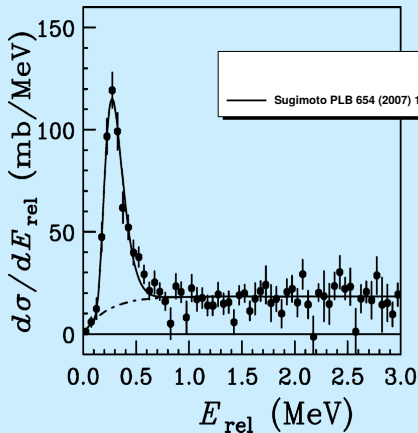


Neutron detection

Cross-talk rejection

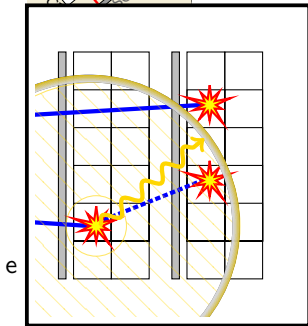
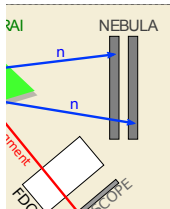


Proof of principle: $^{14}\text{Be} \rightarrow ^{12}\text{Be} + 2n$

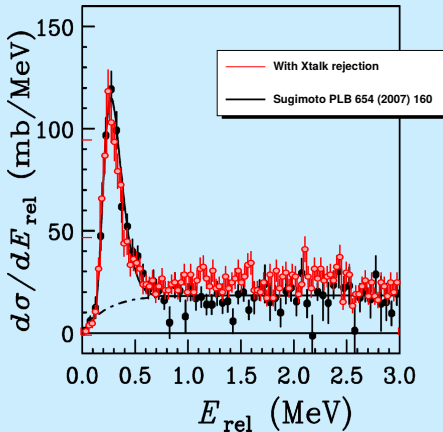


Neutron detection

Cross-talk rejection



Proof of principle: $^{14}\text{Be} \rightarrow ^{12}\text{Be} + 2\text{n}$



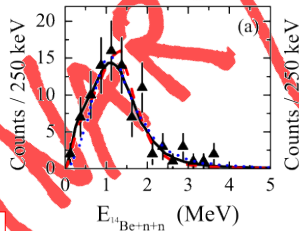
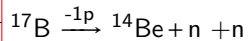
^{16}Be latest results

Spyrou, PRL 108 (2012) 102501

63 MeV/nucleon

Solid Be target

Proton knock-out



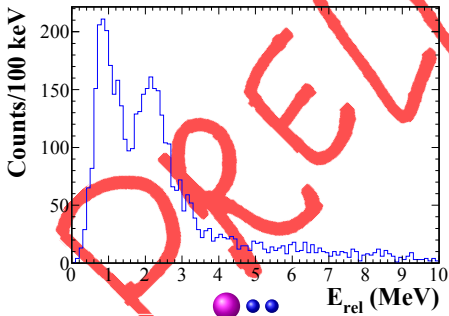
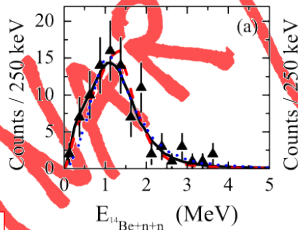
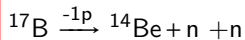
^{16}Be latest results

Spyrou, PRL 108 (2012) 102501

63 MeV/nucleon

Solid Be target

Proton knock-out



Observation of 2 structures !
Large acceptance (0-10 MeV)

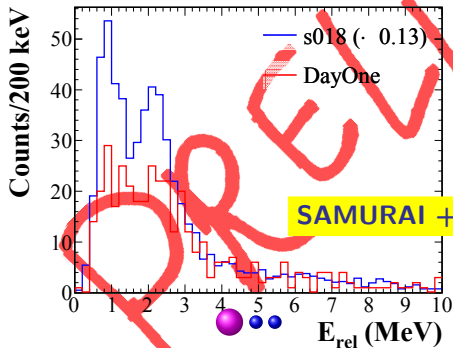
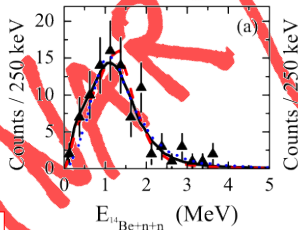
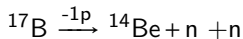
^{16}Be latest results

Spyrou, PRL 108 (2012) 102501

63 MeV/nucleon

Solid Be target

Proton knock-out



Observation of 2 structures !
Large acceptance (0-10 MeV)

SAMURAI + MINOS: $\times 8$ stats

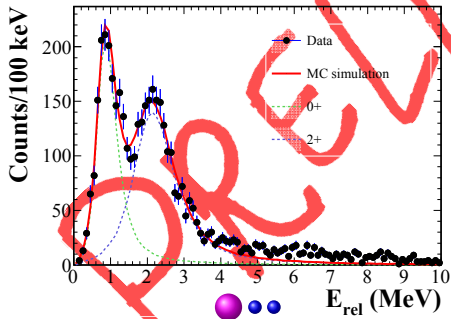
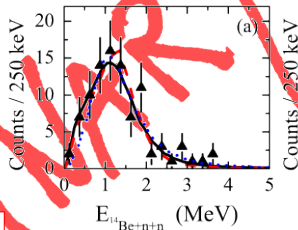
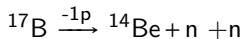
^{16}Be latest results

Spyrou, PRL 108 (2012) 102501

63 MeV/nucleon

Solid Be target

Proton knock-out



Observation of 2 structures !
Large acceptance (0-10 MeV)

Ground State

$$E_{0+} = 0.84 \pm 0.03 \text{ MeV}$$

First excited State

$$E_{2+} = 2.15 \pm 0.05 \text{ MeV}$$

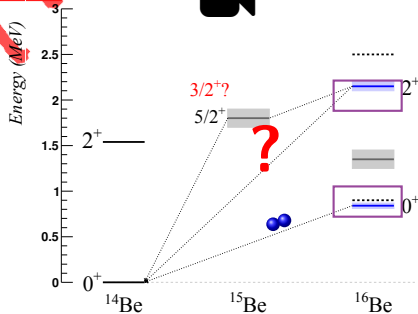
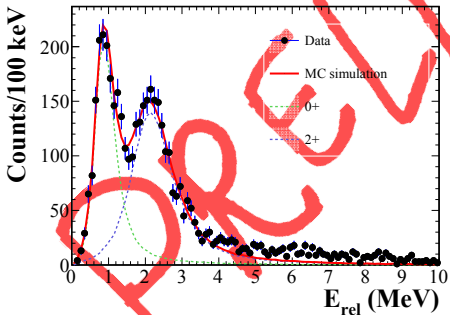
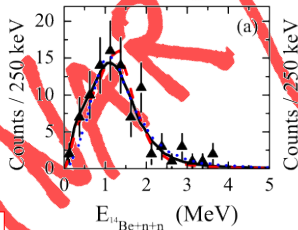
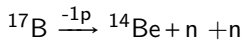
^{16}Be latest results

Spyrou, PRL 108 (2012) 102501

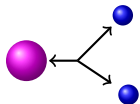
63 MeV/nucleon

Solid Be target

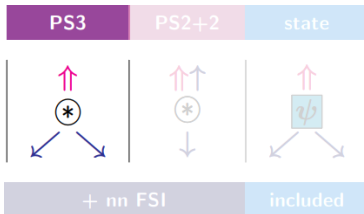
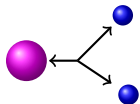
Proton knock-out



^{16}Be latest results



PS3	PS2+2	state
+ nn FSI		included



DIRECT DECAY

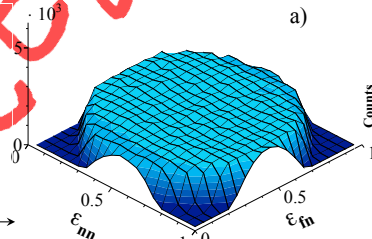
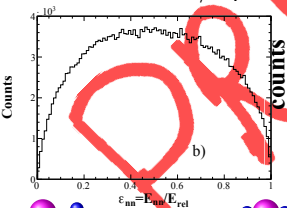
3-body phase space

+
no nn FSI

Dalitz plots

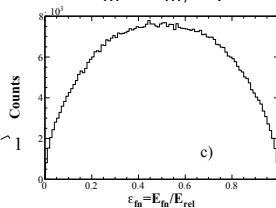
neutron-neutron interaction

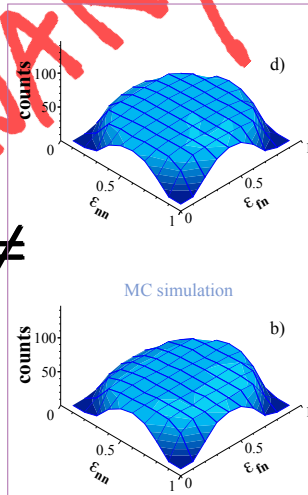
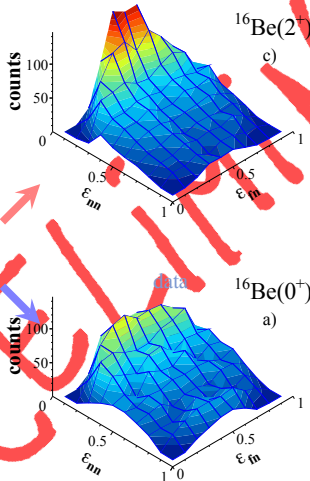
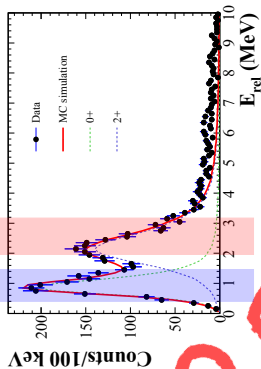
$$\varepsilon_{nn} = E_{nn}/E_T$$

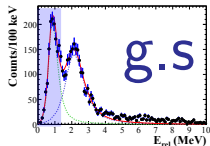


Sequentiality

$$\varepsilon_{fn} = E_{fn}/E_T$$



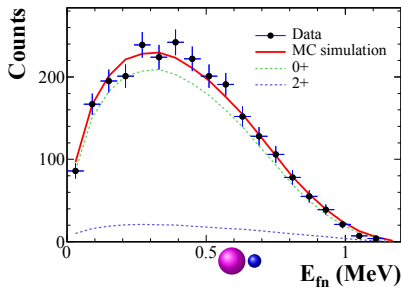
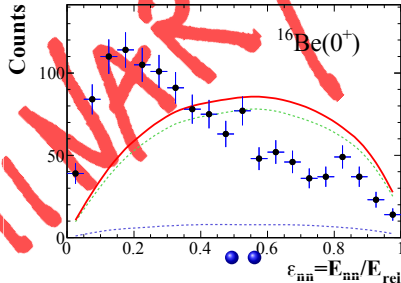




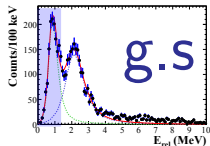
Correlation function

$$C_{ij} = \frac{E_{ij}(\text{data})}{E_{ij}(\text{MC PS})}$$

if data = simulation then $C_{ij} = 1$



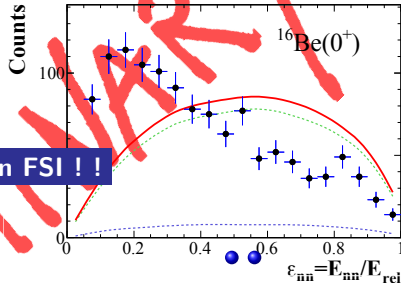
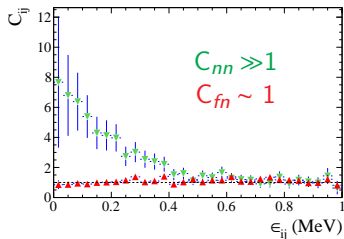
^{16}Be latest results



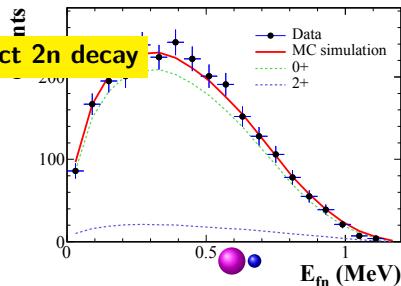
Correlation function

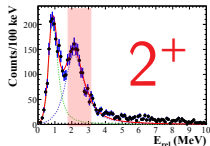
$$C_{ij} = \frac{E_{ij}(\text{data})}{E_{ij}(\text{MC PS})}$$

if data = simulation then $C_{ij} = 1$



Direct 2n decay

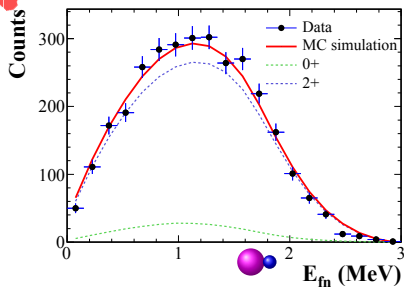
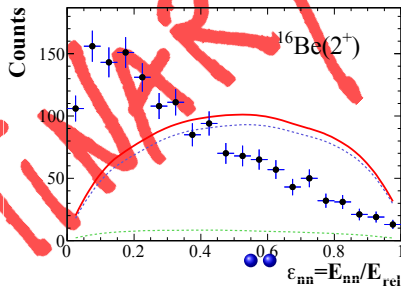




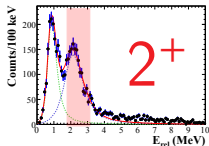
Correlation function

$$C_{ij} = \frac{E_{ij}(\text{data})}{E_{ij}(\text{MC PS})}$$

if data = simulation then $C_{ij} = 1$



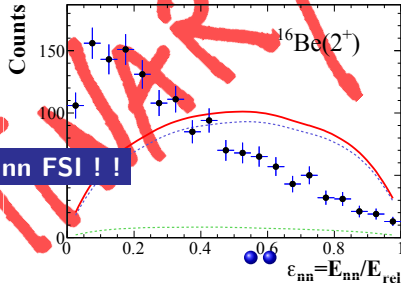
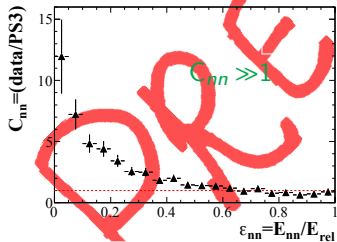
^{16}Be latest results



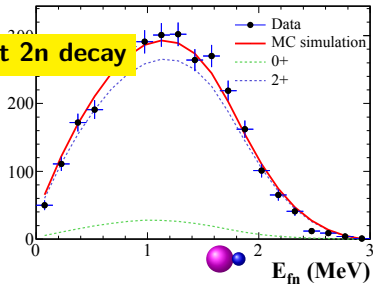
Correlation function

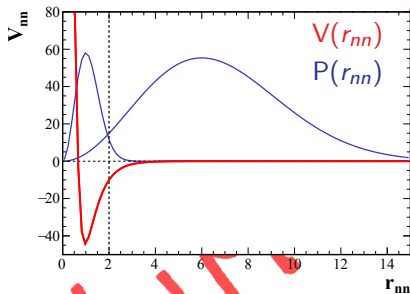
$$C_{ij} = \frac{E_{ij}(\text{data})}{E_{ij}(\text{MC PS})}$$

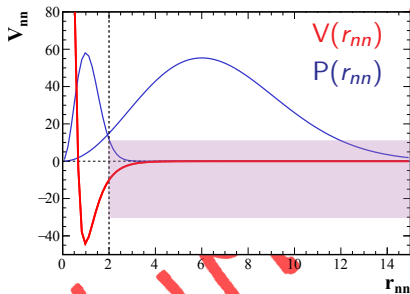
if data = simulation then $C_{ij} = 1$



Direct 2n decay



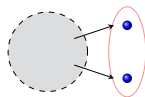




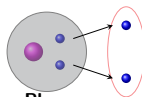
Asymptotic behaviour

$$a_{nn} \sim 18 \text{ fm}$$

Phenomenological



FSI



Phase
space
+
FSI

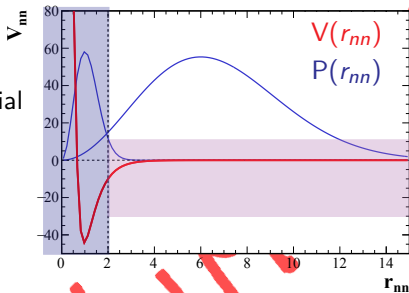
Complete potential

$$V_{nn}(r)$$

+

$$V_{fn}(r)$$

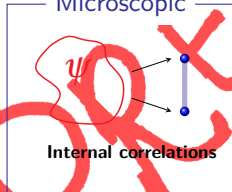
$$V_{fnn}(r)$$



Asymptotic behaviour

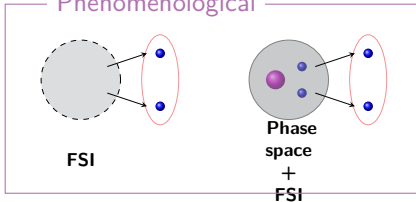
$$a_{nn} \sim 18 \text{ fm}$$

Microscopic

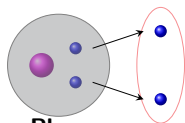


Internal correlations

Phenomenological



^{16}Be FSI model: Good description of correlations

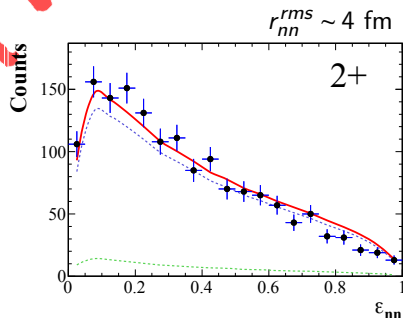
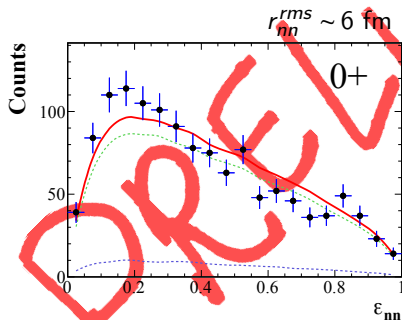


Phase
space
+
FSI

$$\sigma \approx \sigma_{PS} C_{nn}(q_{nn})$$

nn interaction: $a_{nn} = -18.5 \text{ fm}$

Relative nn distance: r_{nn}



$$r_{nn}(2^+) < r_{nn}(0^+)?$$

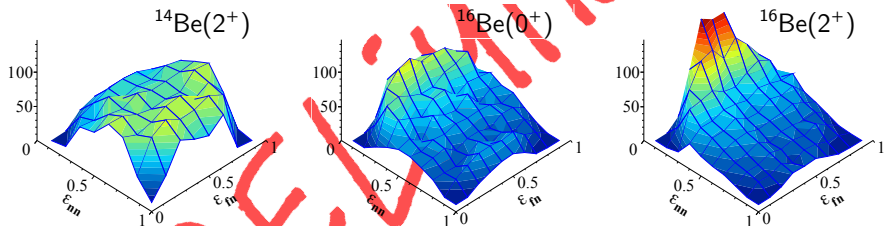
^{16}Be FSI model: Physical interpretation?

✓ Description of data

✗ **Interpretation?**

Gaussian source of independent neutrons

Direct two-neutron decay



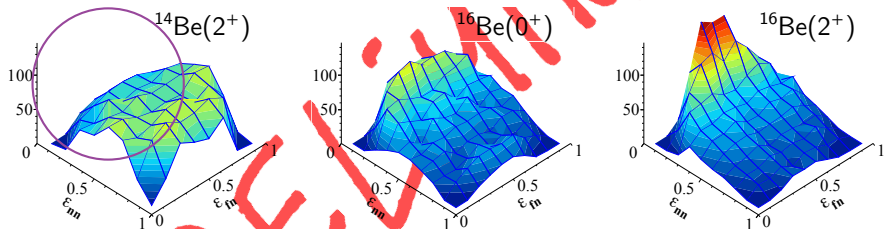
^{16}Be FSI model: Physical interpretation?

✓ Description of data

✗ **Interpretation?**

Gaussian source of independent neutrons

Direct two-neutron decay



no nn correlations?

Revel, PRL 120, (2018) 152504

Grigorenko, PRC 97, (2018) 034605

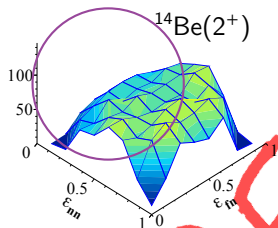
^{16}Be FSI model: Physical interpretation?

✓ Description of data

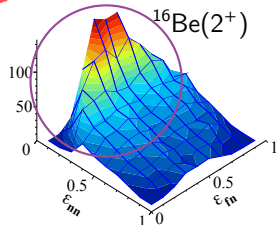
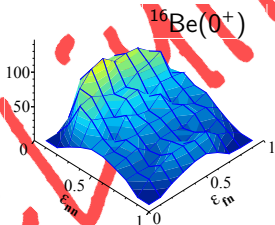
✗ **Interpretation?**

Gaussian source of independent neutrons

Direct two-neutron decay



no nn correlations?



Stronger nn signal?

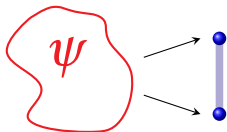
Revel, PRL 120, (2018) 152504

Grigorenko, PRC 97, (2018) 034605

a_{nn} : s-wave nn FSI?

^{16}Be : p- or d-wave components?

^{16}Be Three-body calculations



Characterization of **core+n+n decays**

Structure \longleftrightarrow **Particle Correlations**
of the system of 3-body decay

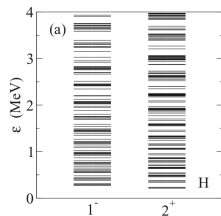
Casal, PRC 97 (2018) 034613

$\psi_n^{j\mu}$ basis of pseudo states in hyperspherical coordinates

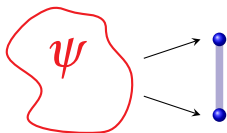
Analytical extended HO

$$\mathcal{H}\psi_n^{j\mu} = \varepsilon_n\psi_n^{j\mu}$$

Discrete continuum



¹⁶Be Three-body calculations



Characterization of **core+n+n decays**

Structure \longleftrightarrow **Particle Correlations**
of the system of 3-body decay

Casal, PRC 97 (2018) 034613

$\psi_n^{j\mu}$ basis of pseudo states in hyperspherical coordinates

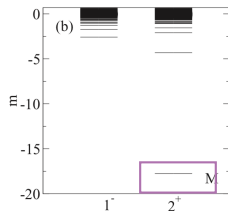
Analytical extended HO

$$\mathcal{H}\psi_n^{j\mu} = \varepsilon_n\psi_n^{j\mu}$$

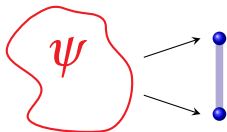
Discrete continuum

$$M = \mathcal{H}^{-1/2} V \mathcal{H}^{1/2}$$

Select resonant state



¹⁶Be Three-body calculations



Characterization of **core+n+n decays**

Structure \longleftrightarrow **Particle Correlations**
of the system of 3-body decay

Casal, PRC 97 (2018) 034613

$\psi_n^{j\mu}$ basis of pseudo states in hyperspherical coordinates

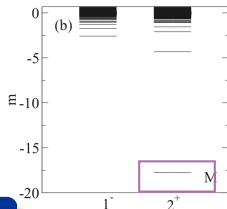
Analytical extended HO

$$\mathcal{H}\psi_n^{j\mu} = \varepsilon_n \psi_n^{j\mu}$$

Discrete continuum

$$M = \mathcal{H}^{-1/2} V \mathcal{H}^{1/2}$$

Select resonant state

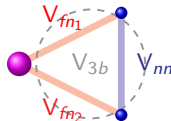


Interaction potential

$$V_{\beta'\beta}^{j\mu} = \langle \mathcal{Y}_{\beta}^{j\mu}(\Omega) | \mathbf{V}_{nn} + \mathbf{V}_{fn1} + \mathbf{V}_{fn2} | \mathcal{Y}_{\beta'}^{j\mu}(\Omega) \rangle + \delta_{\beta\beta'} \mathbf{V}_{3b}(\rho)$$

V_{ij} interaction between pairs

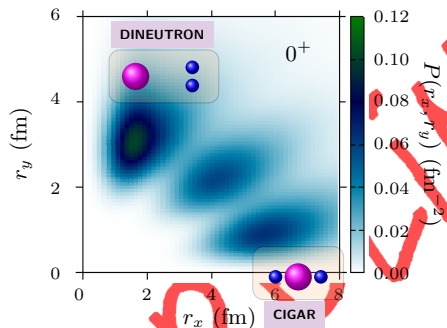
V_{3b} phenomenological 3-body force



^{16}Be latest results

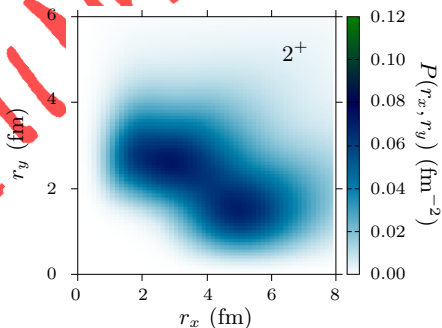
J.Casal, private communication

$$P(r_x, r_y) = r_x^2 r_y^2 \int |\psi(r_x, r_y)|^2 d\hat{x} d\hat{y}$$



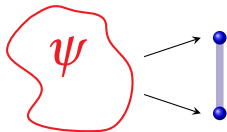
0.8 MeV ($E_{\text{exp}}=0.84 \text{ MeV}$)

strong **dineutron** component!



1.9 MeV ($E_{\text{exp}}=2.15 \text{ MeV}$)

equal contribution



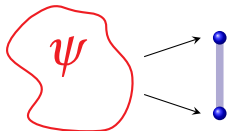
Characterization of $\alpha + n + n$ decays

Structure \longleftrightarrow **Particle Correlations**
of the system of 3-body decay

J. Casal & B. Monteagudo, in progress

Theory vs Experiment

Detected particles: no V influence, $t \rightarrow \infty$



Characterization of $\alpha+n+n$ decays

Structure \longleftrightarrow **Particle Correlations**
of the system of 3-body decay

J. Casal & B. Monteagudo, in progress

Theory vs Experiment

Detected particles: no V influence, $t \rightarrow \infty$

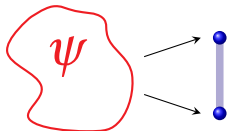
ψ_n free evolution within a given state

\Rightarrow **Probability current** $j(t, \rho, \alpha)$

$t, \rho \gg 0$

Compromise: $t_0, \rho_0 \Rightarrow j(t_0, \rho_0, \alpha) \approx j(\alpha)$

$$\psi_n \xrightarrow{j_\psi} E_{nn}$$



Characterization of **core+n+n decays**

Structure \longleftrightarrow **Particle Correlations**
of the system of 3-body decay

J. Casal & B. Monteagudo, in progress

Theory vs Experiment

Detected particles: no V influence, $t \rightarrow \infty$

ψ_n free evolution within a given state

\Rightarrow **Probability current** $j(t, \rho, \alpha)$

$t, \rho \gg 0$

Compromise: $t_0, \rho_0 \Rightarrow j(t_0, \rho_0, \alpha) \approx j(\alpha)$

$$\psi_n \xrightarrow{j_\psi} E_{nn}$$

$$\frac{dP(E_{nn})}{dE_{nn}} \propto \frac{j(t_0, \rho_0, \alpha)}{E_r \sin 2\alpha}$$

Theoretical distribution

MC simulation
(Cross-talk)

$$\frac{dP(E_{nn})}{dE_{nn}}$$

Filtered distribution

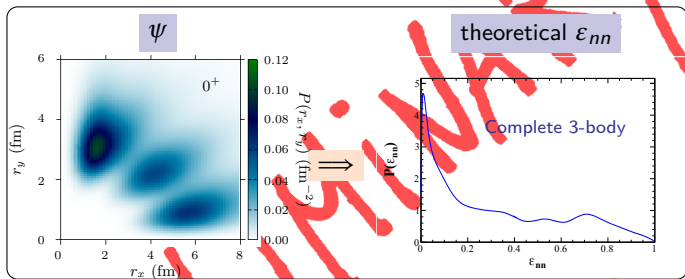
Probing $^{16}\text{Be}(0^+)$ wave function (PRELIMINARY)

V_{nn}

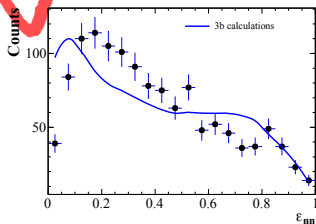
V_{fn1}

V_{fn2}

V_{3b}



Filtered

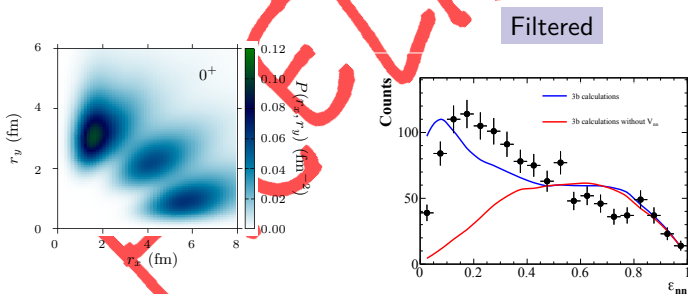
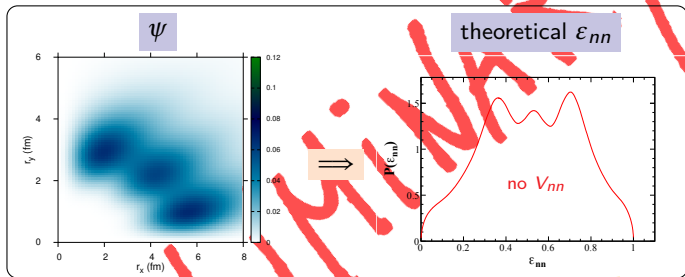


MC simulation

Good agreement

no fit!

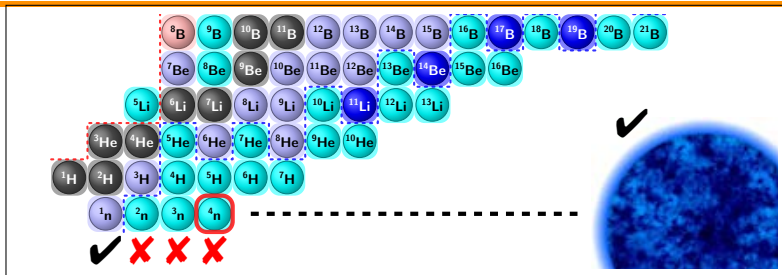
Probing $^{16}\text{Be}(0^+)$ wave function (PRELIMINARY)



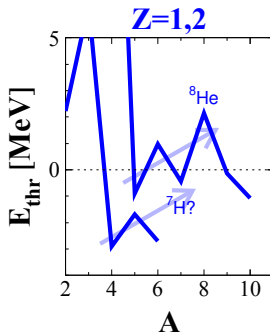
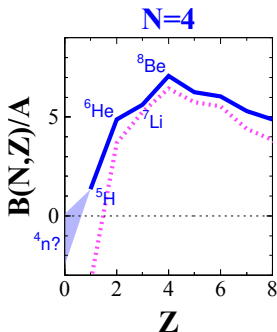
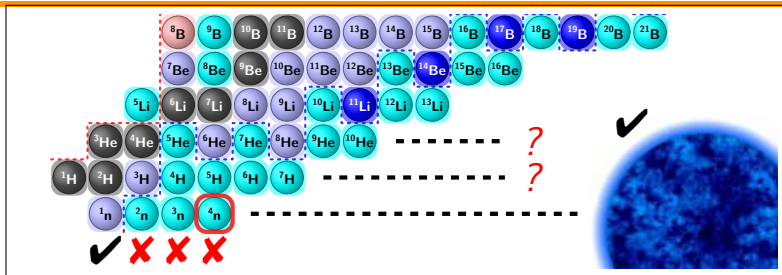
MC simulation

The tetra-neutron, a 4 body resonance

Tetra neutron : position of the problem



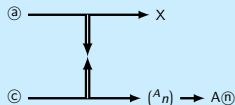
Tetra neutron : position of the problem



Tetra neutron experiments

Marqués & Carbonell EPJA 57 (2021) 105

Neutron detection



- ✓ unambiguous detection
- ✓ breakup or resonant decay
- ✓ neutron correlations
- ✗ extremely low efficiency



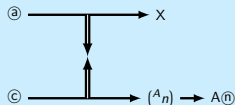
4 experiments

Marqués, PRC 65 (2002) 044006

Tetra neutron experiments

Marqués & Carbonell EPJA 57 (2021) 105

Neutron detection



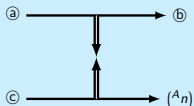
- ✓ unambiguous detection
- ✓ breakup or resonant decay
- ✓ neutron correlations
- ✗ extremely low efficiency



4 experiments

Marqués, PRC 65 (2002) 044006

Missing mass



- ✓ detection charged particle
- ✓ bound & resonant states
- ✓ mass number well defined
- ✗ insensit. intern. structure
- ✗ X-section all protons \Rightarrow b
- ✗ beam/target contaminant \neq a/c



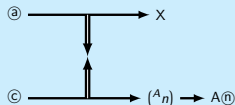
24 experiments

Kisamori, PRL 116 (2016) 052501

Tetra neutron experiments

Marqués & Carbonell EPJA 57 (2021) 105

Neutron detection



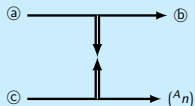
- ✓ unambiguous detection
- ✓ breakup or resonant decay
- ✓ neutron correlations
- ✗ extremely low efficiency



4 experiments

Marqués, PRC 65 (2002) 044006

Missing mass



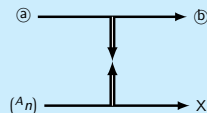
- ✓ detection charged particle
- ✓ bound & resonant states
- ✓ mass number well defined
- ✗ insensit. intern. structure
- ✗ X-section all protons \Rightarrow (b)
- ✗ beam/target contaminant \neq (a)/(c)



24 experiments

Kisamori, PRL 116 (2016) 052501

Two steps



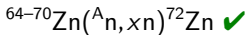
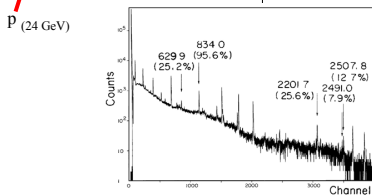
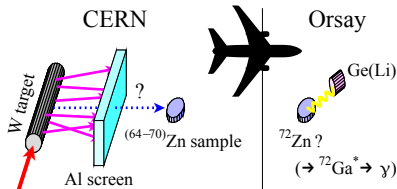
- ✓ detection of 1 charged particle
- ✗ only bound states in 2 step
- ✗ insensitive to the energy
- ✗ only lower limit of A inferred
- ✗ contaminant \neq (a) \Rightarrow (b)
- ✗ uncontrolled step \Rightarrow bkg \Rightarrow (b)



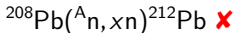
8 experiments

Détraz, PL 66B (1977) 333

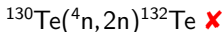
Two steps



Détraz, PL 66B (1977) 333



Turkevich, PRL 38 (1977) 1129



de Boer, NP A350 (1980) 149

Volume 66B, number 4

PHYSICS LETTERS

14 February 1977

POSSIBLE EXISTENCE OF BOUND NEUTRAL NUCLEI

Claude DÉTRAZ

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 ($^6n-^{12}n$) 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 underestimated²⁵).

Charge exchange

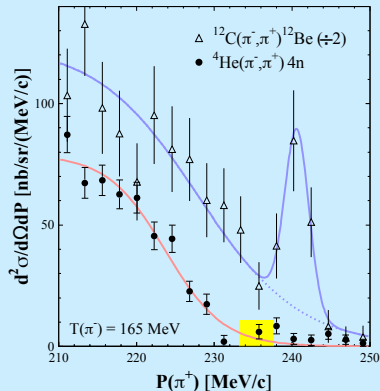
$${}^{3,4}\text{He}(\pi^+, \pi^-){}^{3,4}\text{n}$$

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

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

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

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



Charge exchange

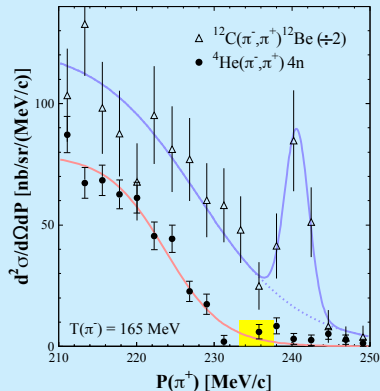
$${}^3,4\text{He}(\pi^+, \pi^-){}^3,4\text{n}$$

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

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

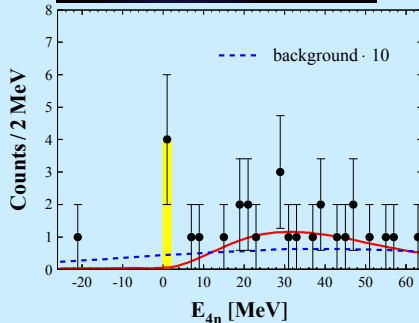
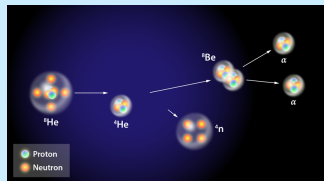
(3n) Sperinde, NP B78 (1974) 345

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



$${}^4\text{He}({}^8\text{He}, {}^8\text{Be}){}^4\text{n}, \quad {}^8\text{Be} \equiv \alpha + \alpha$$

(4n) Kisamori, PRL 116 (2016) 052501



Charge exchange

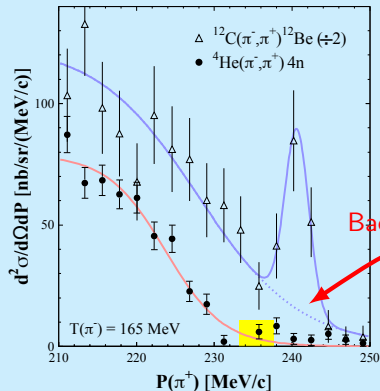
$${}^3,4\text{He}(\pi^+, \pi^-){}^3,4\text{n}$$

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

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

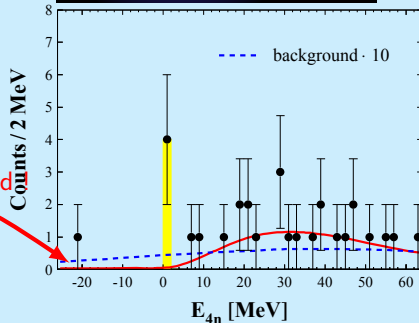
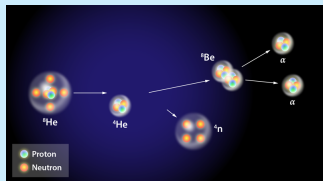
(3n) Sperinde, NP B78 (1974) 345

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



$${}^4\text{He}({}^8\text{He}, {}^8\text{Be}){}^4\text{n}, \quad {}^8\text{Be} \equiv \alpha + \alpha$$

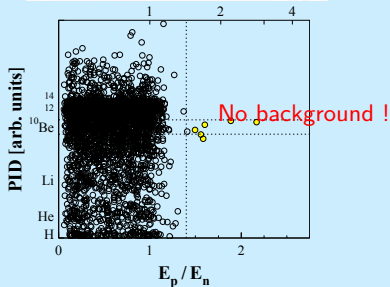
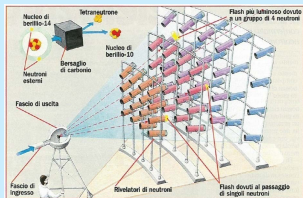
(4n) Kisamori, PRL 116 (2016) 052501



Direct measurement



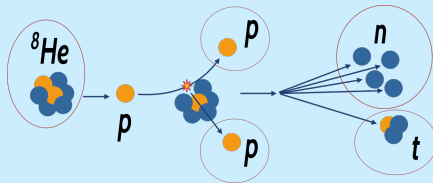
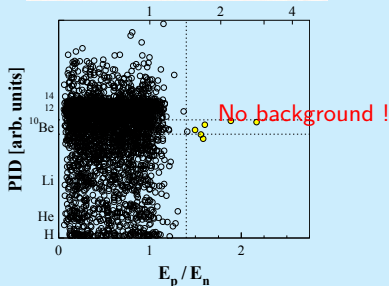
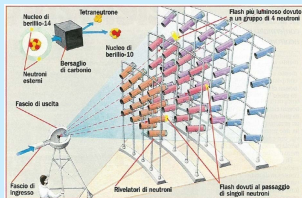
(4n) Marqués, PRC 65 (2002) 044006



Direct measurement



(4n) Marqués, PRC 65 (2002) 044006



Two approaches

Missing mass *via* protons

Invariant mass *via* neutrons and tritons



Analysis is in progress...