ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

NN scattering length
&
X17

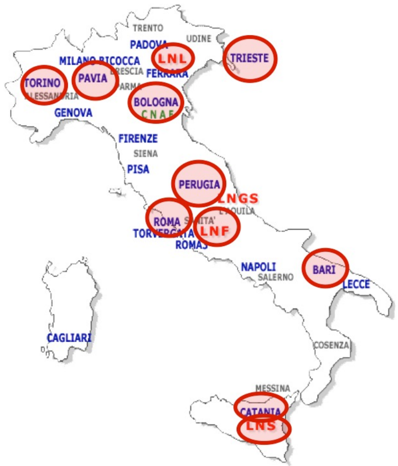
Cristian Massimi
Department of Physics and Astronomy

NSTAPP - Neutrons in Science, Technology and Applications

22 November 2021
CERN
Europe/Zurich timezone

This day of celebration for the 20 years of the n_TOF activities represents a milestone for our research institutes, in particular for INFN
(*Istituto Nazionale di Fisica Nucleare*)

National Institute for Nuclear Physics



~ 40 researchers from 11 INFN divisions
+
ENEA
INAF
CNR

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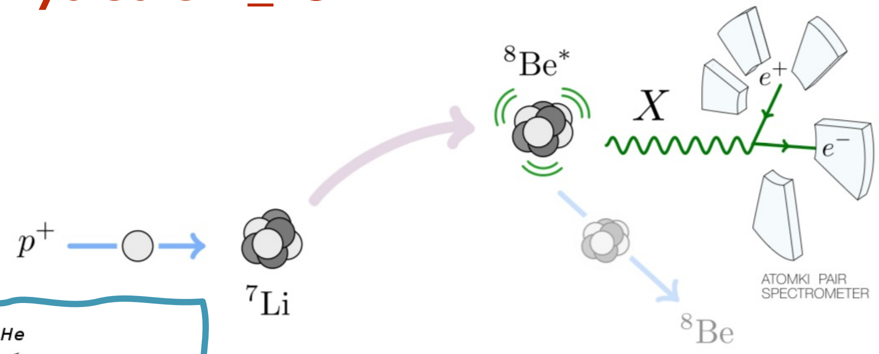
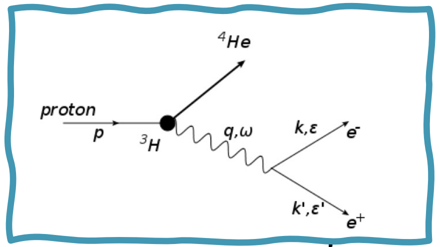
Outline: examples of nuclear physics @ n_TOF

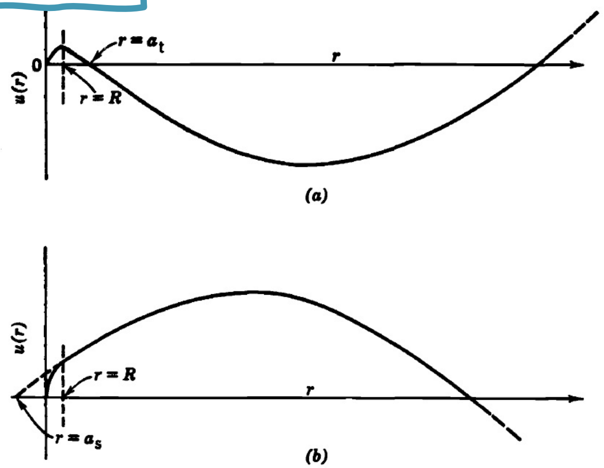
1. Study of the X17 anomaly (or puzzle)





L. Feng, et. al, Phys. Rev. D **95** 035017

2. Neutron-neutron (NN) scattering length



K .S. Krane,
Introductory nuclear physics
J. Wiley & Sons

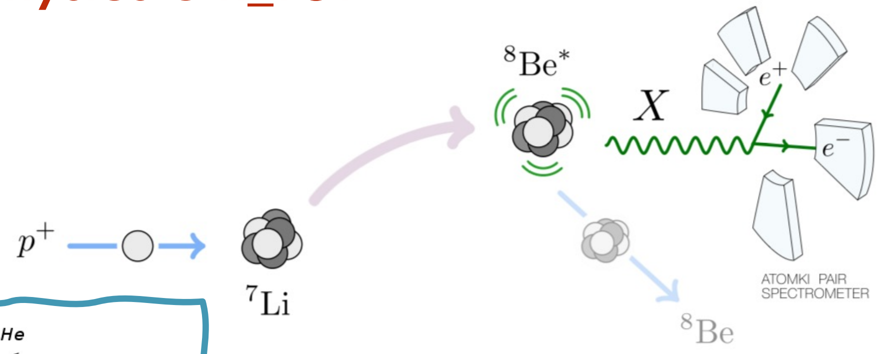
Outline: examples of nuclear physics @ n_TOF

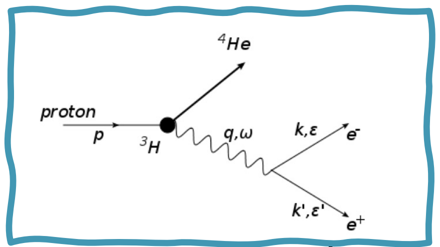
1. Study of the X17 anomaly (or puzzle)

Carlo Gustavino (Roma1)

M. Viviani (Pisa)

P.F. Mastinu (LNL)





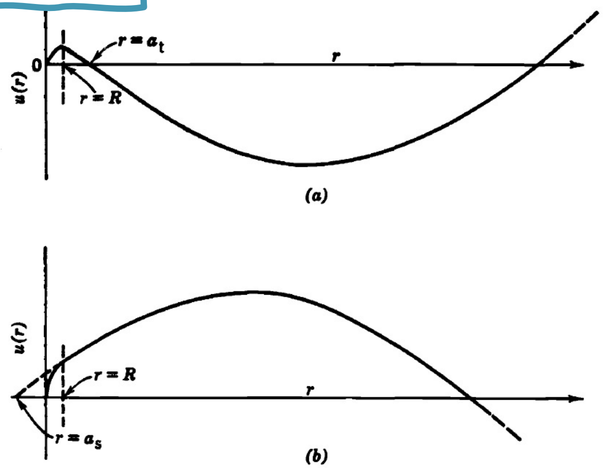
L. Feng, et. al, Phys. Rev. D **95** 035017

2. Neutron-neutron (NN) scattering length

C. Massimi (Bologna)

A. Musumarra (Catania)

N. Patronis (Univ. Ionnina)



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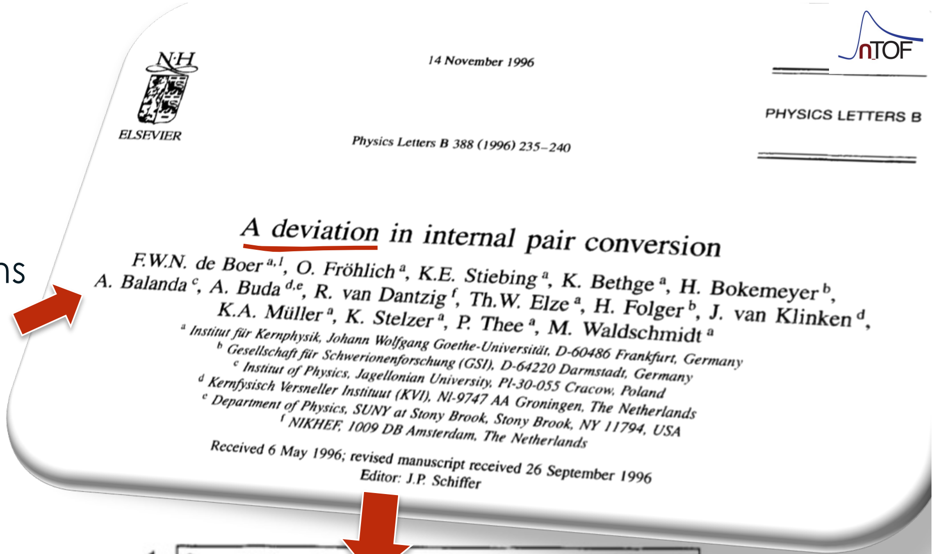
X17, some history

- The **search** for possible signals form nuclear reactions of short-lived neutral bosons with mass ~ MeV **dates back to 1996**


14 November 1996

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 388 (1996) 235–240

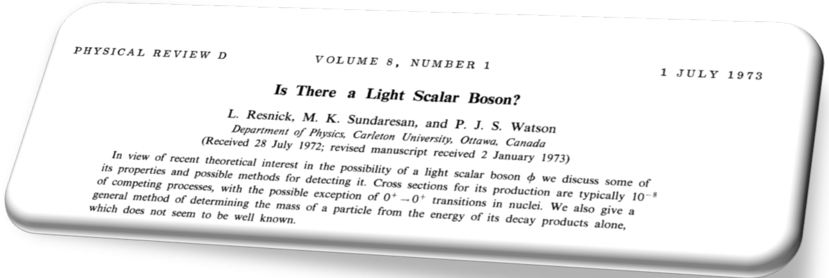
A deviation in internal pair conversion

F.W.N. de Boer[a,1], O. Fröhlich[a], K.E. Stiebing[a], K. Bethge[a], H. Bokemeyer[b], A. Balanda[c], A. Buda[d,e], R. van Dantzig[f], Th.W. Elze[a], H. Folger[b], J. van Klinken[d], K.A. Müller[a], K. Stelzer[a], P. Thee[a], M. Waldschmidt[a]

[a] Institut für Kernphysik, Johann Wolfgang Goethe-Universität, D-60486 Frankfurt, Germany
[b] Gesellschaft für Schwerionenforschung (GSI), D-64220 Darmstadt, Germany
[c] Institut of Physics, Jagellonian University, Pl-30-055 Cracow, Poland
[d] Kernfysisch Versneller Instituut (KVI), Nl-9747 AA Groningen, The Netherlands
[e] Department of Physics, SUNY at Stony Brook, Stony Brook, NY 11794, USA
[f] NIKHEF, 1009 DB Amsterdam, The Netherlands

Received 6 May 1996; revised manuscript received 26 September 1996
Editor: J.P. Schiffer

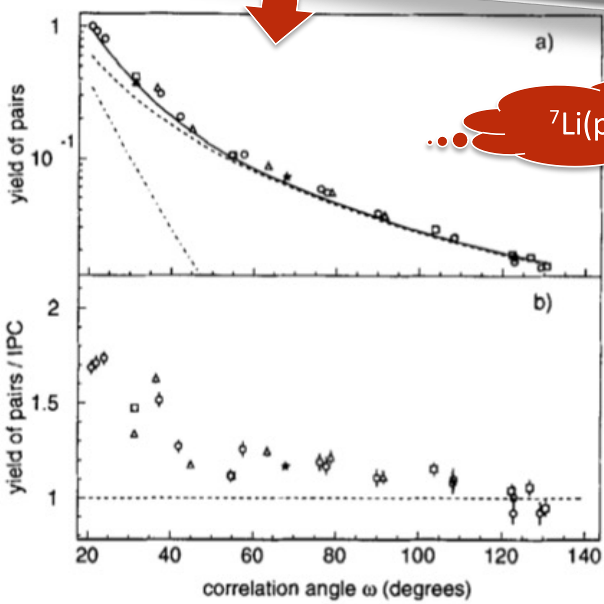
- **Theoretical interest** in light bosons is even **earlier**


PHYSICAL REVIEW D VOLUME 8, NUMBER 1 1 JULY 1973

Is There a Light Scalar Boson?

L. Resnick, M. K. Sundaresan, and P. J. S. Watson
Department of Physics, Carleton University, Ottawa, Canada
(Received 28 July 1972; revised manuscript received 2 January 1973)

In view of recent theoretical interest in the possibility of a light scalar boson ϕ we discuss some of its properties and possible methods for detecting it. Cross sections for its production are typically 10^{-8} of competing processes, with the possible exception of $0^+ \to 0^+$ transitions in nuclei. We also give a general method of determining the mass of a particle from the energy of its decay products alone, which does not seem to be well known.



$^7Li(p,e^+e^-)^8Be$

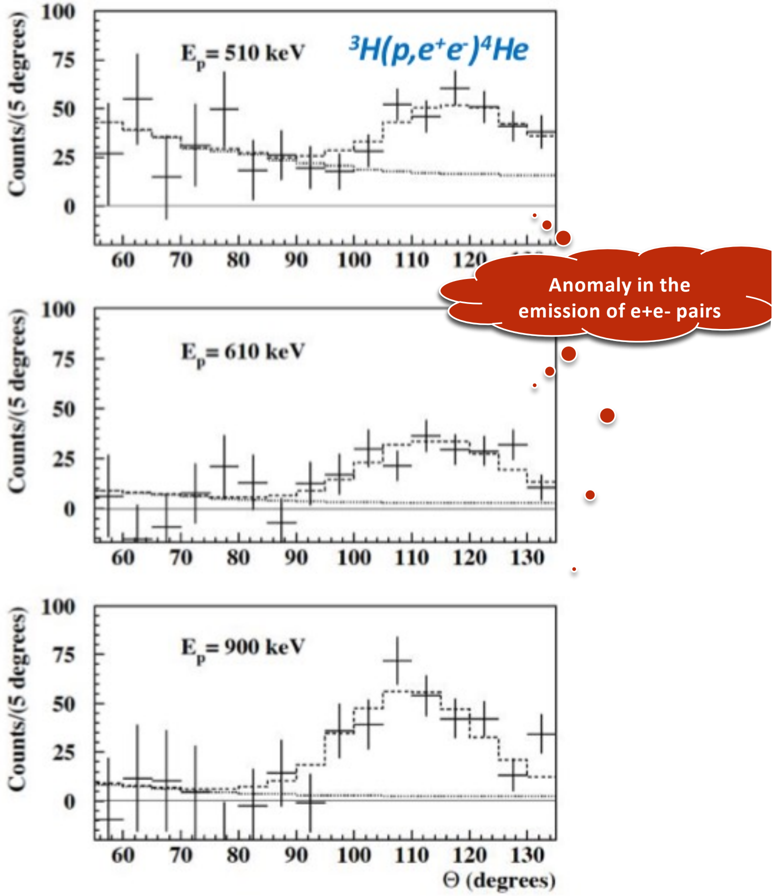
- **Recently** Krasznahorkay et al. (ATOMKI) provided **new experimental evidence** of an anomaly in IPC nTOF

X17, some history – ATOMKI (recent) results

1. Krasznahorkay et al., Phys. Rev. Lett. **116**, 042501 (**2016**):"**Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson**"

2. Krasznahorkay et al., arXiv:1910.10459 (23 October **2019**): "**New evidence supporting the existence of the hypothetic X17 particle**"

3. Krasznahorkay *et al.*, arXiv:2104.10075 (20 April **2021**): "**A new anomaly observed in ^{4}He supports the existence of the hypothetical X17 particle**"



Reaction	$M_{x17} \pm \Delta M_{stat} \pm \Delta m_{syst}$ (MeV)	Statistical evidence	τ (sec)
^{7}Li(p,e+e-)^{8}Be	16.70 ± 0.35 ± 0.50	> 5 σ	10^{-14}
^{3}H(p,e+e-)^{4}He	16.94 ± 0.12 ± 0.21	> 9 σ	

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- **Signature of a BOSON (X17) beyond Standard Model?**
- **X17 mediator of a fifth (protophobic) force?**

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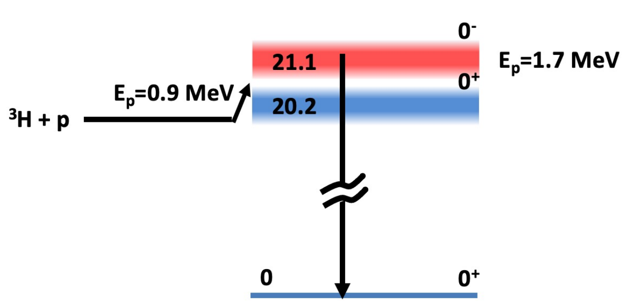
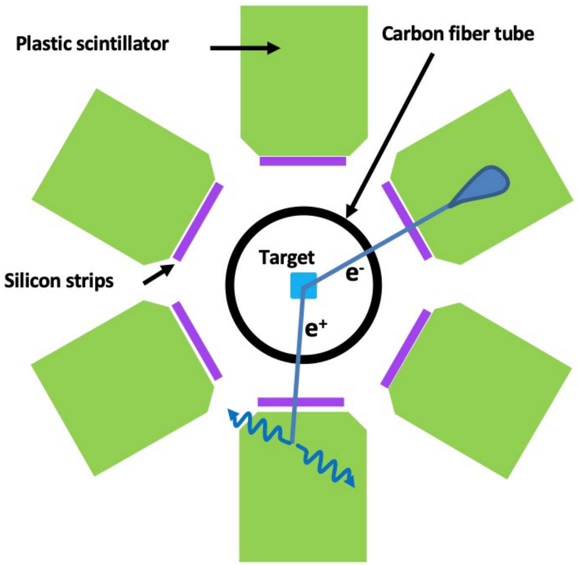
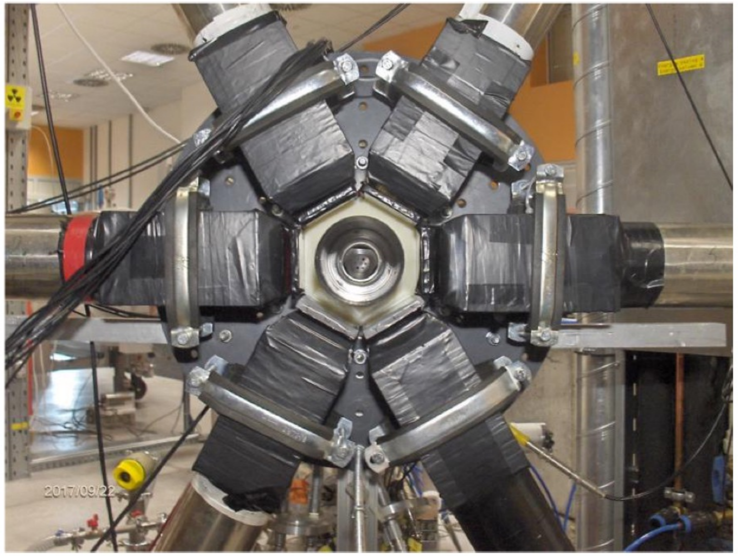
X17, $^3H(p,e+e-)^4He$ setup @ ATOMKI



Forbidden $0^- \rightarrow 0^+$ and $0^+ \rightarrow 0^+$ EM transitions

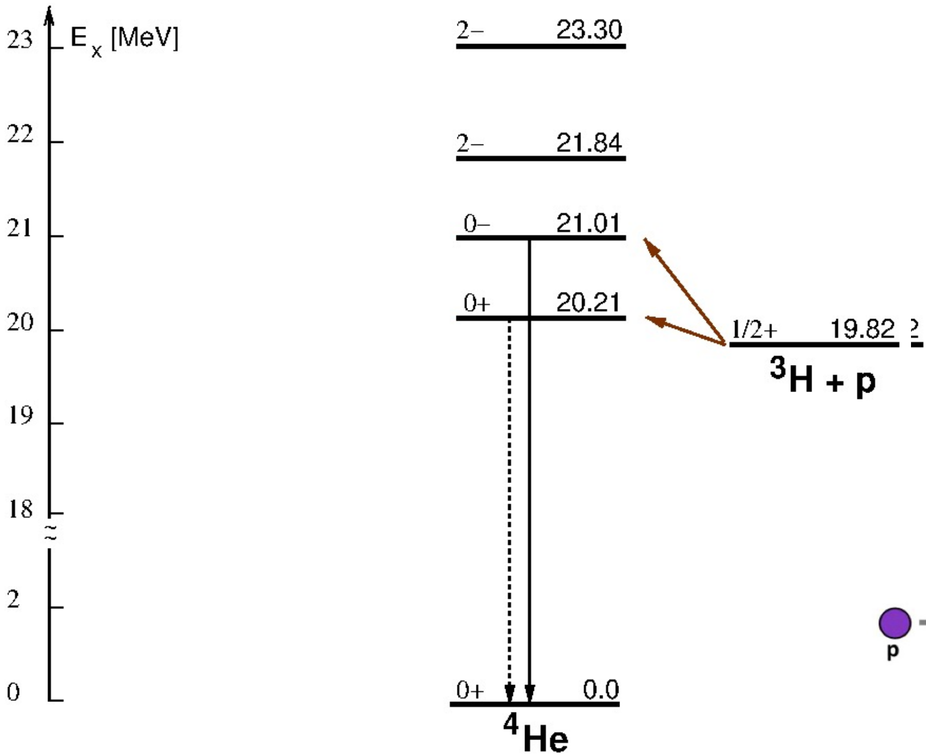




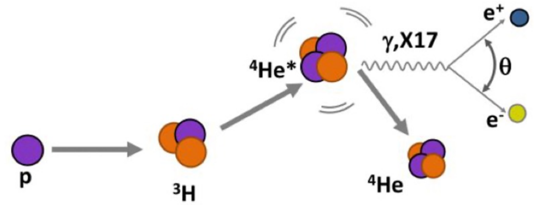
In a nutshell:

- **^{3}H** adsorbed on a **Ti layer**
- 6 **plastic scintillators** 8x8x8 cm^3
- **double-sided silicon strip detector** (3 mm wide strips, 0.5 mm thick)
- 1 mm thick carbon fiber tube
- **Detector** acceptance only **around 90°** with respect to the beam axis
- **no tracking**

X17 @ n_TOF, basic idea: study of ^{4}He excited states



$^{3}H(p,e^{+}e^{-})^{4}He$



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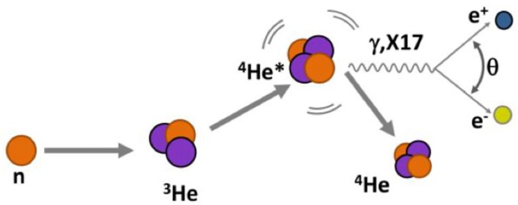
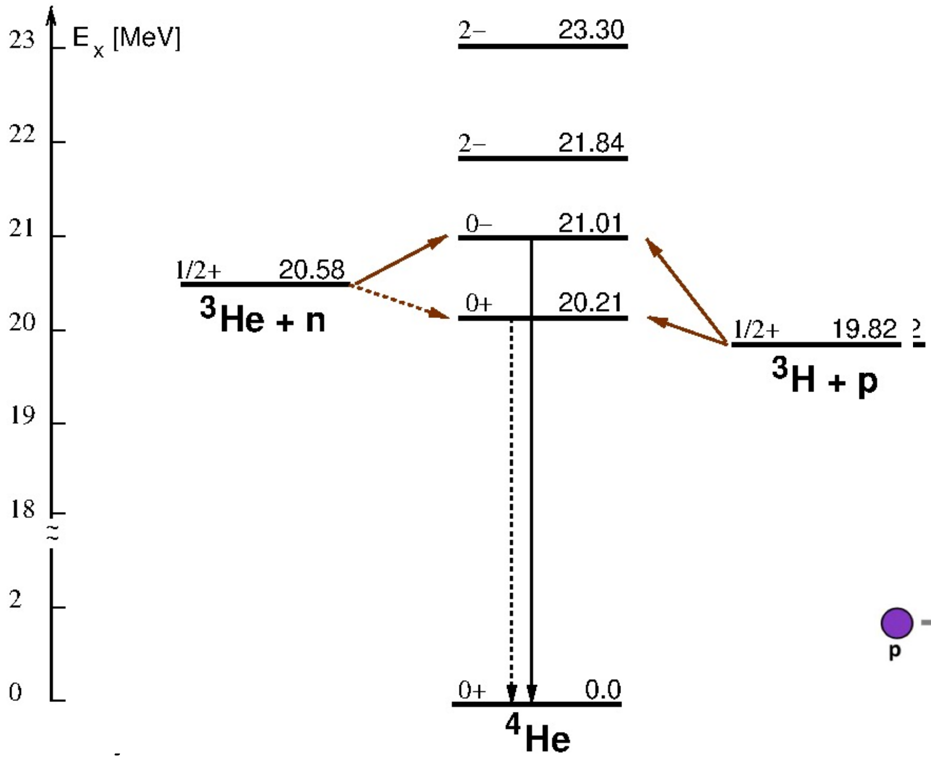
X17 @ n_TOF, basic idea: study of ^{4}He excited states

$^3He(n,e+e-)^4He$





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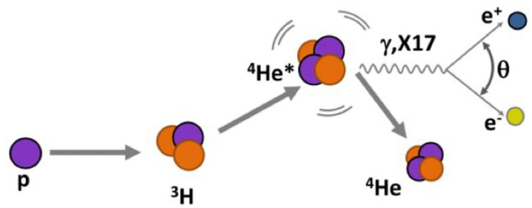

- Probing X17 existence
- X17 Mass, quantic numbers, coupling, life time,..
- proto-phobic nature of the fifth force.
- First measurement of $\sigma(E)$ $^3He(n,e+e-)^4He$
- Theoretical nuclear physics

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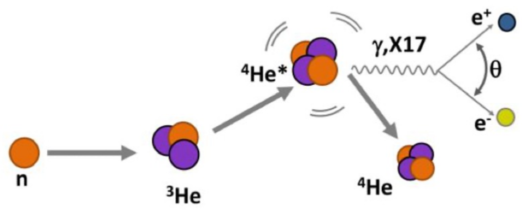
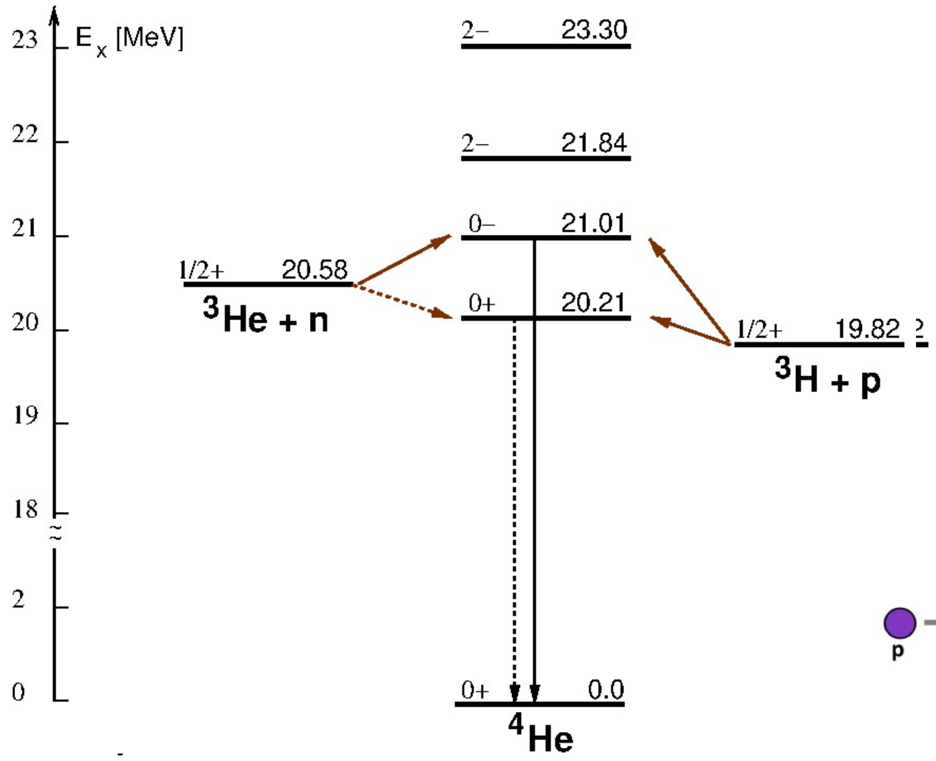
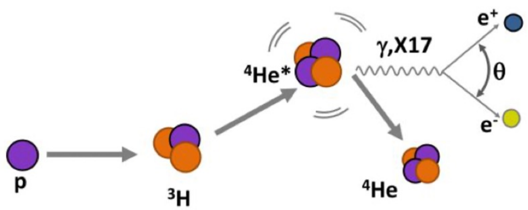
X17 @ n_TOF, basic idea: study of ^{4}He excited states

^{3}He(n,e+e-)^{4}He





^{3}H(p,e+e-)^{4}He



- Probing X17 existence
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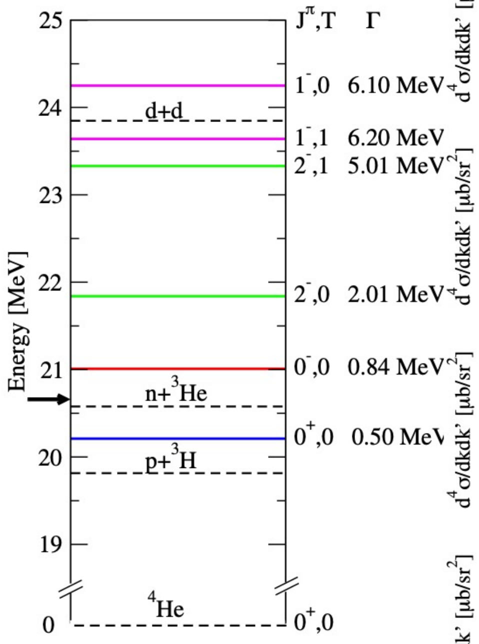
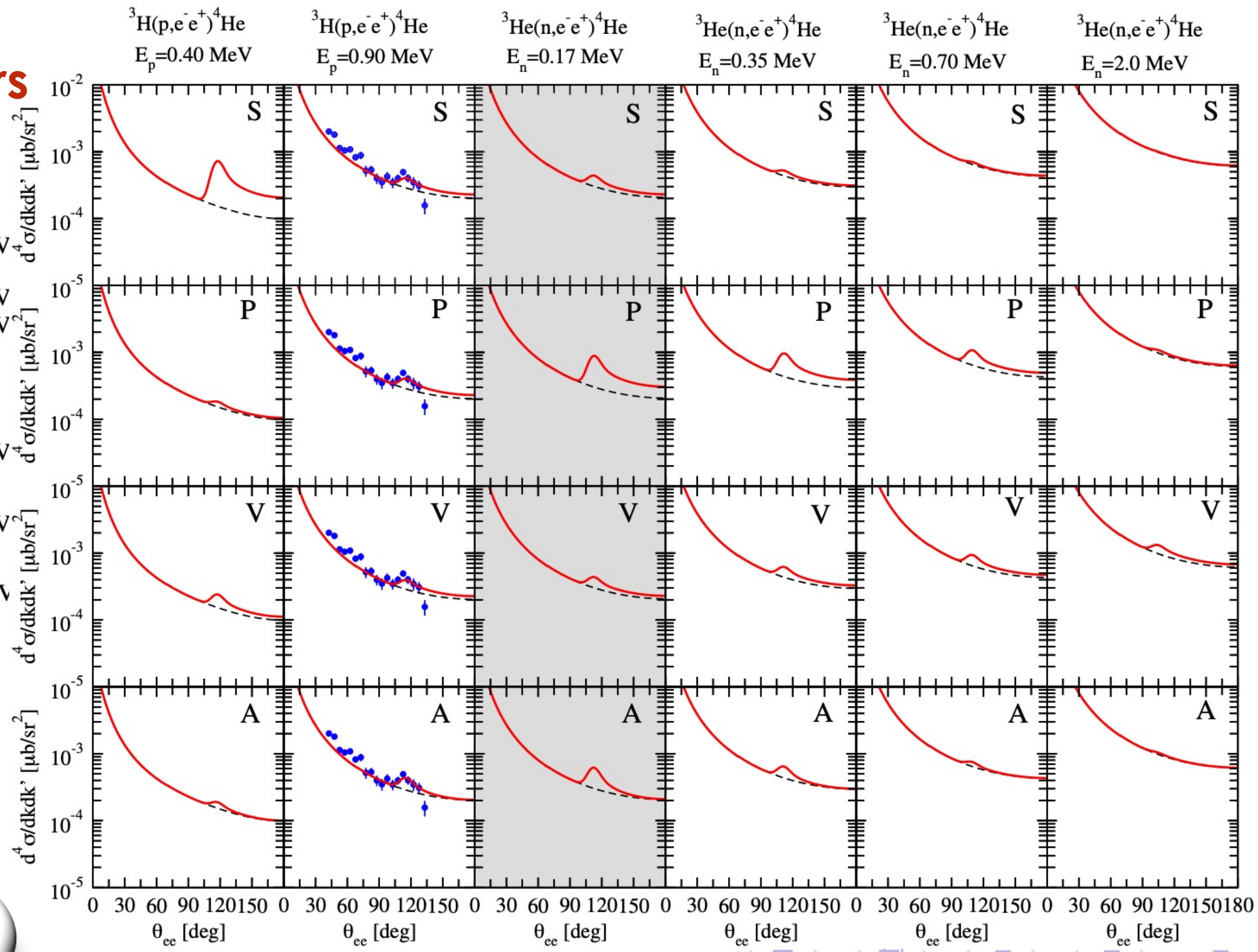
X17 quantum numbers



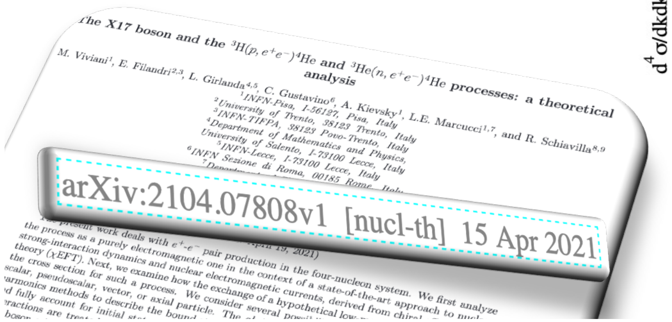


J=0⁺

J=0⁻

J=1⁻

J=1⁺



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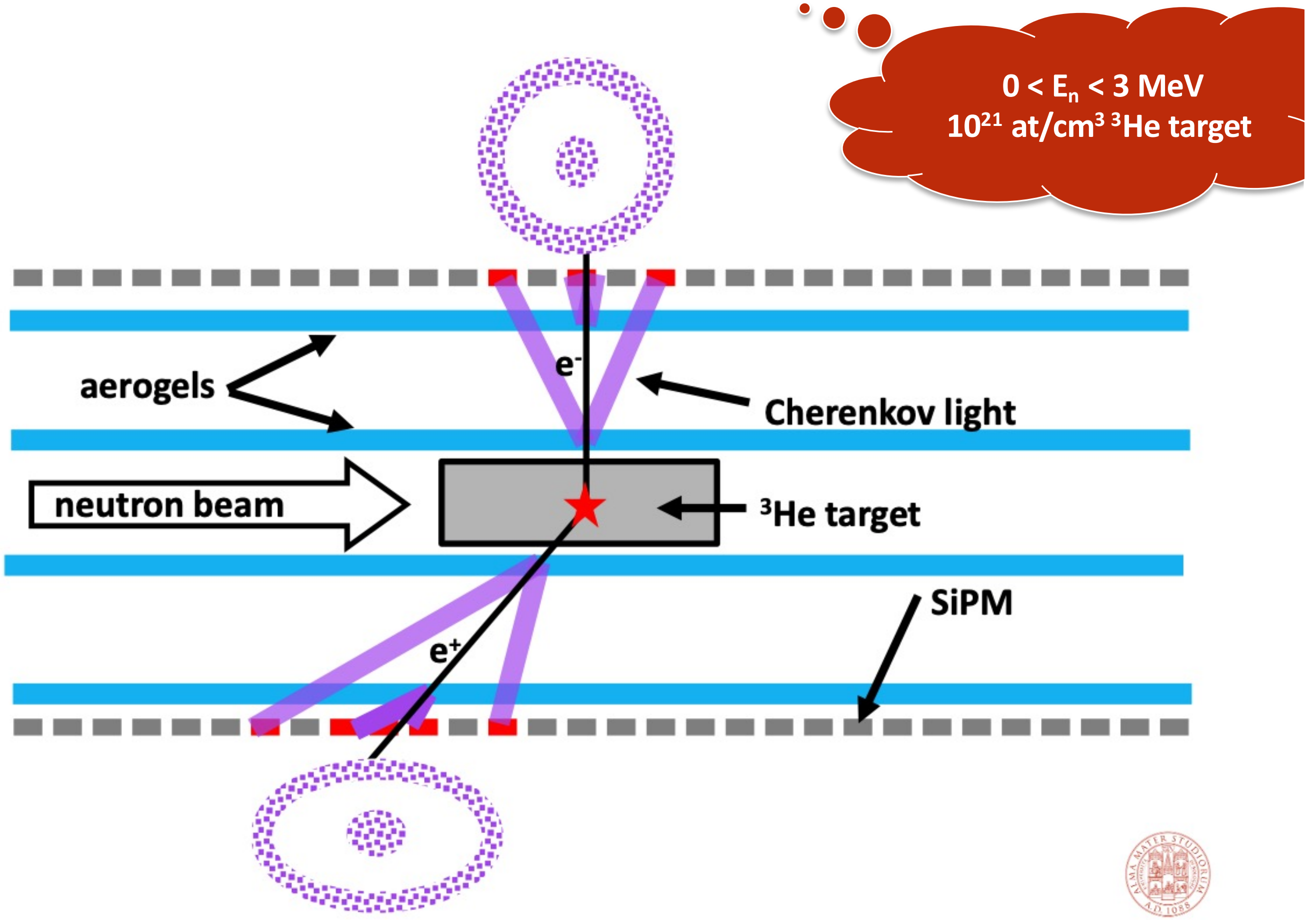
X17 @ n_TOF: possible experimental setups - EAR2 1/2

RICH:

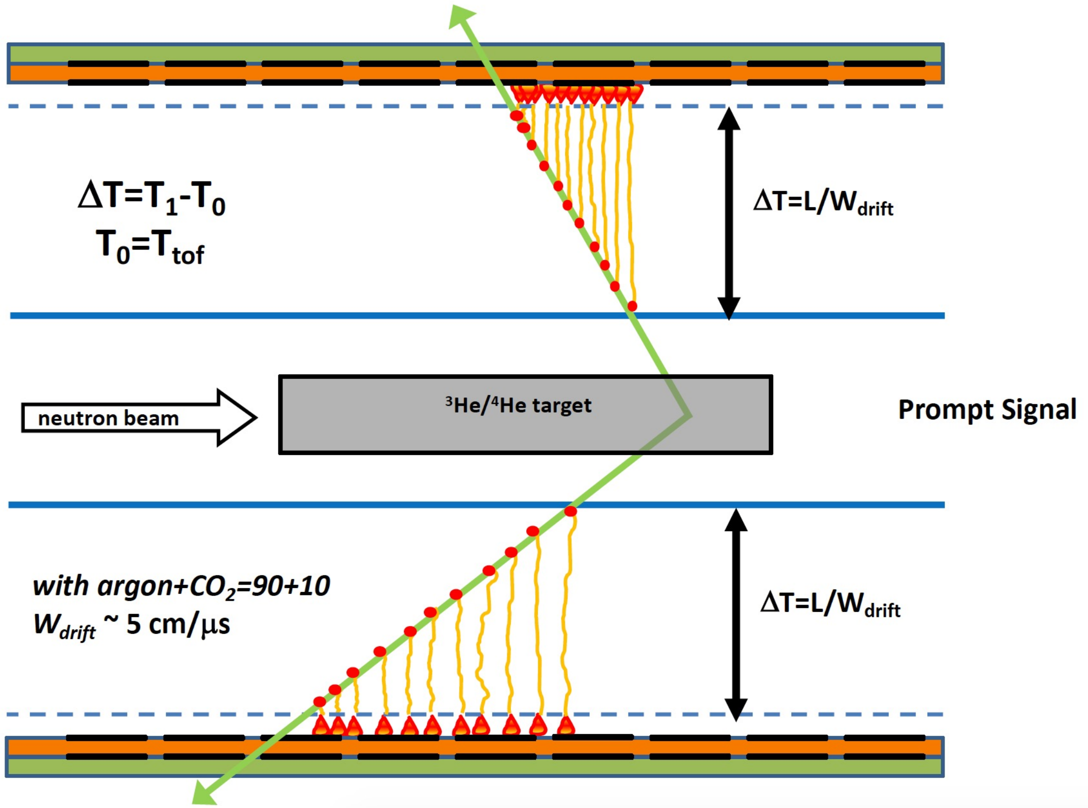
- β(e-,e+) @ 8 MeV = 0,993
- β(p) @ 100 MeV = 0,42 (below threshold)
- ^{3}He(n,γ)^{4}He small background

Working principle:
RECONSTRUCTION in TIME and SPACE

- **Ellipse centers**: e+e- impact point
- **Ellipse shapes**: e+e- direction



X17 @ n_TOF: possible experimental setups - EAR2 2/2

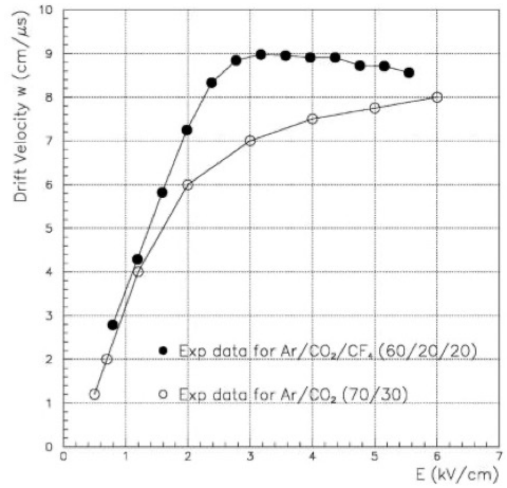


TPC with MGPD

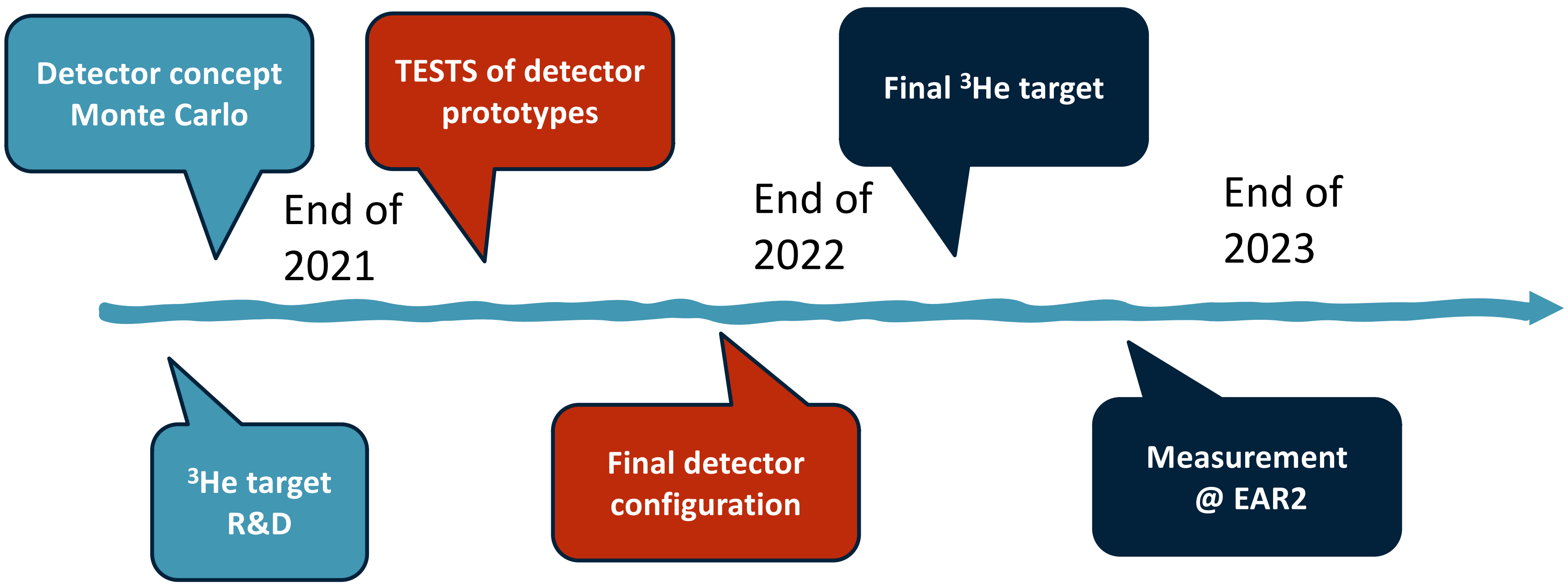
with Ar/CO_2=/CF4=60/20/20

$1/W_{drift}$ ~ 10 ns/mm

→300 ns signals (crossing e+e- pairs)

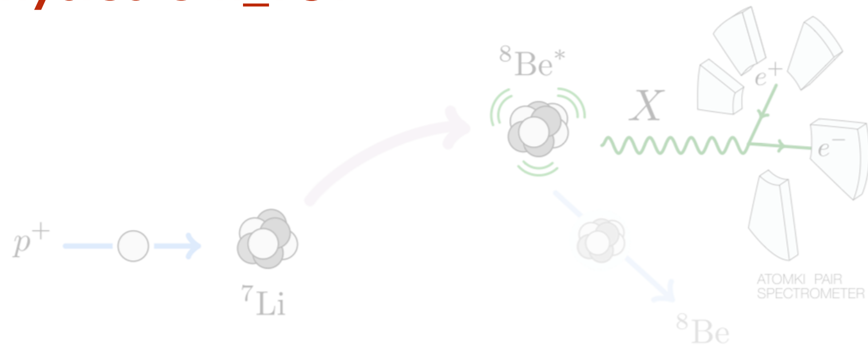


X17 @ n_TOF: (optimistic) timeline



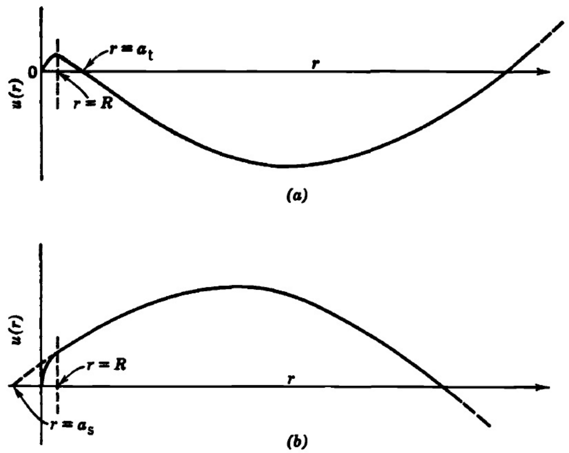
Outline: examples of nuclear physics @ n_TOF

1. Study of the X17 anomaly (or puzzle)



L. Feng, et. al, Phys. Rev. D **95** 035017

2. Neutron-neutron (NN) scattering length



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Outline: examples of nuclear physics @ n_TOF

FIRST TOF COLLABORATION MEETING

7th & 8th of January, CERN - Council Room

Preliminary PROGRAMME on the 7th of January

09:00-09:15 (5')	Welcome address.	C. Detraz	CERN-DG
09:15-09:30 (5')	The role of the CERN Facility in Europe	P. Pavlopoulos	Univ. Basel
09:30-10:05 (15')	The target-moderator station and the beam-layout of the CERN TOF Facility.	E. Radermacher	CERN-SL
10:05-10:45 (10')	GELINA and the planned CERN neutron source: complementarity and possible co-operations.	H. Weigmann	JRC-IRMM-EC - Geel
10:45-11:15	***Coffee break***		
11:15-11:45 (10')	TSL-Uppsala and the CERN TOF Neutron Facility: complementarity and co-operation.	J. Blomgren	TSL-Uppsala
11:45-12:15 (10')	Neutron Cross Sections for ATW Applications and Basic Science.	E. Henry	LLNL-Livermore
12:30-14:00	***LUNCH***		
14:00-14:30 (10')	Physics aspects at the CERN Facility and EU-Russian co-operation.	W. Furman & Y. Popov	JINR-Dubna
14:30-15:05 (10')	Pre- and post-fission neutron multiplicity measurements with the DEMON detector.	G. Rudolf	IReS-Strasbourg
15:05-15:40 (10')	The structure of the neutron and its interaction processes.	H. Leeb	TU Vienna
15:40-16:05 (10')	n-n final state interaction in the reaction n+d -> p+n+n.	P. Assimakopoulos	U Ioannina
16:05-16:30	***Coffee break***		
16:30-17:10 (10')	The LOHENGRIN facility in nuclear research and application.	S. Oberstedt	ILL-Grenoble
17:10-17:35 (10')	Large fission chamber with alpha particle rejection.	P. Cennini	CERN-EP
17:35-18:00 (10')	Gas scintillation detectors with GEM readout.	A.Tzima	Univ. Thessaloniki
18:00-18:30	***ROUND TABLE DISCUSSION ON FISSION DETECTORS***		

FIRST TOF COLLABORATION MEETING

7th & 8th of January, CERN - Council Room

Preliminary PROGRAMME on the 8th of January

09:00-09:30	Theoretical Nuclear Astrophysics as a Challenge for Our Understanding of Neutron-Rich Heavy Nuclei.	T. Rauscher	U Basel
09:30-10:10 (10')	Nuclear Astrophysics measurements at the border of stability - complementary possibilities at FZK and CERN.	F. Kaeppeler	FZK-Karlsruhe
10:10-10:30 (5')	Which neutron capture detector for measurements at the CERN facility ?	F. Corvi	JRC-IRMM-EC - Geel
10:30-11:00	***Coffee break***		
11:00-11:30 (10')	The CeF2 gamma detector.	J.M. Loiseaux	ISN-Grenoble
11:30-12:00 (10')	Liquid-Xenon 4π-gamma detectors.	V. Chepel	U - Coimbra
12:00-12:30	***ROUND TABLE DISCUSSION ON CAPTURE DETECTORS***		
12:30-14:00	***LUNCH***		
14:00-14:30 (10')	Double ionization chamber for alpha-particles with compensation for primary gamma-flash and gamma-background.	W. Furman & Y. Popov	JINR-Dubna
14:30-15:00 (10')	Large surface Si-microstrips detector.	P. Assimakopoulos	U Ioannina
15:00-15:30	***ROUND TABLE DISCUSSION ON PARTICLE DETECTORS***		
15:30-16:00	***Coffee break***		
16:00-17:00	***ROUND TABLE DISCUSSION ON ORGANISATION AND THE PROPOSAL TO THE 5th FRAMEWORK PROGRAMME***		
17:00-17:15	CONCLUSIONS		

NN scattering length, why?

In a nutshell:
Forces between nucleons are charge independent
(once EM effects are removed)
→ Charge Symmetry

Q: "**Neutrons** and **protons** behave in the **same** way under **nuclear interaction**?"

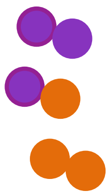
A: **YES! Neutrons** and **protons** can be considered as **2 eigenstates** of the same particle, the **nucleon.** → **New symmetry: isospin** [W. Heisenberg, 1932 https://doi.org/10.1007/BF01342433]

ISOSPIN T = 1

$T_z = 1$ proton – proton

$T_z = 0$ neutron – proton

$T_z = -1$ neutron – neutron



$[H_S, T] = 0$

H_S = strong Hamiltonian

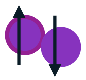
Because of
- **u-d quark mass difference**
- **Electromagnetism**

Isospin invariance and charge symmetry are only approximate symmetries

NN scattering length, why?

a_{nn} = -18.9 ± 0.4 fm
a_{pp} = -17.3 ± 0.4 fm

Charge Symmetry Breaking (CSB) of the nucleon-nucleon interaction refers to a **difference** between **proton-proton** and **neutron-neutron** interactions, only.



Experimental evidences?

- $\mathbf{m_p < m_n}$ (would be $m_n < m_p$ for Coulomb interaction only)
- $\mathbf{a_{nn} \neq a_{pp}}$ **(different scattering length)**
- $^3H - {}^3He$ binding energy

- non-vanishing forward-backward asymmetry for the reaction $n + p \rightarrow {}^2H + \pi^0$
- ….

Because of
- **u-d quark mass difference**
- **Electromagnetism**

Isospin invariance and charge symmetry are only approximate symmetries

NN scattering length, in the literature

In the literature mostly **indirect methods** can be found for the **determination of a_{nn},** based on **deuteron breakup.**

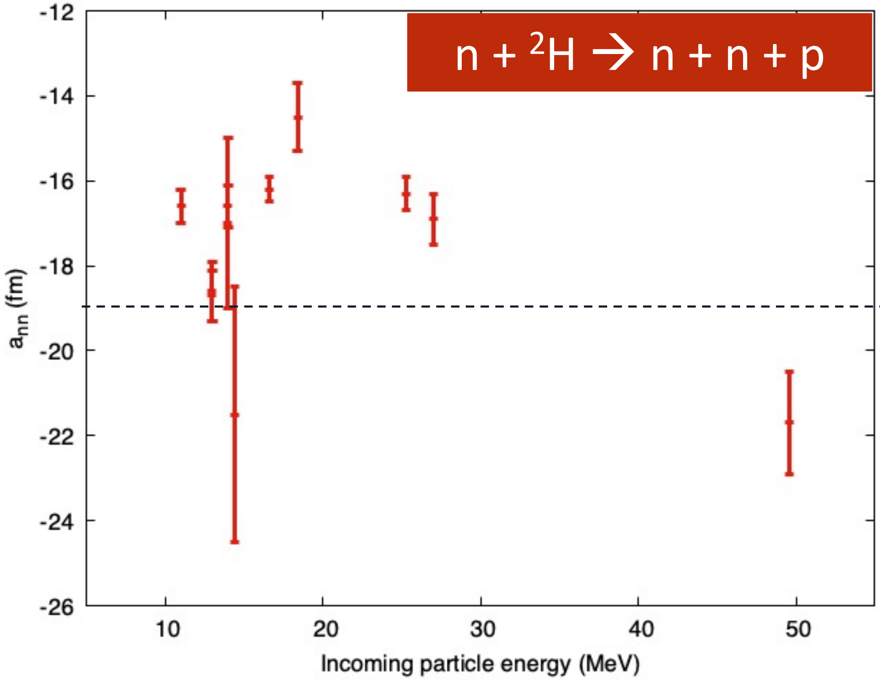
a_{nn} = -18.9 ± 0.4 fm
a_{pp} = -17.3 ± 0.4 fm

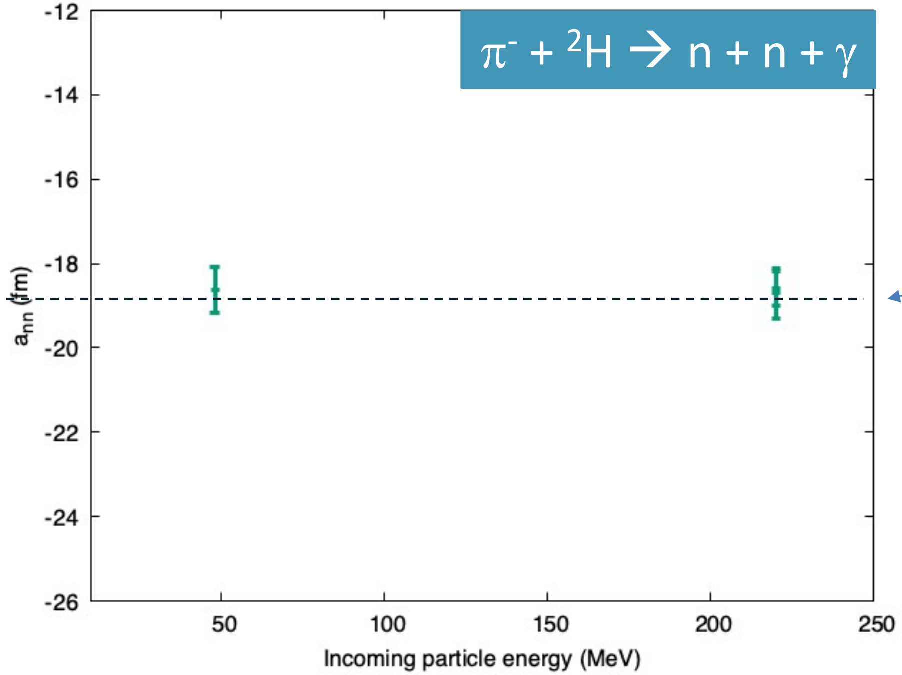
NN scattering length, in the literature

In the literature mostly **indirect methods** can be found for the **determination of a_{nn},** based on **deuteron breakup.**

$\Delta p = 0$

a_{nn} = -18.9 ± 0.4 fm
a_{pp} = -17.3 ± 0.4 fm





NN scattering length, in the literature

Some considerations:

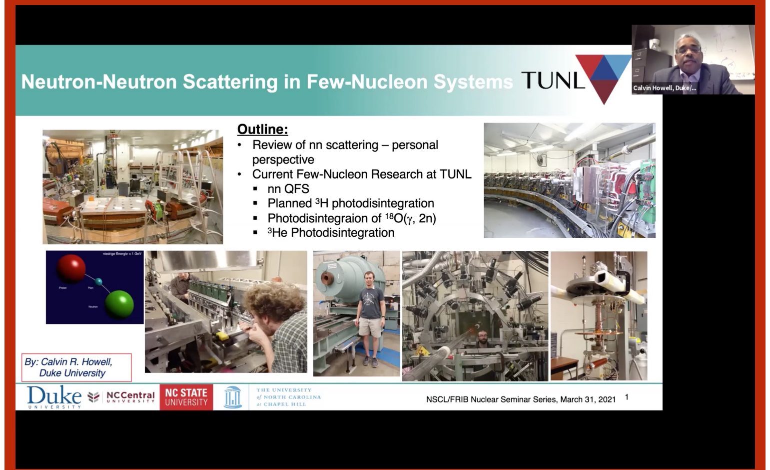
1. So far, experiments have determined the **neutron-neutron scattering length** at **fixed incoming-particle energy** and/or at **limited angular coverage** of the outgoing particles

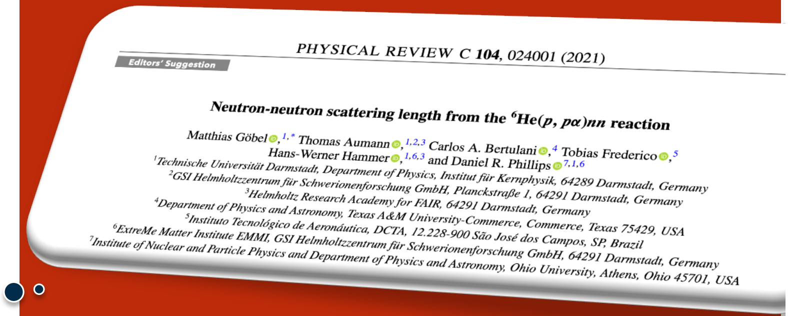
2. While the determination of $\mathbf{a_{nn}}$ is quite **complex**; $\mathbf{a_{np}}$ is **well known** and considered as a refence.

Q: How to go **beyond the present knowledge** on the topic**?**
A: by studying the **trend of $\mathbf{a_{nn}}$** (and a_{np}) as a **function of energy**.

Measurement at NFS in 2022 ?

HOT topic




Editors' Suggestion

PHYSICAL REVIEW C **104**, 024001 (2021)

Neutron-neutron scattering length from the ^{6}He$(p, p\alpha)nn$ reaction

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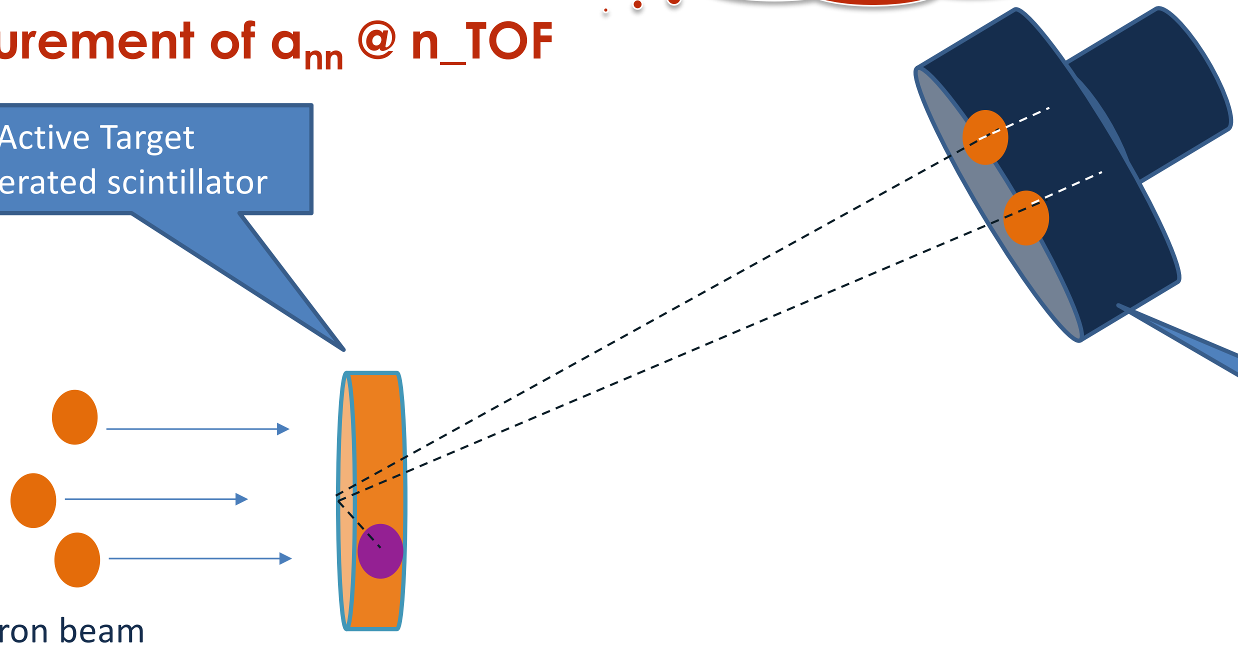
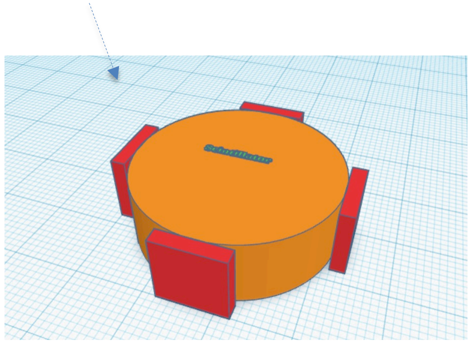
Measurement of a_{nn} @ n_TOF

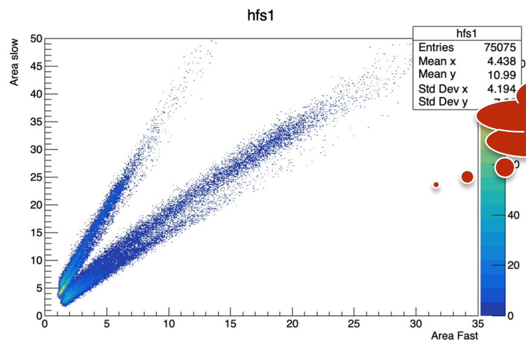
$5 < E_n < 50$ MeV

Active Target
Deuterated scintillator



Neutron detector with tracking capability
A. Musumarra et al., arXiv:2109.11543





Particle discrimination

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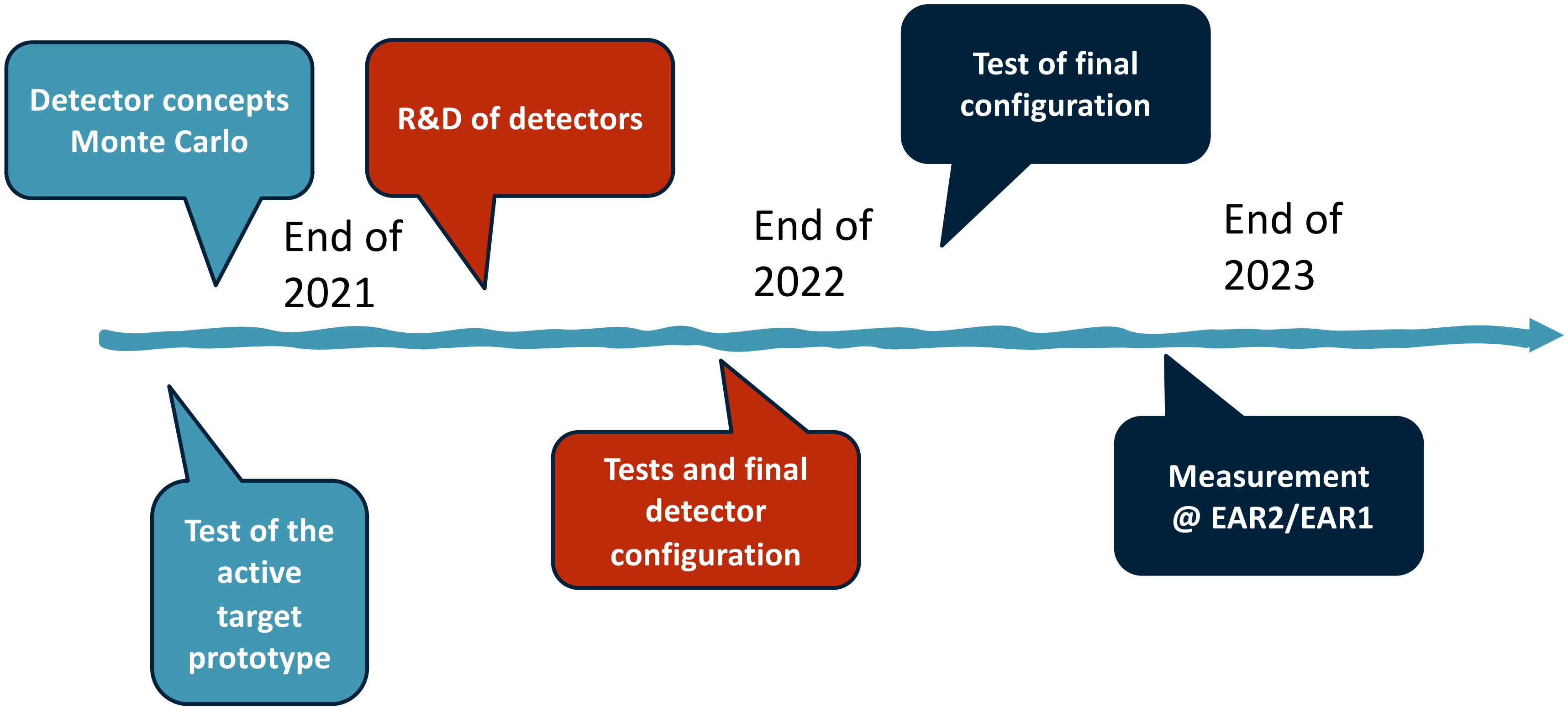
X17 @ n_TOF: (optimistic) timeline



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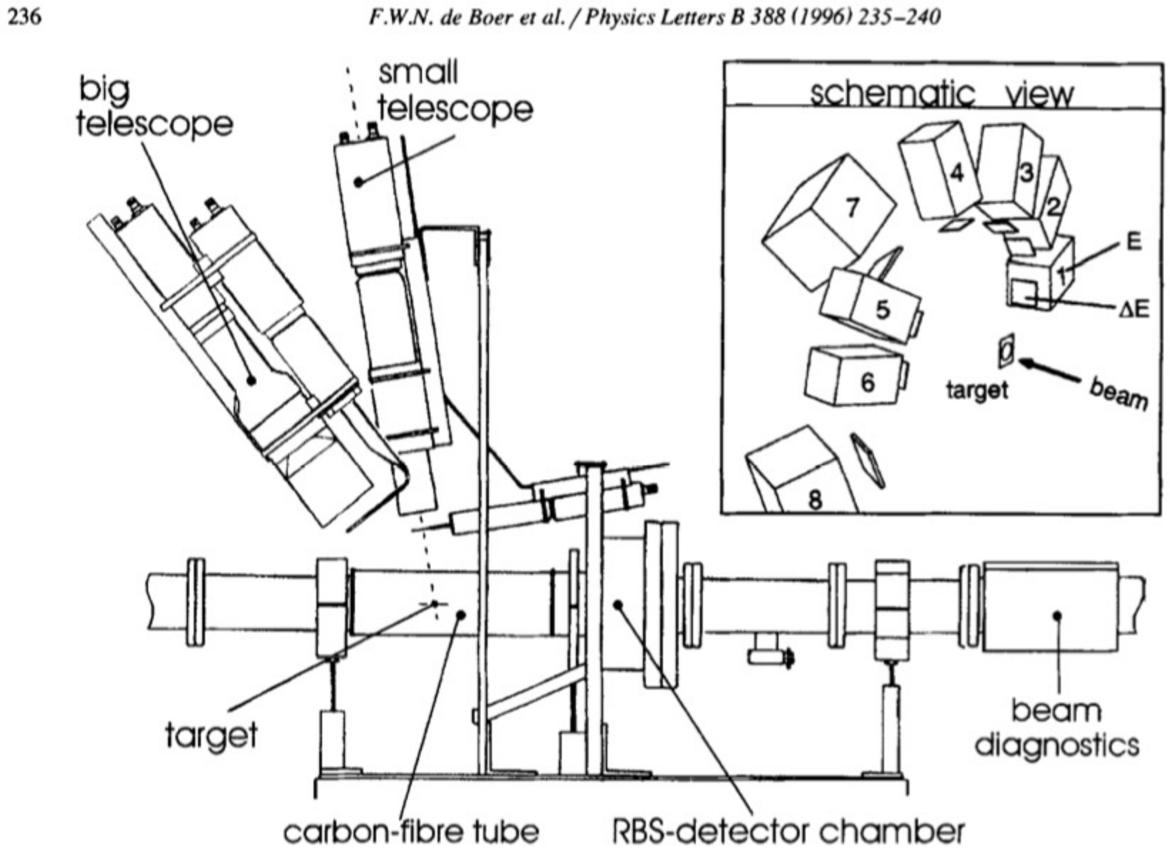
a_{nn}

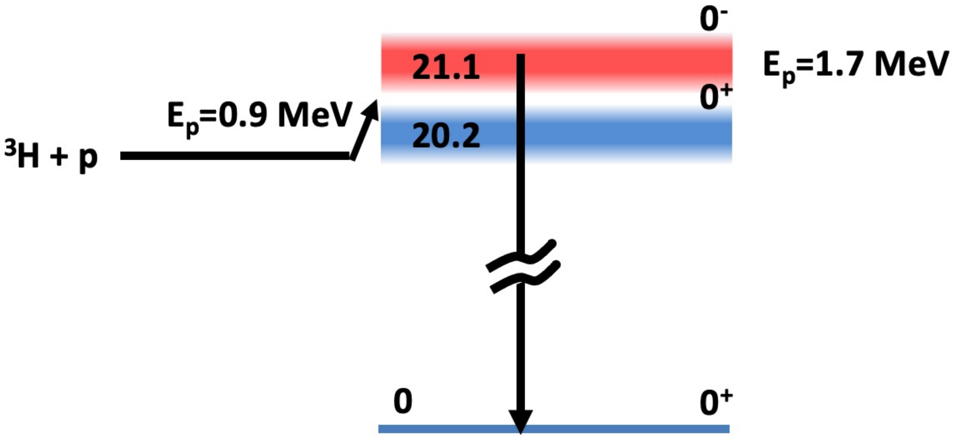
Year	Energy (MeV)	Process	Detected	$a_{nn} \pm \Delta a_{nn}$ (fm)
1965	$E_{\pi^-} = 130$	$d(\pi^-, \gamma)nn$	$n\gamma$	-16.4 ± 1.9
1967	$E_n = 14.4$	$d(n,p)nn$	p	-21.7 ± 1
1967	$E_n = 14.4$	$d(n,p)nn$	p	$-21.5 + 3 - 1$
1967	$E_d = 32.5$	$^3H(d,^3He)nn$	^3He	-16.1 ± 1.0
1972	$E_n = 18.4$	$d(n,p)nn$	nn	-14.5 ± 0.8
1972	$E_n = 49.6$	$d(n,p)nn$	p	-21.7 ± 1.2
1973	$E_n = 14.1$	$d(n,p)nn$	p	-18.3 ± 0.2
1974	$E_n = 14.3$	$d(n,p)nn$	nnp	-16.0 ± 1.2
1974	$E_n = 14.3$	$d(n,p)nn$	nnp	-16.8 ± 1.3
1975	$E_n = 14.1$	$d(n,p)nn$	nnp	-16.3 ± 1.6
1975	$E_{\pi^-} = 150$	$d(\pi^-, \gamma)nn$	$n\gamma$	-16.7 ± 1.3
1977	$E_n = 11$	$d(n,p)nn$	p	-16.6 ± 0.4
1977	$E_n = 13.98$	$d(n,p)nn$	p	-16.6 ± 0.5
1979	$E_n = 27$	$d(n,p)nn$	p	-16.9 ± 0.6
1979	$E_{\pi^-} = 170$	$d(\pi^-, \gamma)nn$	γ	-18.5 ± 0.4
1987	$E_{\pi^-} = 220$	$d(\pi^-, \gamma)nn$	$nn\gamma$	-18.7 ± 0.6
1998	$E_{\pi^-} = 220$	$d(\pi^-, \gamma)nn$	$n\gamma$	-18.6 ± 0.4
1999	$E_n = 13$	$d(n,p)nn$	$nn\gamma$	-18.7 ± 0.6
2000	$E_n = 16.6$	$d(n,p)nn$	nnp	-16.2 ± 0.3
2000	$E_n = 25.3$	$d(n,p)nn$	nnp	-16.3 ± 0.4
2000	$E_n = 25$	$d(n,p)nn$	nnp	-16.27 ± 0.40
2005	$E_d = 171$	$^2H(d,^2He)nn$	^2He	-18.3 ± 0.4
2006	$E_n = 13$	$d(n,p)nn$	nnp	-18.6 ± 0.7
2008	$E_{\pi^-} = 48$	$d(\pi^-, \gamma)nn$	$nn\gamma$	-18.63 ± 0.54

X17

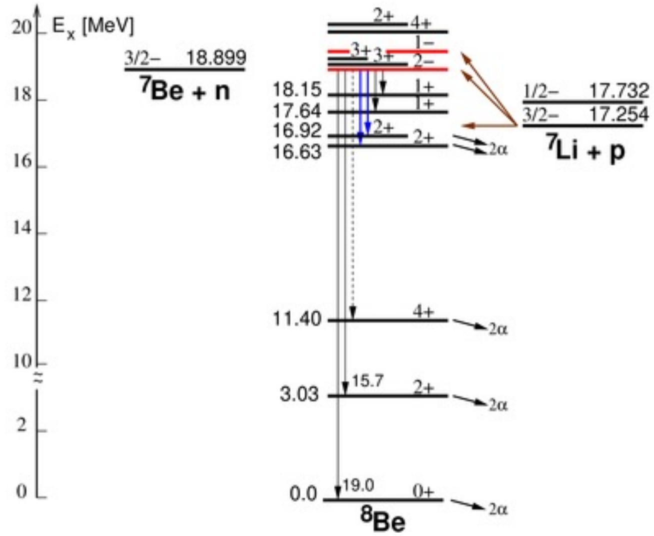

236
F.W.N. de Boer et al. / Physics Letters B 388 (1996) 235–240
big telescope
small telescope
schematic view
7
4
3
2
E
1
ΔE
5
6
target
beam
8
target
carbon-fibre tube
RBS-detector chamber
beam diagnostics

X17

^4He


0-
21.1
E_p=1.7 MeV
E_p=0.9 MeV
0+
³H + p
20.2
0
0+

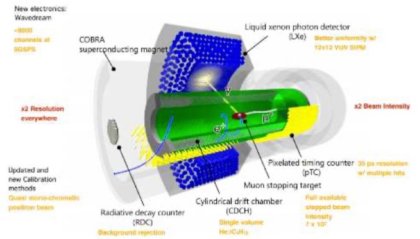
^8Be


E_x [MeV]
20
18
16
14
12
10
2
0
3/2– 18.899
⁷Be + n
2+ 4+
1–
3+ 3+ 2–
18.15
17.64
16.92
16.63
1+
1+
2+
2+
2α
1/2– 17.732
3/2– 17.254
⁷Li + p
11.40
4+
2α
3.03
15.7
2+
2α
0.0
19.0
0+
2α
⁸Be

X17

Experiment	
LHCb	Charm meson decay $D^*(2007)^0 \longrightarrow D^0 A'$ $A' \longrightarrow e^- e^+$
Mu3e	Muon decay channel $\mu^+ \rightarrow e^+ \nu_e \overline{\nu_\mu}$ ($A' \longrightarrow e^- e^+$)
VEPP-3	$e^- e^+ \longrightarrow A' \gamma$
KLOE-2	$e^- e^+ \longrightarrow \gamma (X \longrightarrow e^- e^+)$
MESA	e- beam on gaseous target, to produce A'
Darklight	e- scattering of H gas target, to produce A'
HPS	e- beam on W to study $A' \longrightarrow e^- e^+$ and $A' \longrightarrow \mu^- \mu^+$
PADME	e+ beam on diamond target $e^- e^+ \longrightarrow X\gamma$
NA64	eZ → eZ +*X17*
NSL	^{8}Be (A' ⟶e-e+)
^{8}BeP	^{8}Be (A' ⟶e-e+)
New JEDI	^{8}Be/^{3}He/d… (A' ⟶e-e+)
Montréal	^{8}Be (A' ⟶e-e+)
NSCL	^{8}Be (A' ⟶e-e+)
IUAP CTU	^{8}Be and ^{4}He (A' ⟶e-e+)
n_TOF	**^{4}He and ^{8}Be (A' ⟶e-e+) (proton and neutron beams)**
MEG2	^{8}Be
NUCLEX	^{8}Be

MEG



Other experiments involving people of INFN

- LNL: $^7\mathrm{Li}(p, e^+e^-)^8\mathrm{Be}$ NUCLEX
- PSI: $^7\mathrm{Li}(p, e^+e^-)^8\mathrm{Be}$ MEGII
- Belle II

X17

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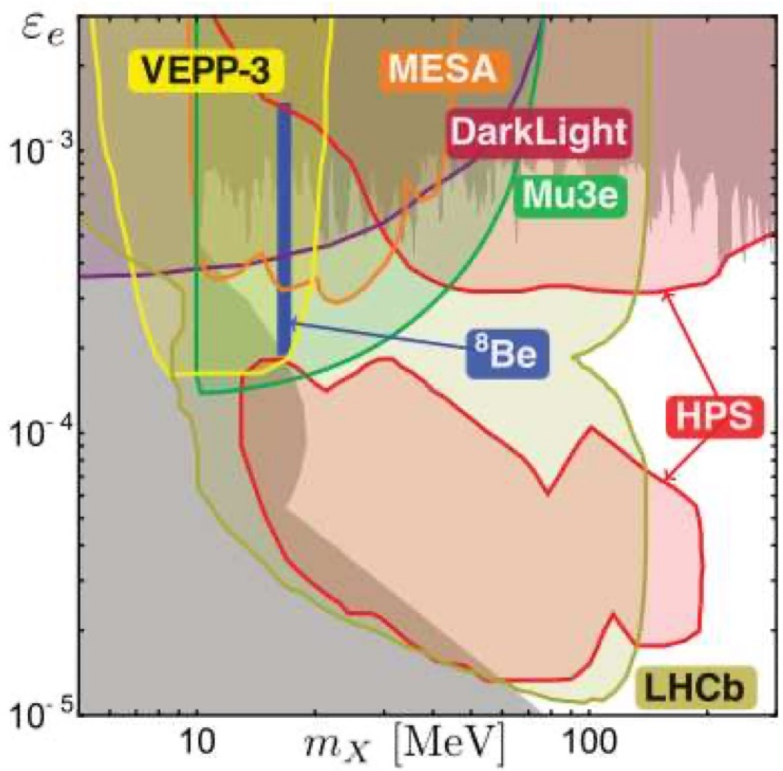

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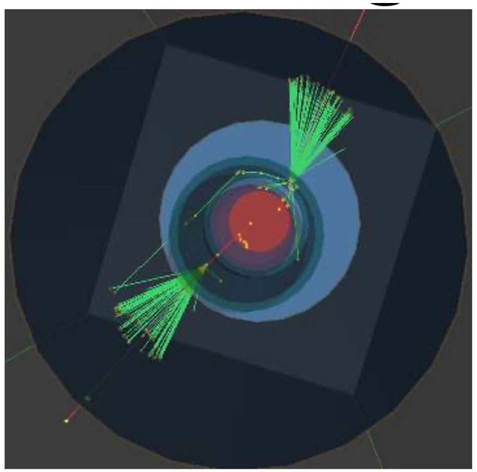
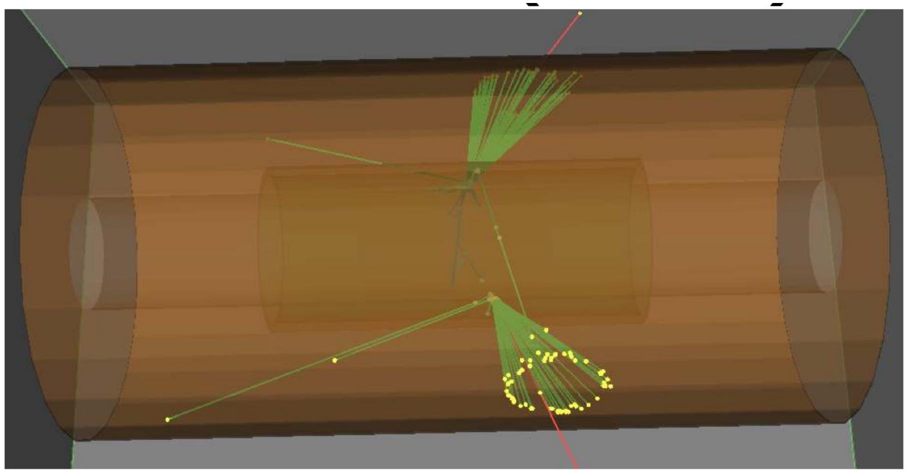
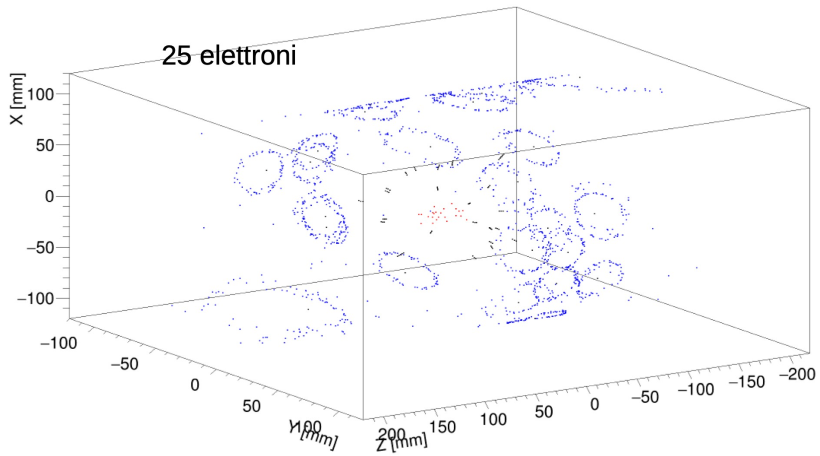





25 elettroni
X [mm]
100
50
0
−50
−100
−100
−50
0
50
100
Y [mm]
200
150
100
50
0
−50
−100
−150
−200
Z [mm]

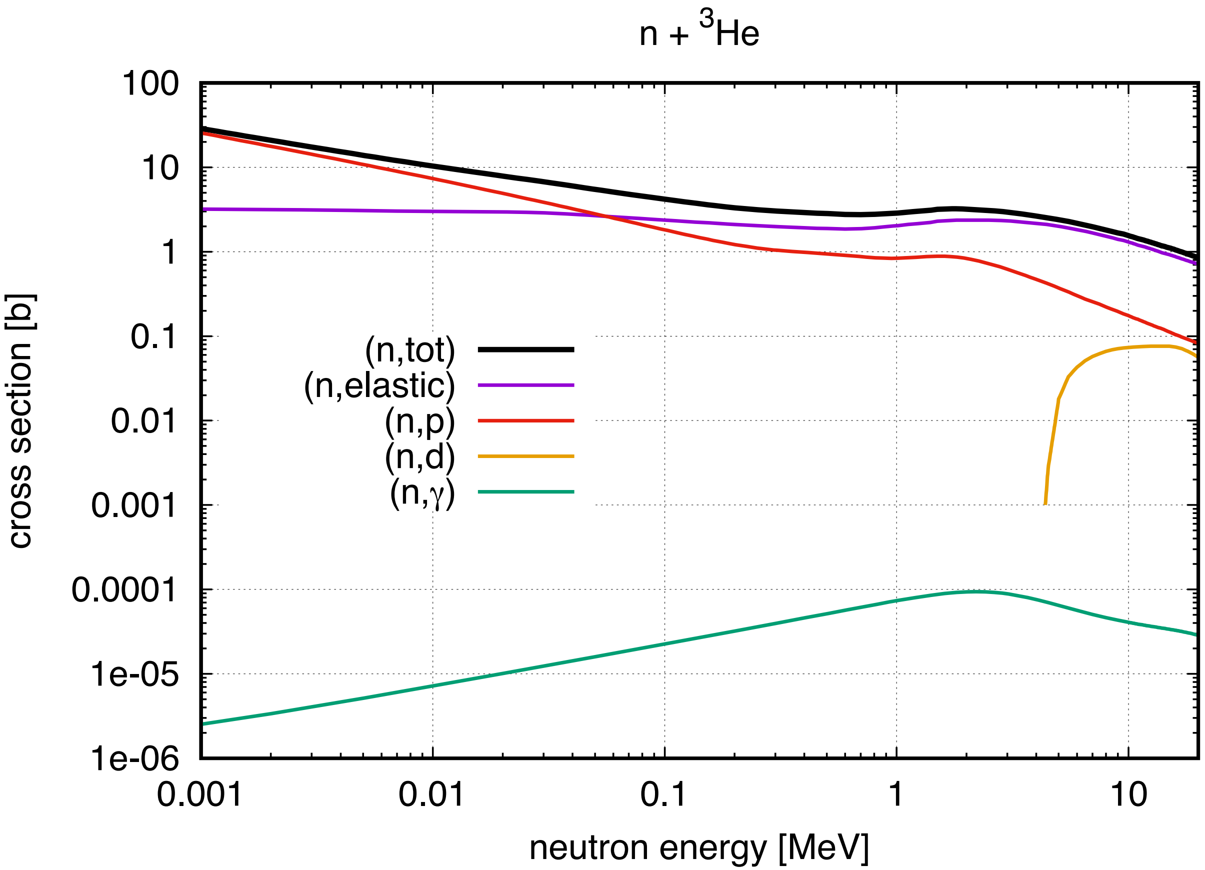
X17

Table and Figure: neutrons per pulse (frequency=1.2 sec)

Assuming:
ρ=8.21*10^{21} atoms/cm^3
target lenght=10 cm
Duty Cycle=100%
efficiency=100%
acceptance=100%

		3He(n,g)4He	3He(n,e+e-)4He	3He(n,X17)4He		
En_min (eV)	En_max (eV)	gamma/pulse	IPC/day	X17/Day (vector)	T_min (us)	T_max (us)
1	10	0,8	120	3	411	1300
10	100	0,9	133	3	130	411
100	1000	1,0	150	4	41	130
1000	1E+04	1,2	182	5	13	41
1E+04	1E+05	2,1	324	8	4	13
1E+05	1E+06	15,7	2518	63	1,30	4
1E+06	1E+07	11,3	1812	45	0,41	1,30
	TOTALI-->	33	5239	131	0,41	1300

X17



n + 3He
100
10
1
0.1
0.01
0.001
0.0001
1e-05
1e-06
0.001
0.01
0.1
1
10
cross section [b]
neutron energy [MeV]
(n,tot)
(n,elastic)
(n,p)
(n,d)
(n,γ)