

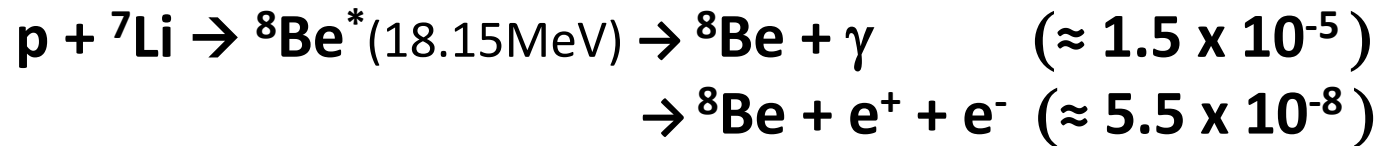
Аномалия внутренней парной конверсии (X17). Новые измерения в Atomki и другие планируемые эксперименты

Atomki (Институт ядерных исследований), Debrecen, Hungary



1. A. J. Krasznahorkay et al., PRL 116, 042501 (2016)

(см. также М.Б Жалов, семинар ОФВЭ 20.06.2017)



Новые измерения после модернизации установки

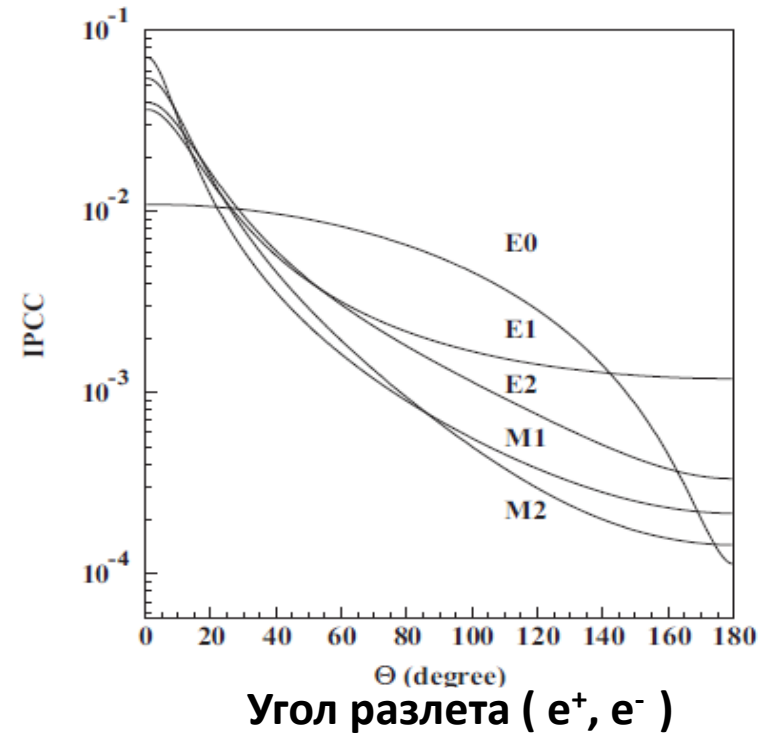
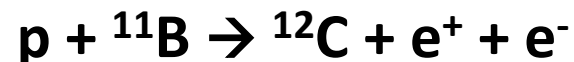
2. A. J. Krasznahorkay et al., Acta Phys. Pol. B 50, 0675 (2019)



3. A. J. Krasznahorkay et al., PRC 104, 044003 (2021)



4. A. J. Krasznahorkay et al., PRC 106, L061601 (2022)

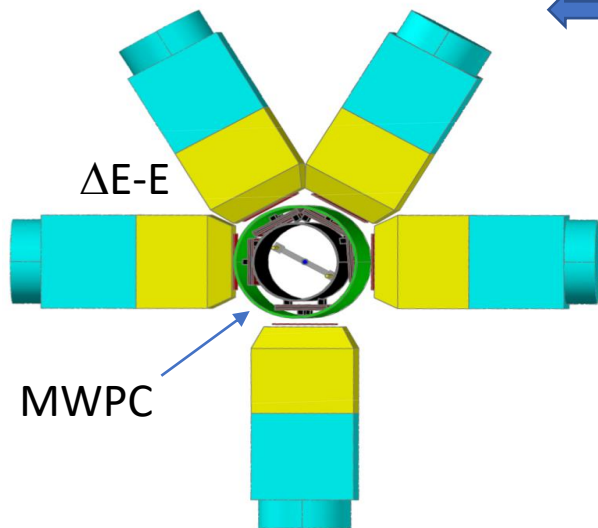


Based on M.E. Rose, Physical Review 76 (1949) 678
M.E. Rose, Physical Review 78 (1950) 184

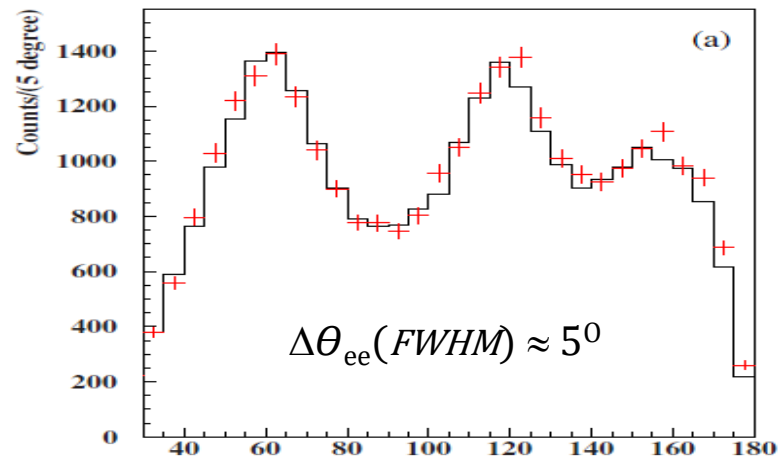
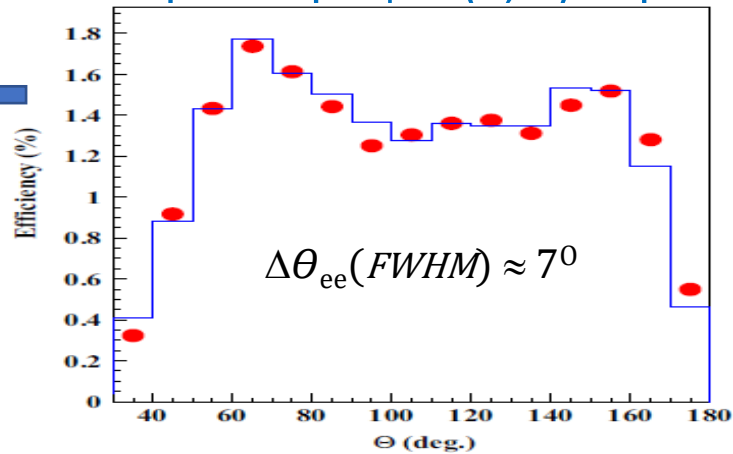
Экспериментальные установки Atomki

Акцептанс + Эффективность
регистрации (e, e) пар

“старая” (до 2016)

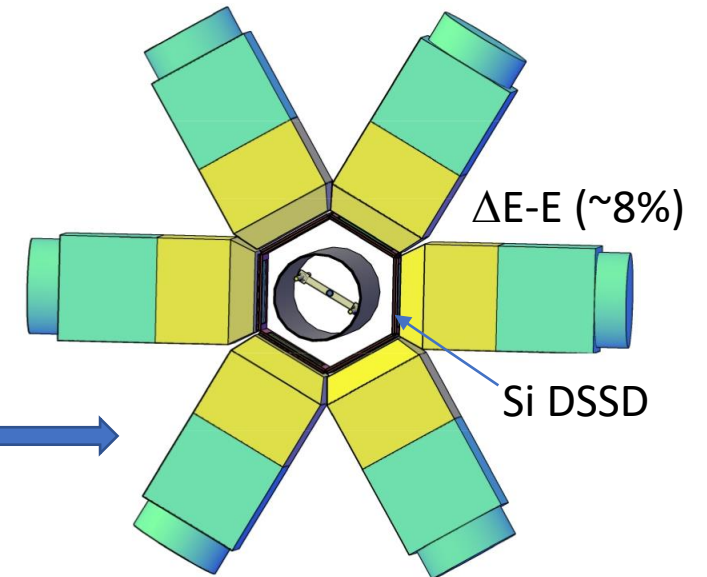


5 MV Van de Graaff accelerator
Мишени : LiF (15 – 70 $\mu\text{g}/\text{cm}^2$)
Li₂O (300 – 700 $\mu\text{g}/\text{cm}^2$)
Li (metallic)
Подложка : Al (10 μm)



Угол разлета (e , e) из разных событий

“модернизированная” (>2017)



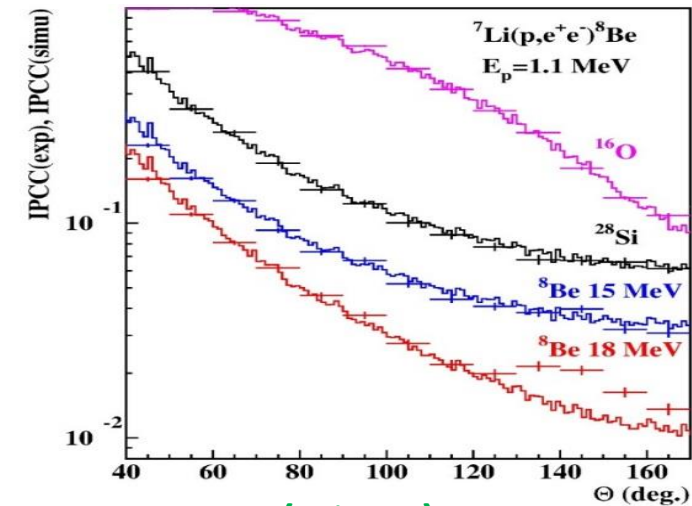
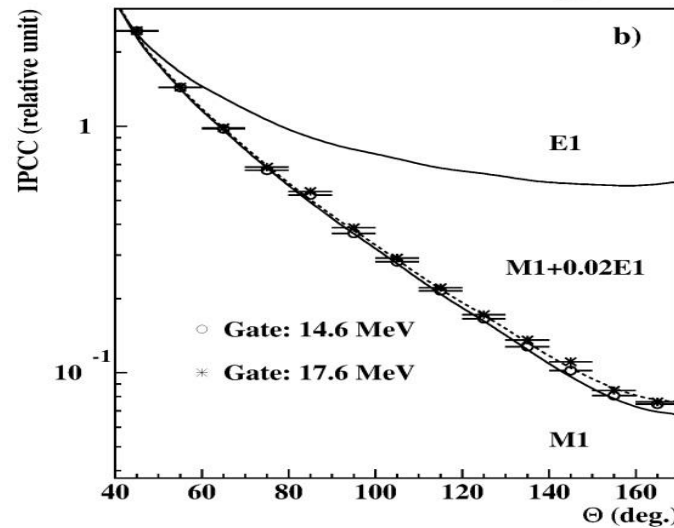
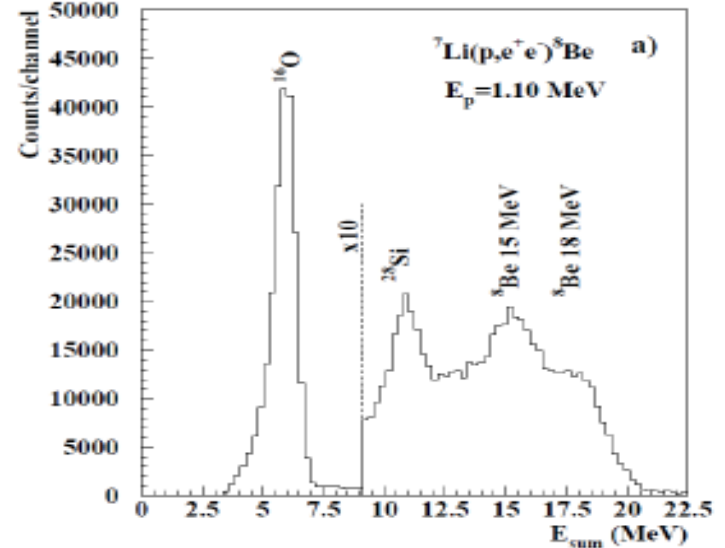
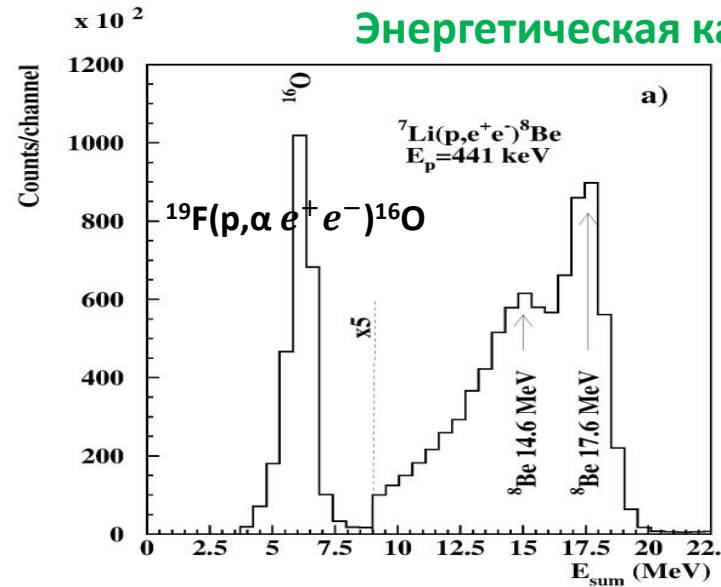
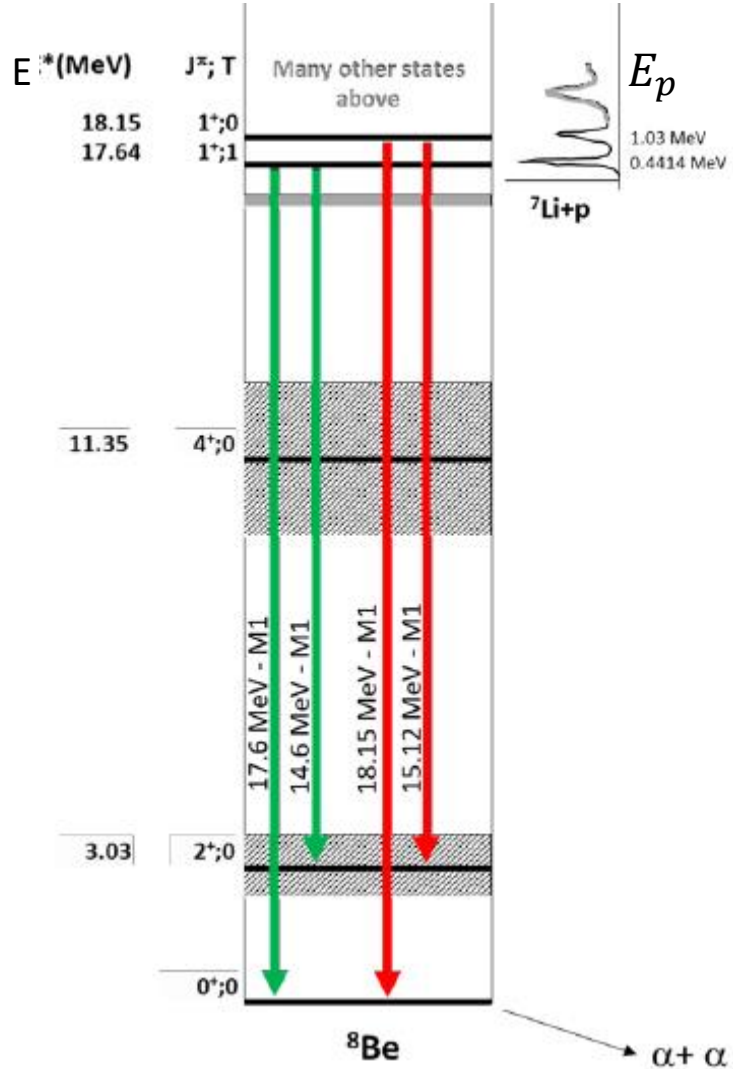
2 MV Van de Graaff accelerator
другой зал

1. $\theta \approx 90^\circ \pm 17^\circ$
2. Заряд e не определяется
3. Трассировки нет

Измерения ${}^7\text{Li}(p, e^+ e^-){}^8\text{Be}$

A. J. Krasznahorkay et al., PRL 116, 042501 (2016)

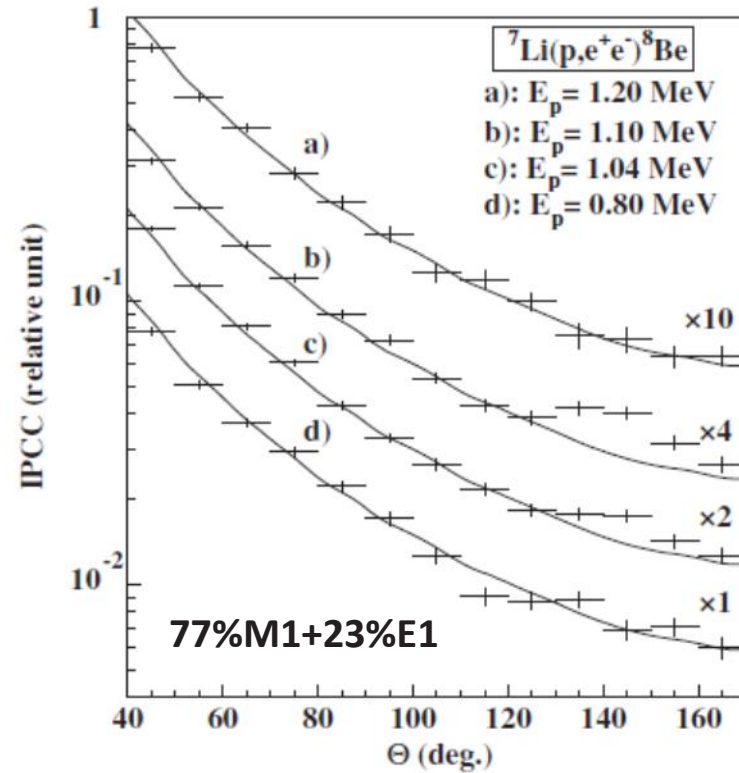
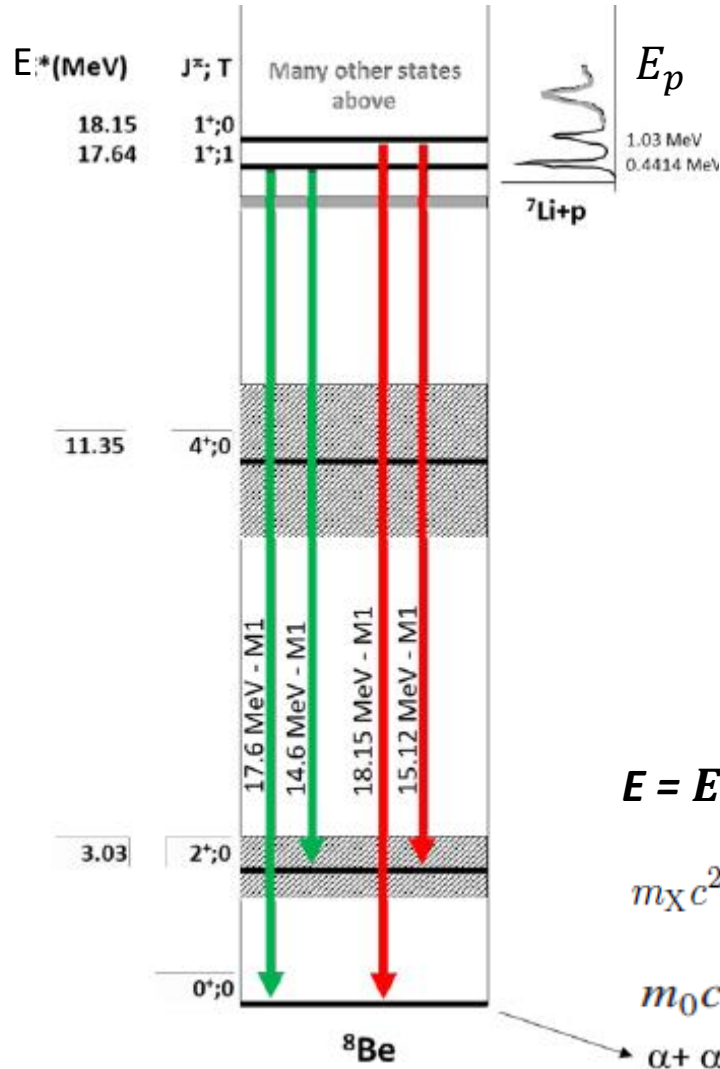
Энергетическая калибровка (p+(LiF+Al))



Распределения по углу разлета (e+, e-) пар

Измерения ${}^7\text{Li}(p, e^+ e^-){}^8\text{Be}$

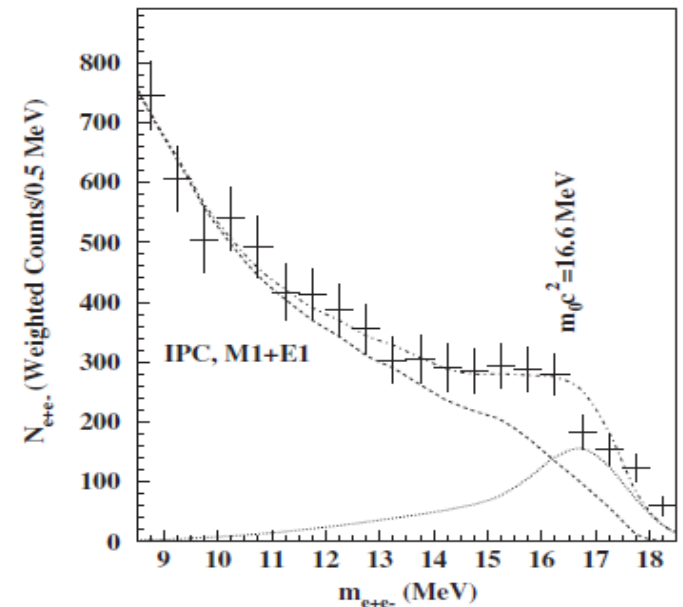
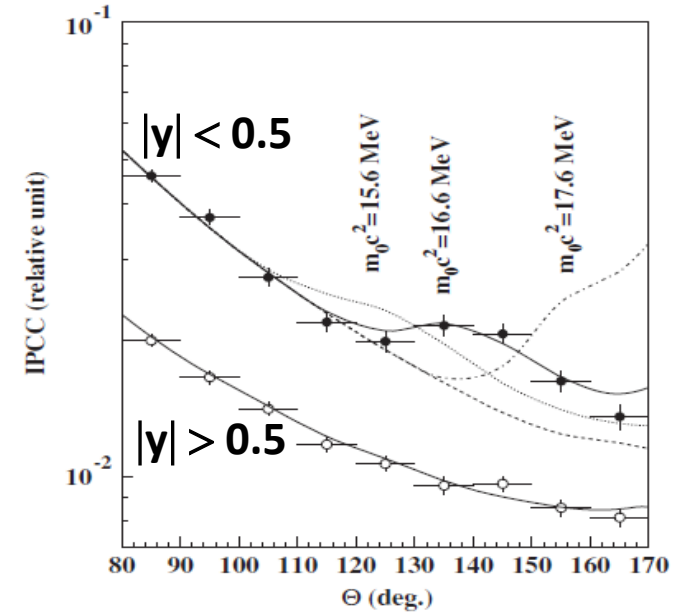
A. J. Krasznahorkay et al., PRL 116, 042501 (2016)



$$E = E_+ + E_-; \quad y = (E_+ - E_-)/(E_+ + E_-)$$

$$m_X c^2 = \sqrt{1 - y^2} E \sin(\theta/2) + 2m_e^2 \left(1 + \frac{(1 + y^2)}{(1 - y^2)} \cos(\theta) \right)$$

$$m_0 c^2 = 16.70 \pm 0.35(\text{stat}) \pm 0.5(\text{syst}) \text{ MeV}$$



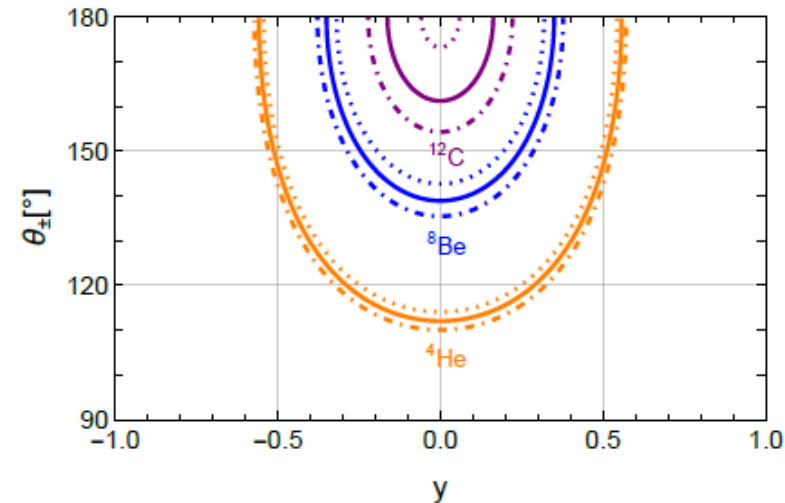
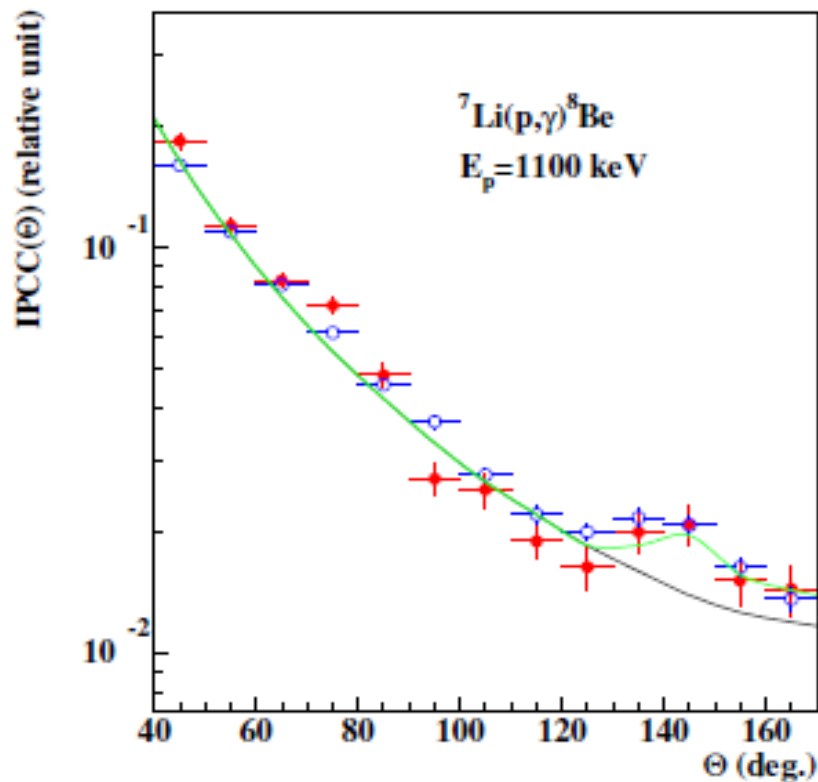
Измерения ${}^7\text{Li}(p, e^+ e^-){}^8\text{Be}$

A. J. Krasznahorkay et al., *Acta Phys. Pol. B* 50, 0675 (2019)

Сравнение измерений на **старой** и **модернизированной** установках

A. J. Krasznahorkay et al., *PRL* 116, 042501 (2016)

A. J. Krasznahorkay et al., *Acta Phys. Pol. B* 50, 0675 (2019)



Кинематика распада
 $X(17 \pm 0.2 \text{ МэВ}) \rightarrow e^+ + e^-$
(from D. Barducci, C.Toni,
JHEP 02 (2023) 154.)

${}^{12}\text{C}$, $E^* = 17.23 \text{ МэВ}$

${}^8\text{Be}$, $E^* = 18.15 \text{ МэВ}$

${}^4\text{He}$, $E^* = 20.21 \text{ МэВ}$

	Previous res. [1]	Exp1	Exp2	Average
$m_0 c^2$ [MeV]	16.70(51)	16.86(6)	17.17(7)	17.01(16)
B_x	5.8×10^{-6}	$6.8(10) \times 10^{-6}$	$4.7(21) \times 10^{-6}$	$6(1) \times 10^{-6}$
Significance	6.8σ	7.37σ	4.90σ	

$$B_x = \frac{\Gamma({}^8\text{Be}(18.15) \rightarrow {}^8\text{Be} + X)}{\Gamma({}^8\text{Be}(18.15) \rightarrow {}^8\text{Be} + \gamma)} \text{BR}(X \rightarrow e^+ e^-)$$

Теоретические интерпретации аномалии

Ядерная физика:

1. X. Zhang and G. A. Miller, *Phys. Lett. B* **773**, 159 (2017).

(**Be-8**. M1-E1-E2 interferences + M1 form factor. Авторы: **Требуемый форм-фактор не реалистичен.**)

2. M. Viviani et al., *Phys. Rev. C* **105**, 014001 (2022)

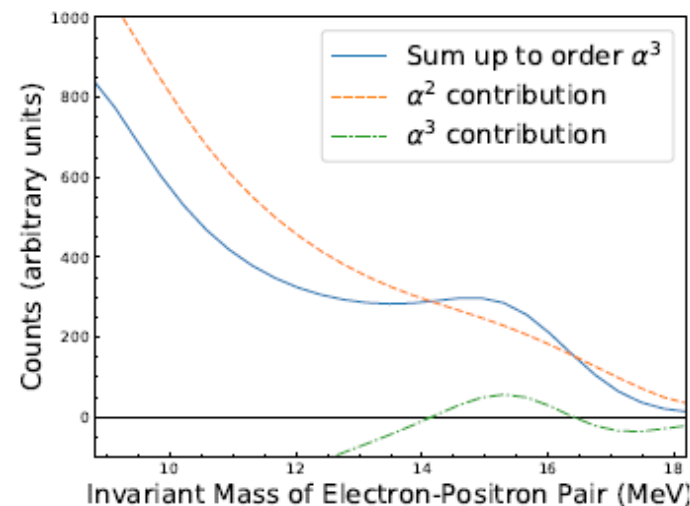
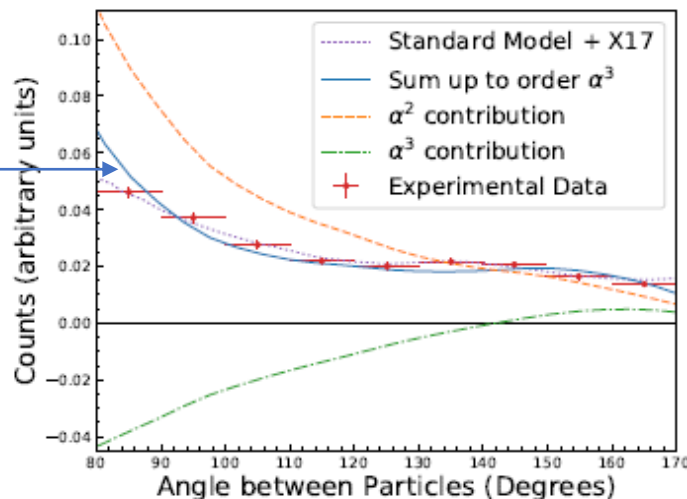
(**He-4**. “We first analyze the process as a purely electromagnetic one in the context of a state-of-the-art approach to nuclear strong-interaction dynamics and nuclear electromagnetic currents, derived from chiral effective field theory (χ EFT).” Авторы: **Аномалия не воспроизводится.**)

3. A. Aleksejevs et al., [arXiv:2102.01127](https://arxiv.org/abs/2102.01127) (не опубликовано)

(**Be-8**. “We show that the observed experimental structure can be reproduced within the Standard Model by adding the full set of second-order corrections and the interference terms to the Born-level decay amplitudes...”)

MC \neq GEANT

включен **только акцептанс**
установки АТОМКИ



Теоретические интерпретации аномалии

Новая легкая массивная частица (бозон вне СМ)

Орбитальный момент в системе X17-N

(from D. Barducci, C.Toni, JHEP 02 (2023) 154.)

Process $N^* \rightarrow N$	X boson spin parity			
	$S^\pi = 1^-$	$S^\pi = 1^+$	$S^\pi = 0^-$	$S^\pi = 0^+$
${}^8\text{Be}(18.15) \rightarrow {}^8\text{Be}$	1	0, 2	1	✗
${}^8\text{Be}(17.64) \rightarrow {}^8\text{Be}$	1	0, 2	1	✗
${}^4\text{He}(21.01) \rightarrow {}^4\text{He}$	✗	1	0	✗
${}^4\text{He}(20.21) \rightarrow {}^4\text{He}$	1	✗	✗	0
${}^{12}\text{C}(17.23) \rightarrow {}^{12}\text{C}$	0, 2	1	✗	1

2. An axial vector boson ($S^\pi = 1^+$)

J. Kozaczuk, D. E. Morrissey, S. R. Stroberg, PRD 95, 115024 (2017) **UV model**

(Расчет матричных элементов, учет экспериментальных ограничений)

3. A pseudoscalar particle ($S^\pi = 0^-$)

U. Ellwanger, S. Moretti, JHEP 11 (2016) 039; C.-Y. Wong, JHEP 08 (2020) 165

A variant of QCD axion model ("Piophobic" axion)

D. S. M. Alves, N. J. Weiner, JHEP 07 (2018) 092;

D. S. M. Alves, PRD 103, 055018 (2021); J. Liu et al, JHEP 05 (2021) 138

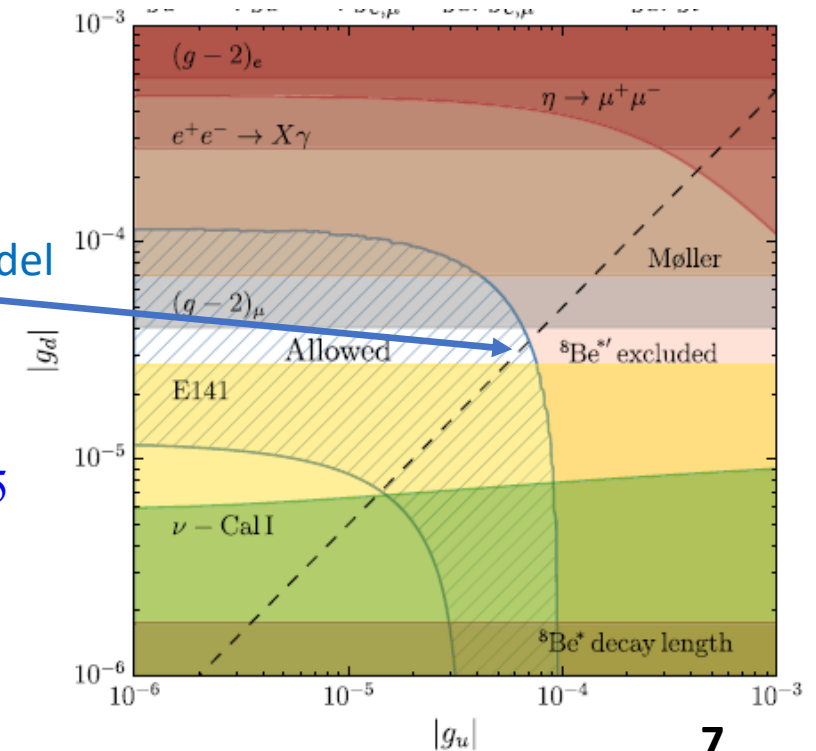
1. A protophobic vector boson ($S^\pi = 1^-$)

J. L. Feng et al, PRL 117, 071803 (2016);

PRD 95, 035017 (2017); PRD 102, 036016 (2020)

$B_X \rightarrow |\epsilon_p + \epsilon_n| \approx 0.01 \gg \epsilon_{\text{max}}(\text{dark photon, NA48/2}) < 8 \cdot 10^{-4}$,
но векторный бозон с $|\epsilon_p / \epsilon_n| < 0.08$ возможен.

Decay $\rightarrow |\epsilon_e| > 1 \cdot 10^{-5}$, не запрещено $2 \cdot 10^{-4} < |\epsilon_e| < 2 \cdot 10^{-3}$



X17 в переходе $\text{Be}^*(17.64) \rightarrow \text{Be} + e^+ + e^-$

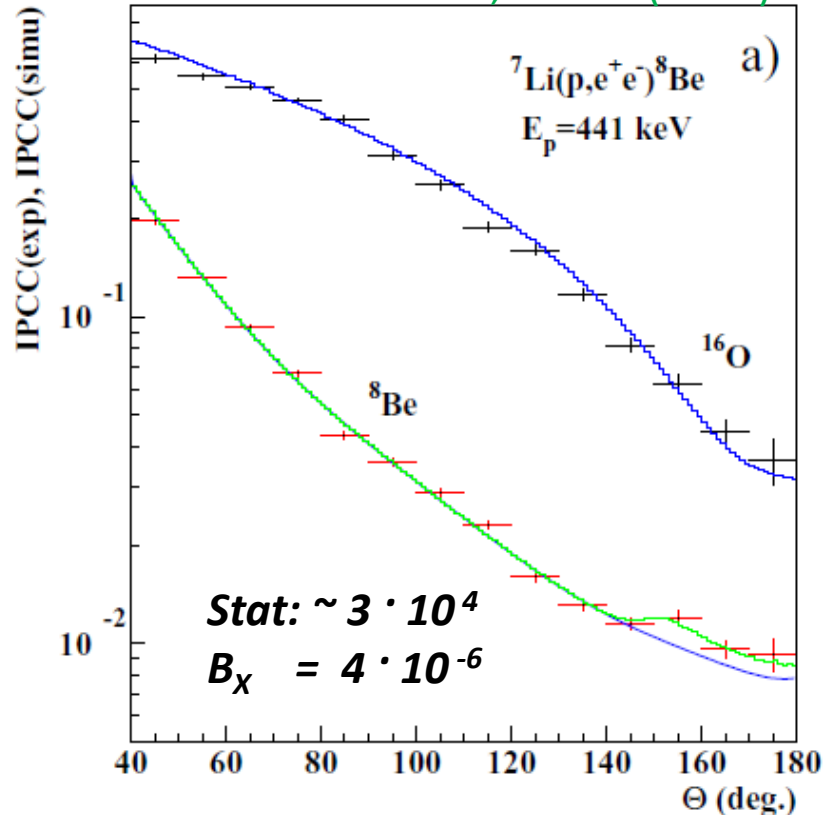
2 MV Van de Graaff , другой зал, установка (5 (ΔE -E) + DSSD), тонкая мишень ($15 \mu\text{g}/\text{cm}^2$)

Предсказания : $B_\chi = 2.6 \cdot 10^{-6}$ («*protophobic*» вектор, J. L. Feng et al, PRL 117, 071803 (2016))

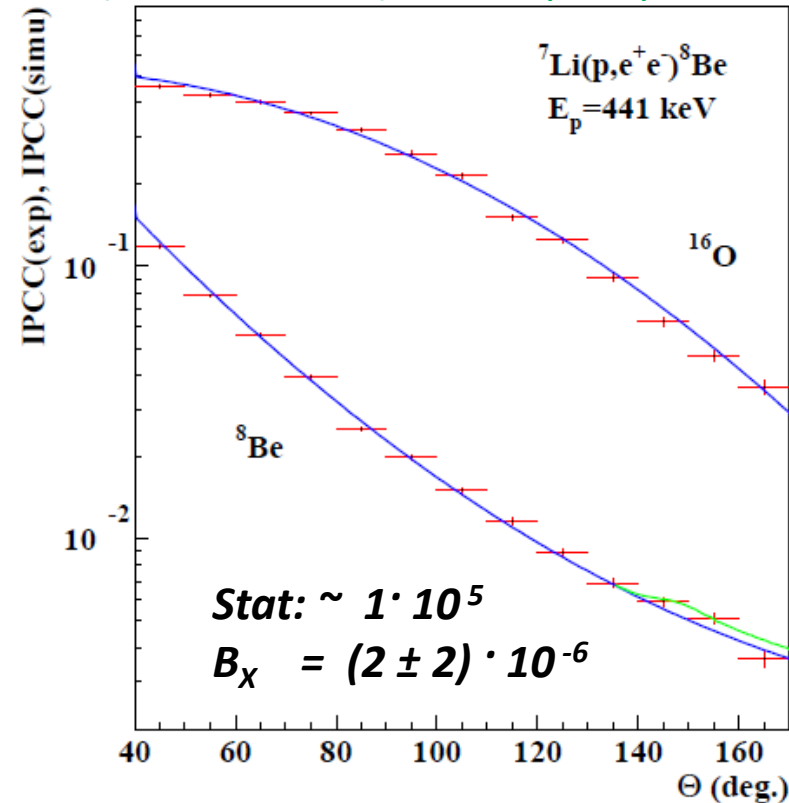
$B_\chi \approx 0.6 \cdot 10^{-6}$ (*псевдоскаляр*, U. Ellwanger, S. Moretti, JHEP 11 (2016) 039)

$B_\chi < 1.0 \cdot 10^{-6}$ (*псевдовектор*, J. Kozaczuk et al, PRD 95, 115024 (2017))

A.J. Krasznahorkay et al,
EPJ Web Conf. 142, 01019 (2017)



A.J. Krasznahorkay et al,
POS(BORMIO2017)036, <https://pos.sissa.it>



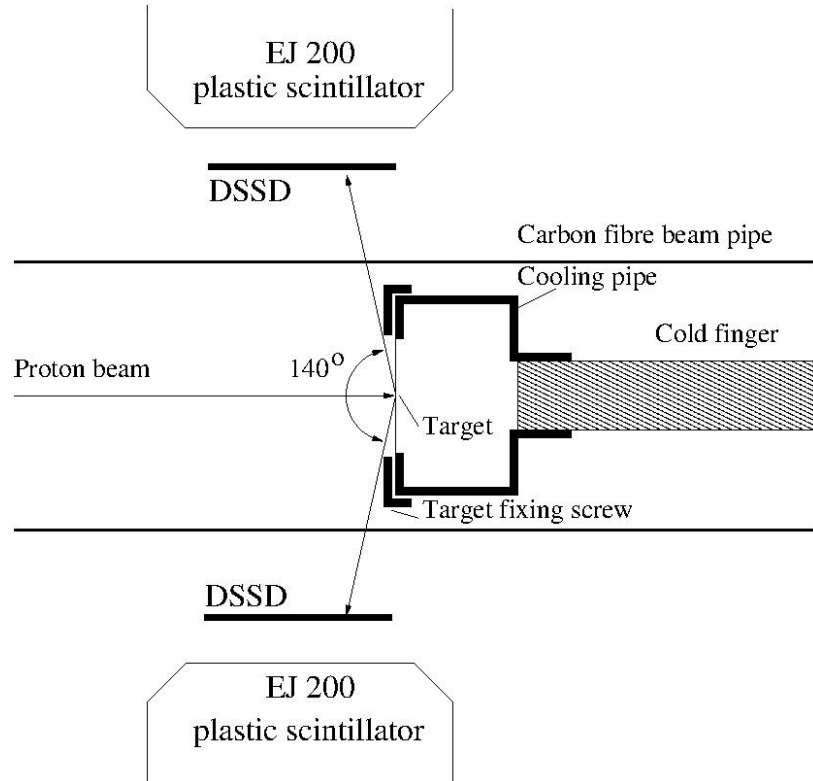
Измерения ${}^3\text{H}(p, e^+ e^-){}^4\text{He}$

A. J. Krasznahorkay et al., PRC 104, 044003 (2021)

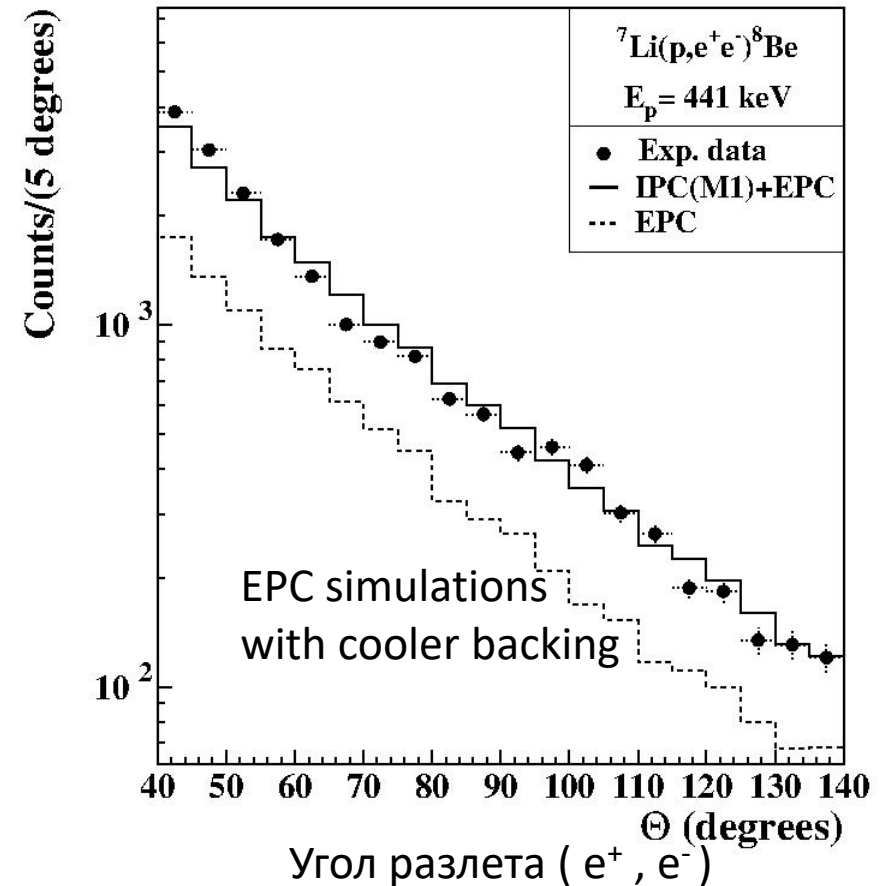
Протонный пучок $1\mu\text{A}$ от 2MV Tandetron

Мишень : ${}^3\text{H}(2 \times 10^{20} \text{ at/cm}^2) + \text{Ti}(4.2 \text{ mg/cm}^2) + \text{Mo}(0.4 \text{ mm})$

охлаждаемая жидким азотом

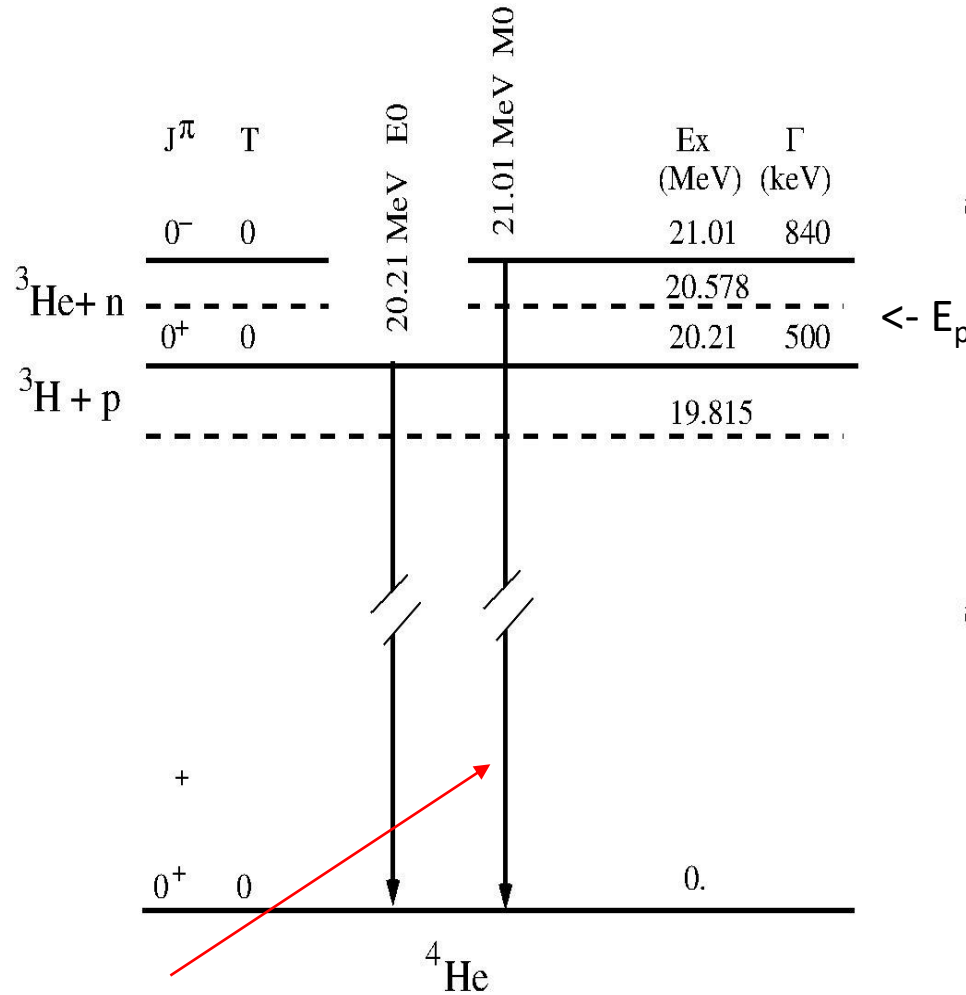


Мишень: Li + Ti + Mo

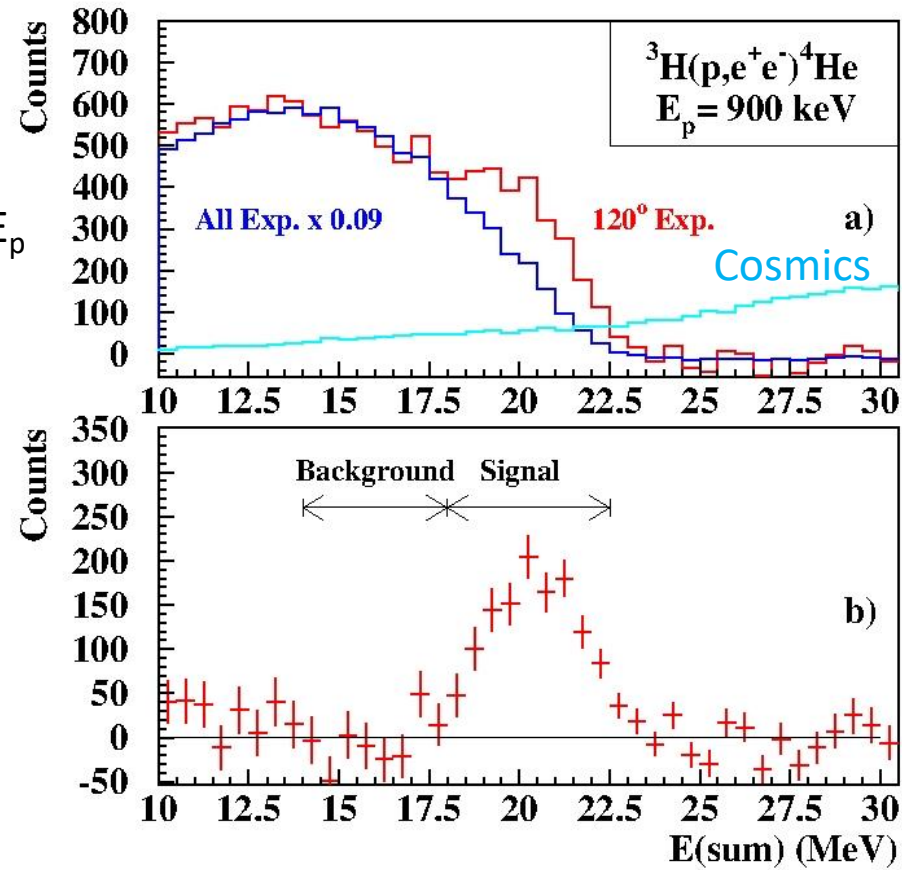


Измерения ${}^3\text{H}(p, e^+ e^-){}^4\text{He}$

A. J. Krasznahorkay et al., PRC 104, 044003 (2021)

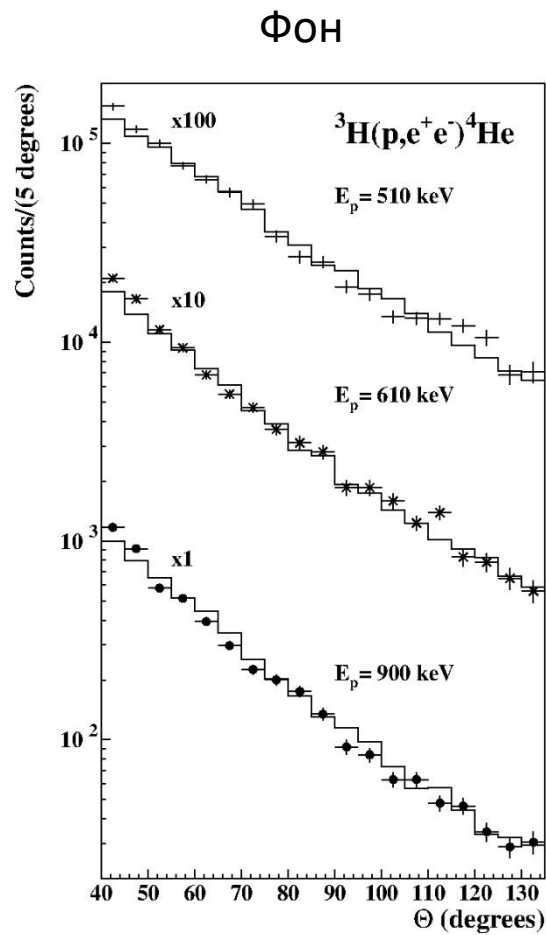


M0 переход $0^- \rightarrow 0^+$ запрещен для $J^P = 1^-$
 возможен для 1^+ и 0^-

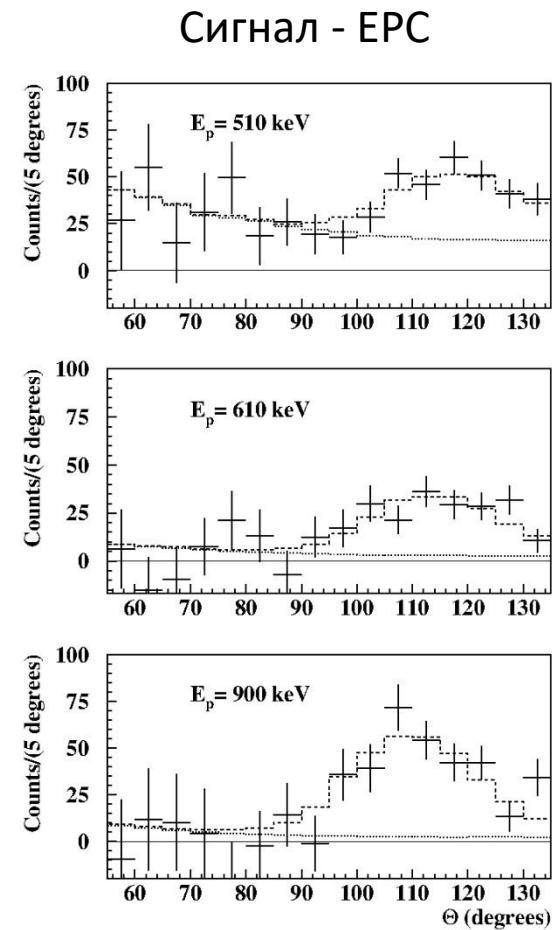
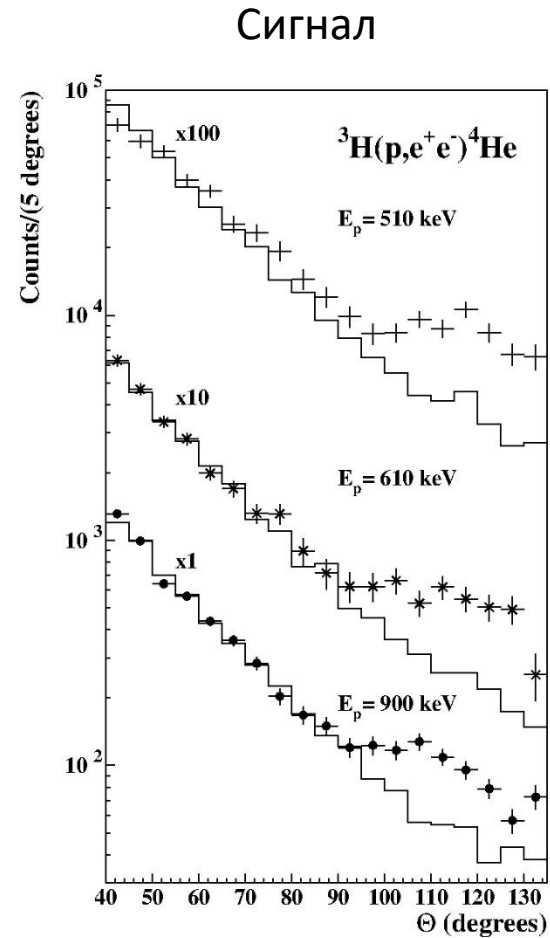


Измерения ${}^3\text{H}(p, e^+ e^-){}^4\text{He}$

A. J. Krasznahorkay et al., PRC 104, 044003 (2021)



Угол разлета (e^+ , e^-)

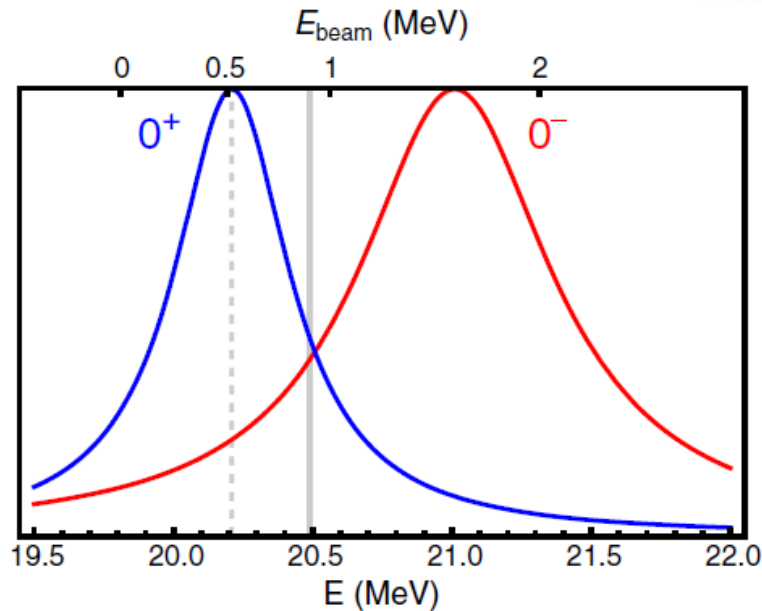


Угол разлета (e^+ , e^-)

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

A. J. Krasznahorkay et al., PRC 104, 044003 (2021)

TABLE I. Internal Pair Creation Coefficients (IPCC), X17 Boson branching ratios (B_x), masses of the X17 particle, and confidences derived from the fits.



E_p (keV)	IPCC $\times 10^{-4}$	B_x $\times 10^{-6}$	Mass (MeV/ c^2)	Confidence	$\Delta M_x(\text{sys})$
510	2.5(3)	6.2(7)	17.01(12)	7.3σ	
610	1.0(7)	4.1(6)	16.88(16)	6.6σ	
900	1.1(11)	6.5(20)	16.68(30)	8.9σ	
Averages		5.1(13)	16.94(12)		± 0.21
${}^8\text{Be}$ values		6	16.70(35)	6.86	± 0.50

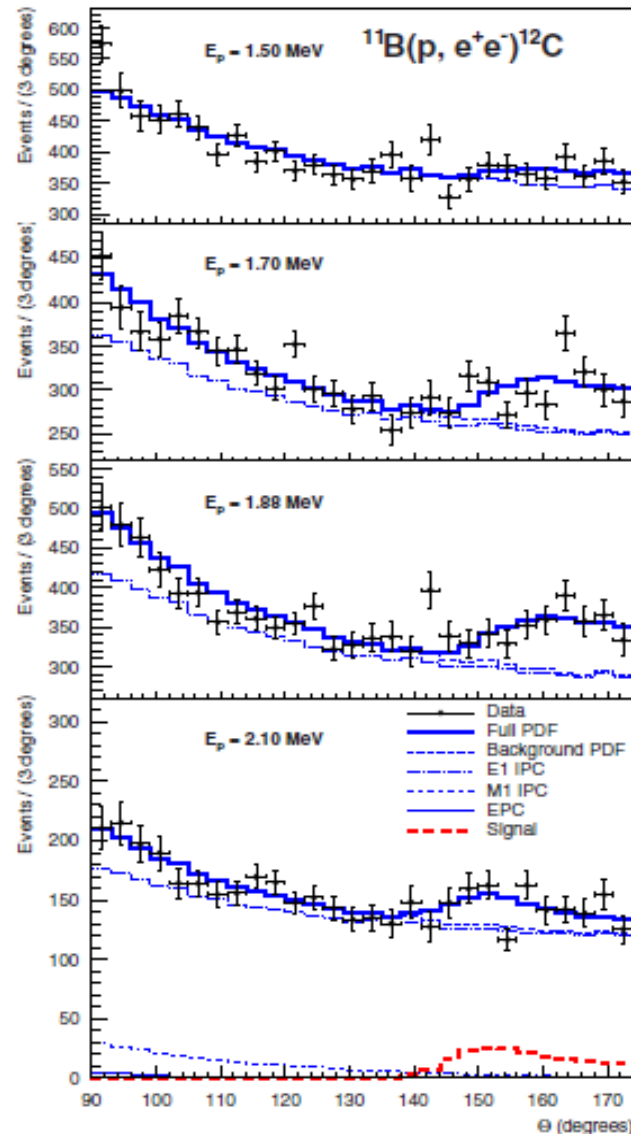
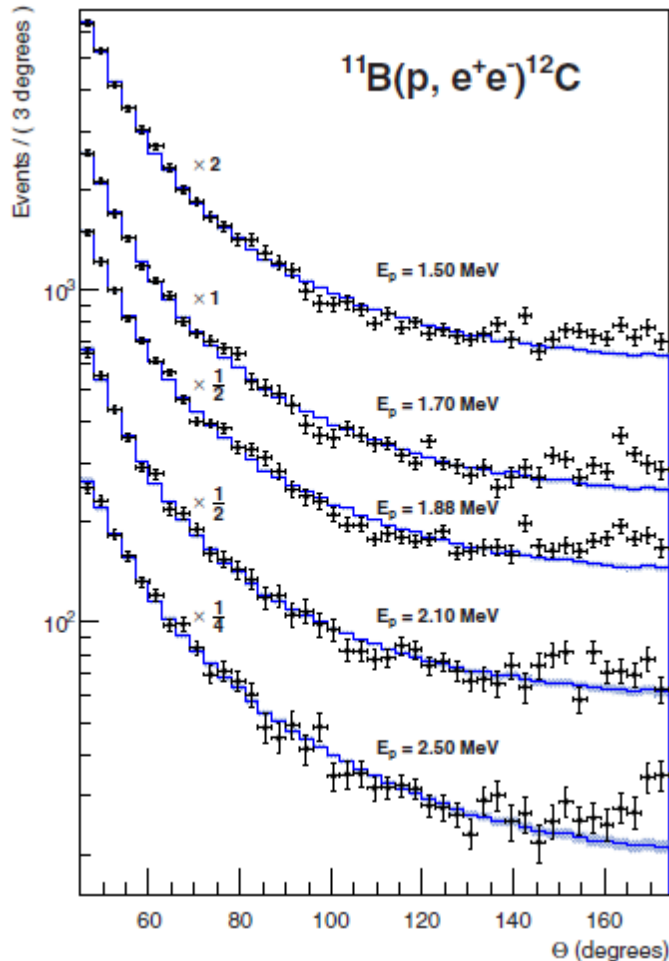
“As shown, the branching ratios of the X17 particle are identical within uncertainties, for the three beam energies proving that the X17 particle was **most likely formed in direct proton capture, which has a dominant multipolarity of $E1$.**”

[as predicted by X. Zhang and G. A. Miller, [PLB 813, 136061\(2021\)](#)]

Измерения $^{11}\text{B}(p, e^+ e^-)^{12}\text{C}$

A. J. Krasznahorkay et al., PRC 106, L061601 (2022)

$^{12}\text{C}^*(17.23 \text{ МэВ}; 1^-; 1) \rightarrow ^{12}\text{C}(0^+; 0)$
 $\Gamma_{\text{tot}} = 1150 \text{ кэВ} (\gamma, \alpha, p)$
 Мишень: ^{11}B (2 mg/cm^2)



“The present observation of the X17 particle in an ***E1*** transition supports its vector character, as suggested by Feng *et al.*”

TABLE I. X17 branching ratios (B_X), masses, and confidences derived from the fits.

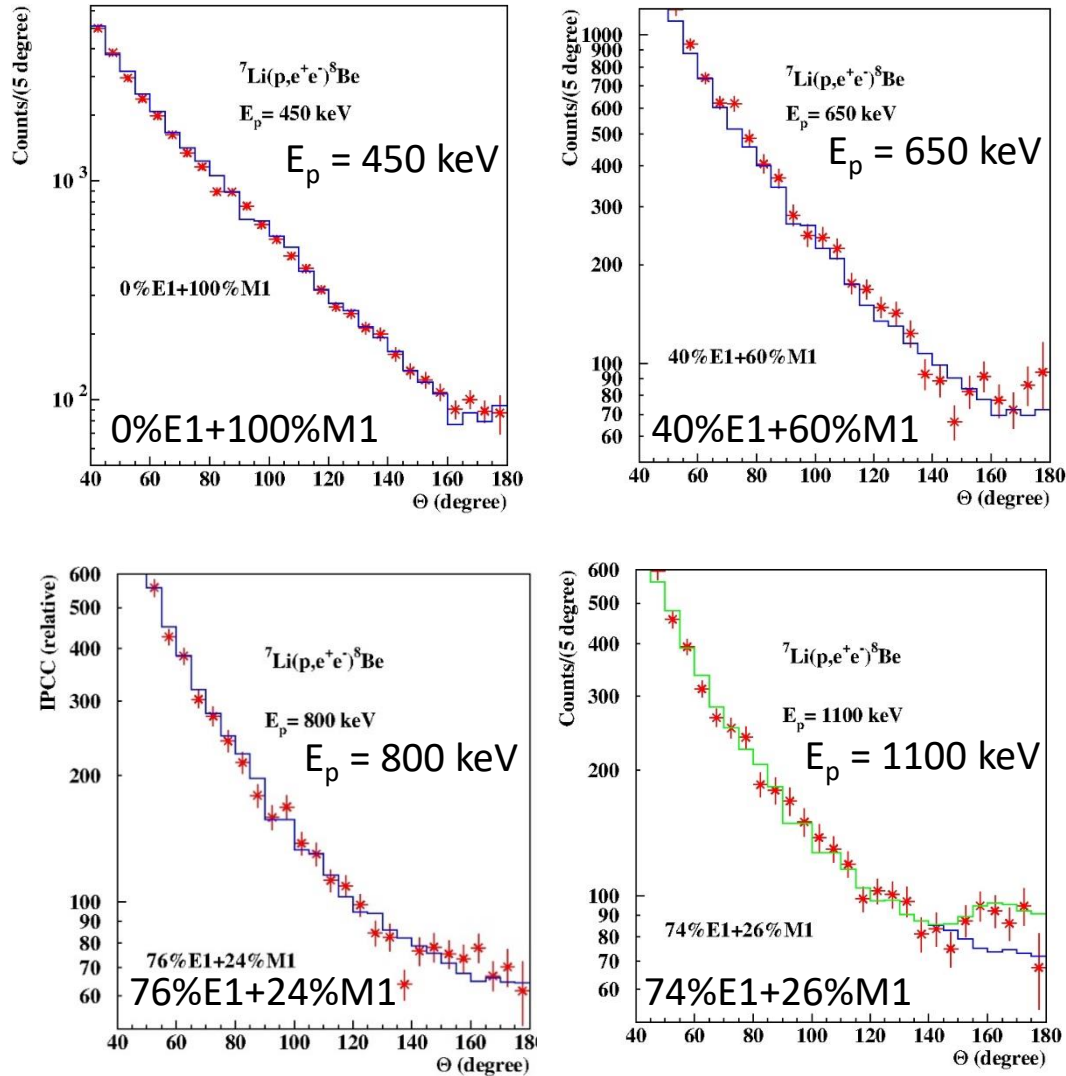
E_p (MeV)	B_X $\times 10^{-6}$	Mass (MeV/ c^2)	Confidence
1.50	1.1(6)	16.81(15)	3σ
1.70	3.3(7)	16.93(8)	7σ
1.88	3.9(7)	17.13(10)	8σ
2.10	4.9(21)	17.06(10)	3σ
Averages	3.6(3)	17.03(11)	
Previous [14]	5.8	16.70(30)	
Previous [31]	5.1	16.94(12)	
Predicted [33]	3.0		

[33] J.L. Feng et al, PRD 102, 036016 (2020)

Prediction for a “protophobic” vector boson

Поиск X17 при прямом захвате протона в ${}^7\text{Li}(p, e^+ e^-){}^8\text{Be}$

A. J. Krasznahorkay, конф. 06-08.09.2021, Rome, Italy
<https://agenda.infn.it/event/26303/sessions/20094>



X. Zhang, G.A. Miller, PLB 813 (2021) 136061

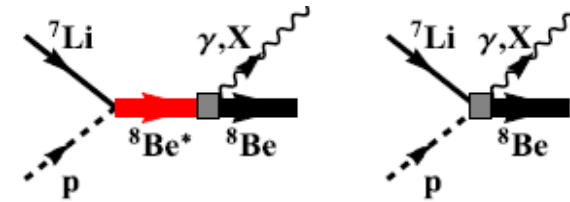
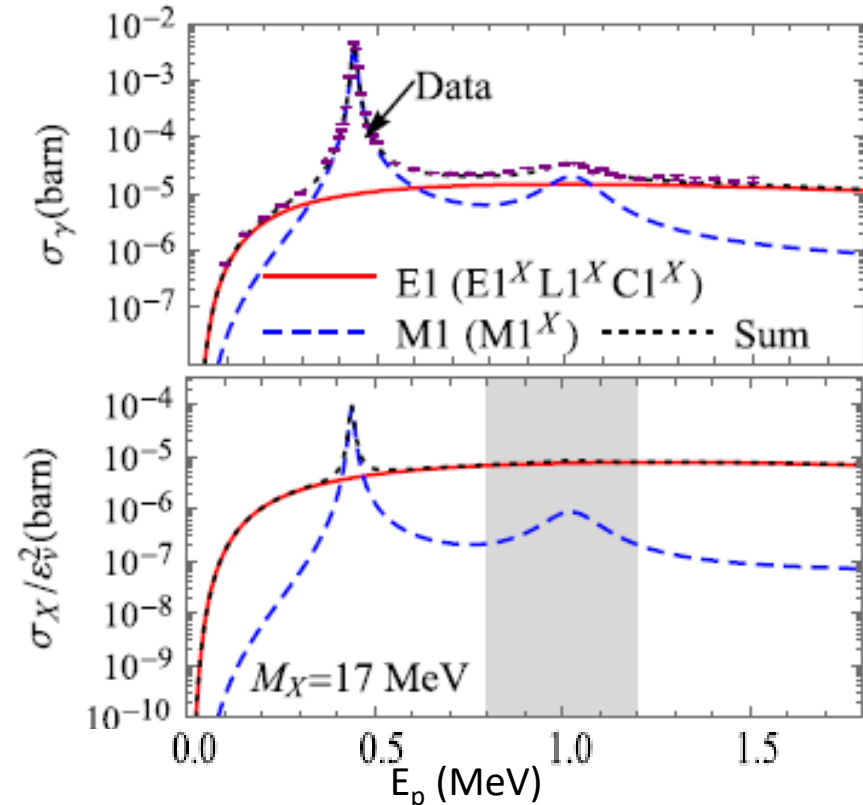


Fig. 2. The Feynman diagrams for the $M1$ and $M1^X$ (left), and $E1$ and $E1^X$ (right) transitions. In the left diagram, the intermediate ${}^8\text{Be}^*$ states are the two 1^+ resonances.



Увеличение статистики: N.J. Sas et al., [arXiv:2205.07744](https://arxiv.org/abs/2205.07744) (ATOMKI)

Data from D. Zahnow et al, Z. Phys. A 351 (1995) 229

Поиск X17 при прямом захвате протона в ${}^7\text{Li}(p, e^+ e^-){}^8\text{Be}$

N.J. Sas et al., [arXiv:2205.07744](https://arxiv.org/abs/2205.07744) (ATOMKI, 2022)

X. Zhang, G.A. Miller, *PLB* 813 (2021) 136061

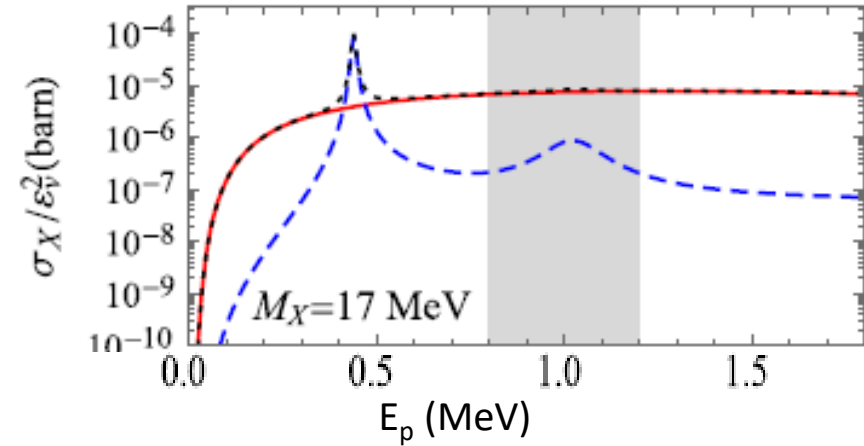
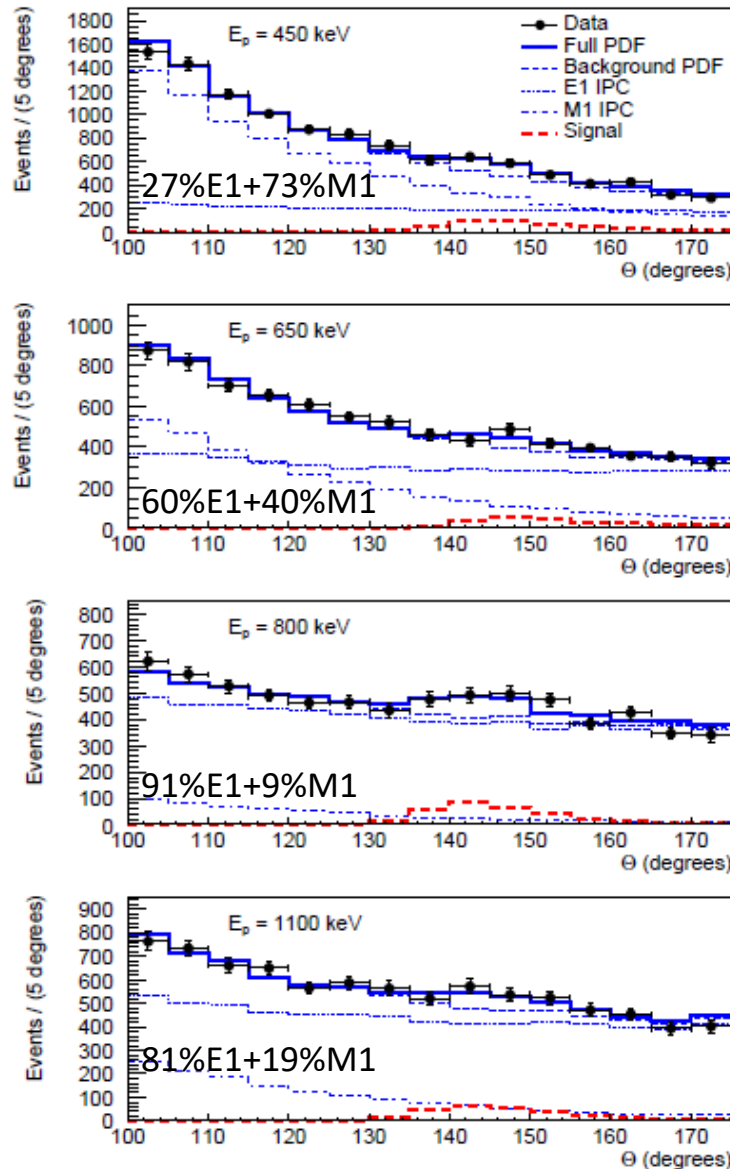


TABLE I. The fitted mass [$m(\text{X17})$] and the integrated yields $I(\text{X17})$, $I(\text{E1})$ and $I(\text{M1})$ of the X17 and the E1 and the M1 contributions. The ratio of $I(\text{X17})/I(\text{E1})$ is also listed [$B(\text{X17})$].

E_p (keV)	$m(\text{X17})$ (MeV/ c^2)	$I(\text{X17})$	$I(\text{E1})$	$I(\text{M1})$	$B(\text{X17})$
450	16.6(3)	43(49)	30(25)	79(2)	1.4(16)
650	16.94(14)	24(16)	46(5)	32(4)	0.5(3)
800	16.81(9)	33(10)	62(4)	5.9(4)	0.53(14)
1100	17.11(12)	28(8)	66(2)	15(1)	0.41(13)

Современное состояние

1. Эксперименты в АТОМКИ.

Аномалия ИРС обнаружена при разряде возбужденных состояний в 3-х ядрах: Be-8, He-4, C-12.

Статистическая значимость в каждом случае - около 7 стандартных отклонений.

Кинематика хорошо согласуется с рождением частицы с массой около 17 МэВ/с² (X17), быстро распадающейся на электрон-позитронную пару.

В ядре Be-8 наблюдается (?) указание на рождение X17 в процессе нерезонансного захвата протона.

2. В рамках СМ ядерной физики объяснения данному явлению пока не найдено.

1

3. В рамках физики элементарных частиц природа X17 однозначно не установлена.

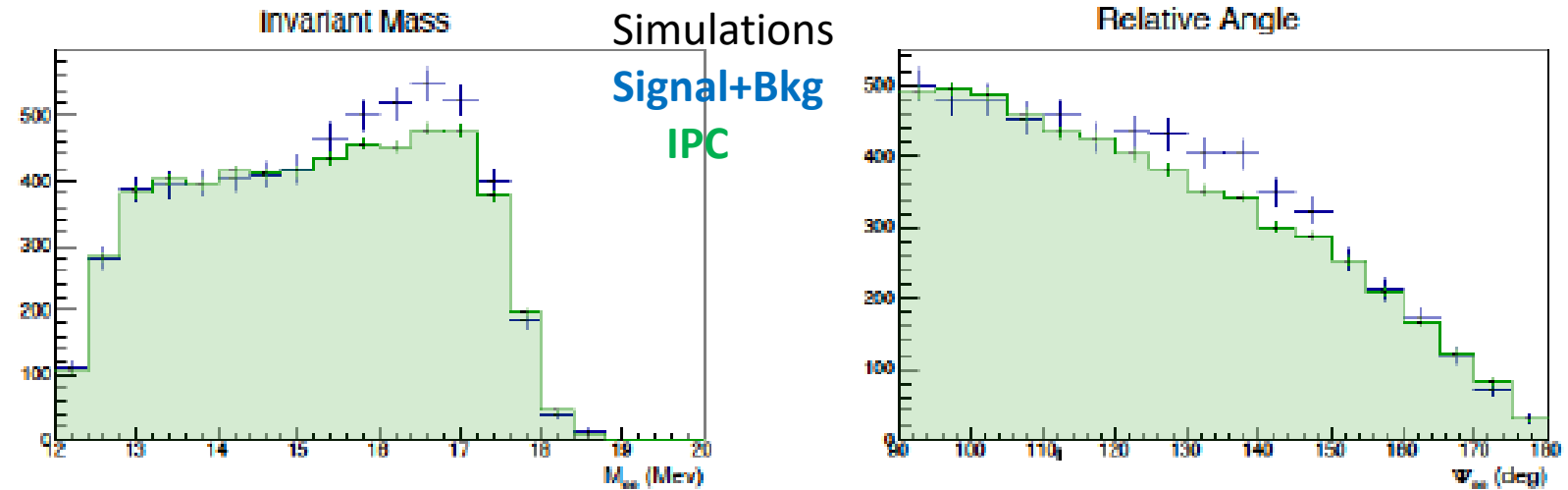
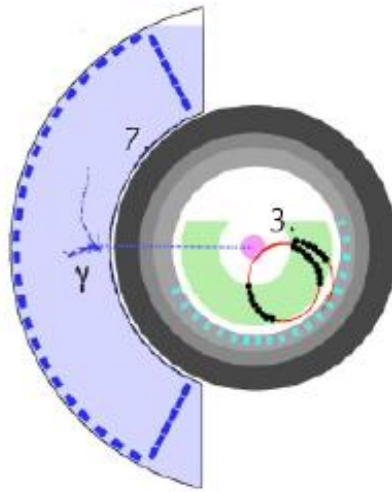
Теоретические исследования продолжаются. (см., например, D. Barducci, C.Toni, JHEP 02 (2023) 154)

4. Подтверждение/опровержение X17 со стороны других экспериментов отсутствует.

Намерения: > 20 (см., например, A.J. Krasznahorkay et al, POS(BORMIO2017)036, <https://pos.sissa.it>)

Beryllium anomaly search with the MEGII experiment at PSI

A. Papa (INFN-Pisa), <https://agenda.infn.it/event/26303/sessions/20094> (2021)



C. Voena (INFN-Roma), “Not Only $\mu \rightarrow e\gamma$: X17 search”, DIS2022. <https://indico.cern.ch/event/1072533>

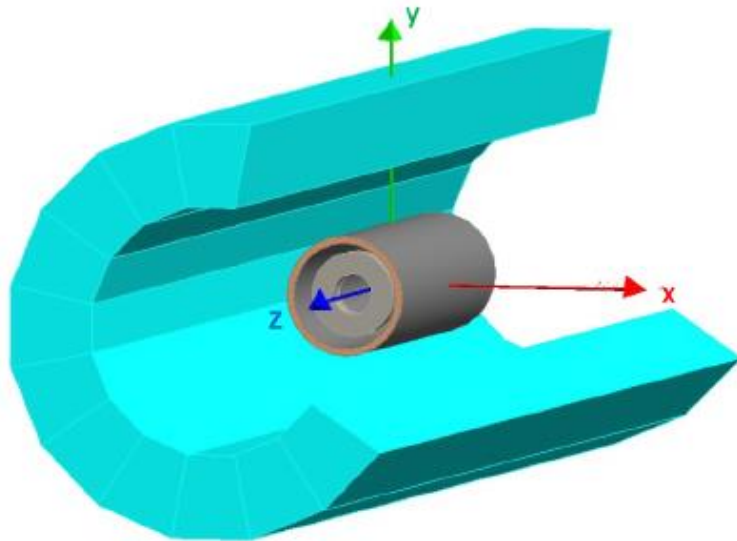
Status:

- Preliminary feasibility studies show that $\sim 5\sigma$ sensitivity could be reached in few days data taking
- First tests done during 2021 and 2022 shutdowns (stability of the setup, trigger...)
- Measurement foreseen in late 2022

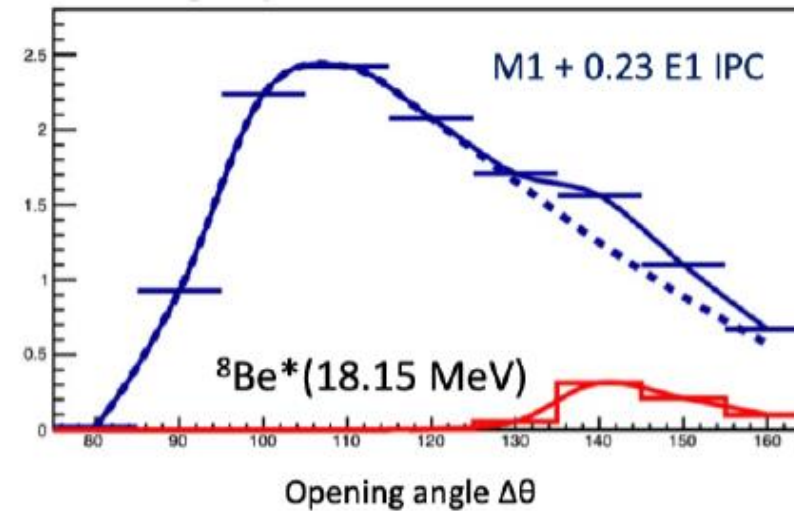
Status of the X17 search in Montreal

G. Azuelos et al 2022 J. Phys.: Conf. Ser. 2391 012008; <https://meetings.triumf.ca/event/262>
(May, 25,2022)

Часть DAPHNE (MWPC + scintillators)



Реакции: ${}^7\text{Li}(p, e^+ e^-){}^8\text{Be}$; ${}^7\text{Li}({}^3\text{He}, e^+ e^-){}^{10}\text{B}$

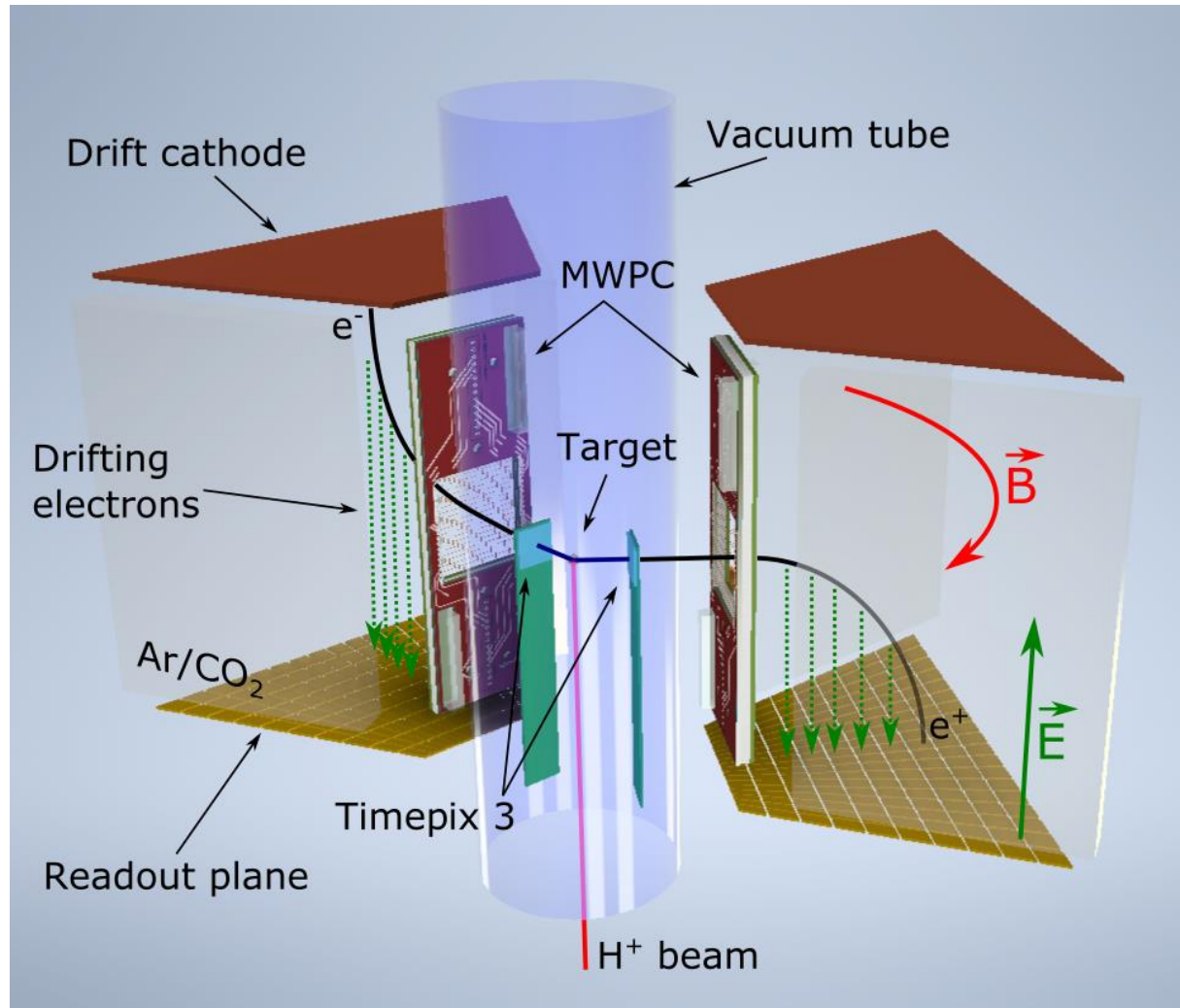


Статус :

1. Установка готова, идет наладка электроники.
2. Измерения (план-график) :
 - 11.2022 – 03.2023 – измерение и анализ Be-8
 - 03.2023 – начало измерений B-10

Institute of Experimental and Applied Physics, Czech Technical University in Prague

A.F.V. Cortez, [Nuclear Inst. and Methods in Physics Research, A 1047 \(2023\) 167858](#)



Пучок: Van de Graaff accelerator in IEAP

Проверка измерений Atomki.

1. Трассировка и восстановление вершины.
2. Знак заряда частиц.

Статус: “ A spectrometric system integrating TPX3, MWPC and TPC detectors is under construction...”

X17 @ nToF

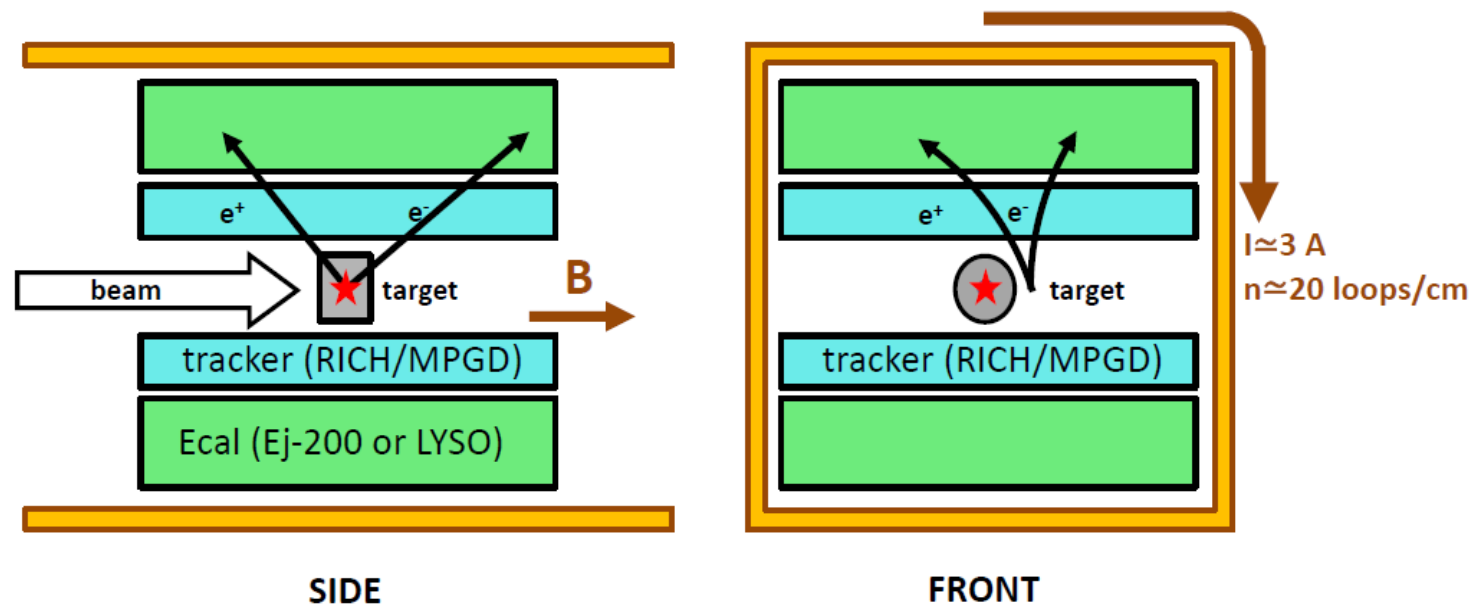
Conference «Shedding light on X17», Sep, 2021, Centro Ricerche Enrico Fermi, Rome, Italy
(<https://agenda.infn.it/event/26303/sessions/20094/#20210908>)

${}^3\text{He}(n, X17){}^4\text{He}$ (new!)

\searrow
 e^+e^-

Measurements:

2022-24 (CERN Lol approved)



${}^3\text{He}(n, X17){}^4\text{He}$, ${}^7\text{Be}(n, X17){}^8\text{Be}$, ${}^2\text{H}(n, X17){}^3\text{H}$ @ n_ToF, Demokritos...

${}^3\text{H}(p, e+e-){}^4\text{He}$, ${}^7\text{Li}(p, X17){}^8\text{Be}$, ${}^2\text{H}(p, X17){}^3\text{He}$ @ LUNA, ENEA/Frascati...

Setup is in preparation. Most of the concerns will be clarified at the end of this year with beam tests at n_ToF (backgrounds) and ENEA/Frascati (detector performance)

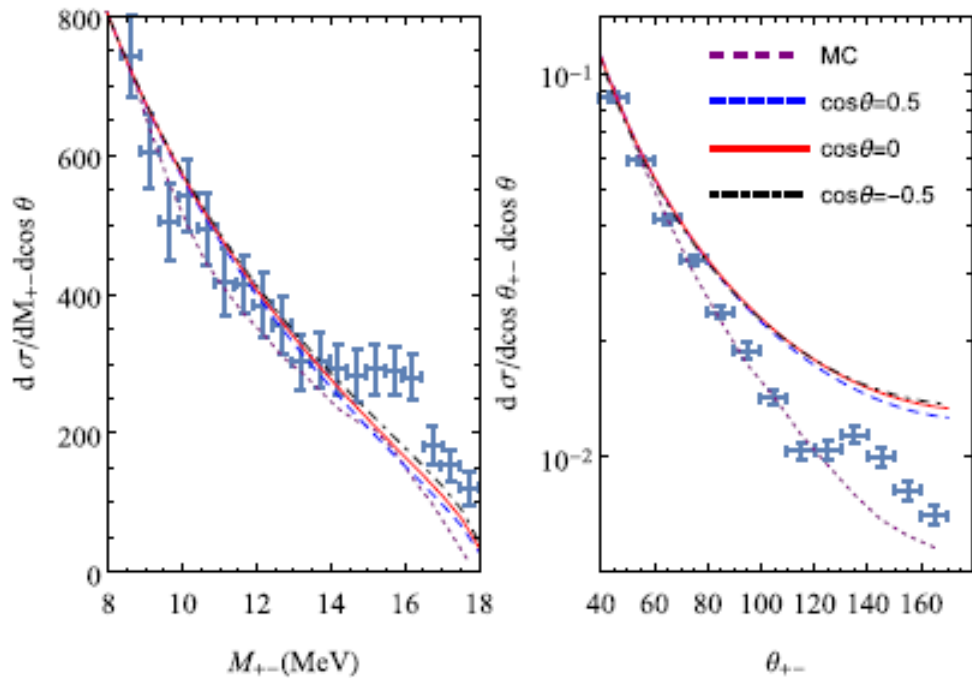
Спасибо за внимание!

Backup

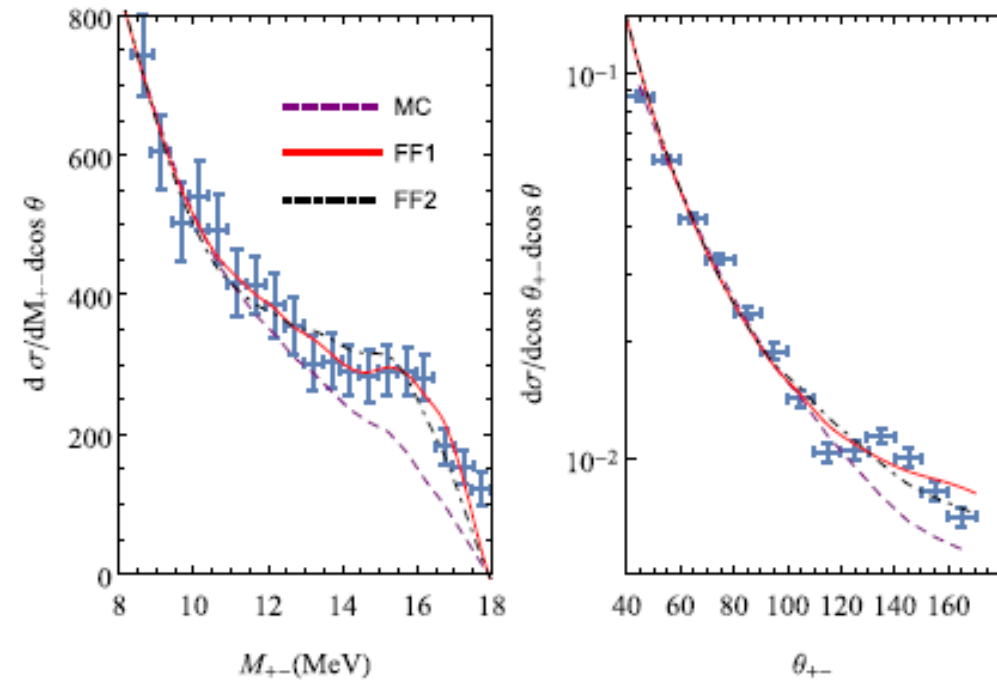
Can nuclear physics explain the anomaly observed in the internal pair production in the Beryllium-8 nucleus?

In this work, we improve the nuclear physics modeling of the reaction by studying the pair emission anisotropy and the interferences between different multipoles in an effective field theory inspired framework. We then explore the nuclear transition form factor as a possible origin of the anomaly, and find **the required form factor to be unrealistic** for the ^8Be nucleus.

M1-E1-E2 interferences



M1-E1 interference +M1 form factor



MC – background simulations from Atomki

A. Aleksejevs, S. Barkanova, Yu.G. Kolomensky, B. Sheff,
 A Standard Model Explanation for the “ATOMKI Anomaly”, arXiv:2102.01127

We use this model to demonstrate that an interference between the Born-level IPC amplitude and a subleading nonresonant component (an amplitude with a broad phase-space structure) could produce effects observed by ATOMKI. (**Расчеты и MC моделирование сделаны только для реакции ${}^7\text{Li}(p, e^+ e^-){}^8\text{Be}$**)

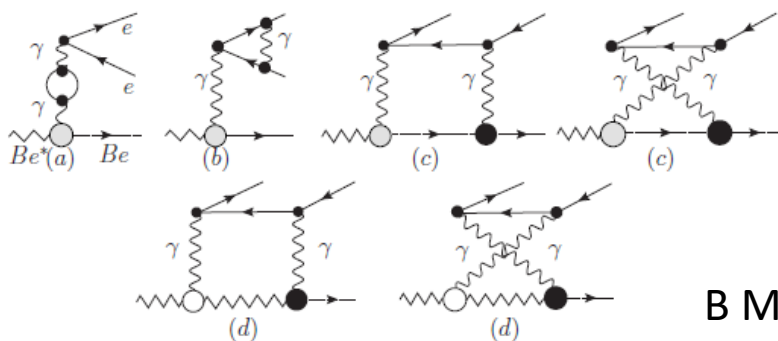
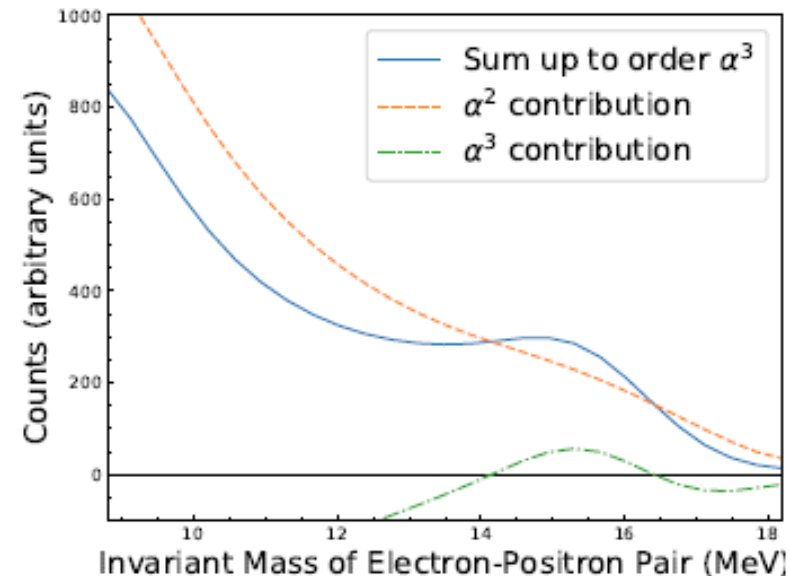
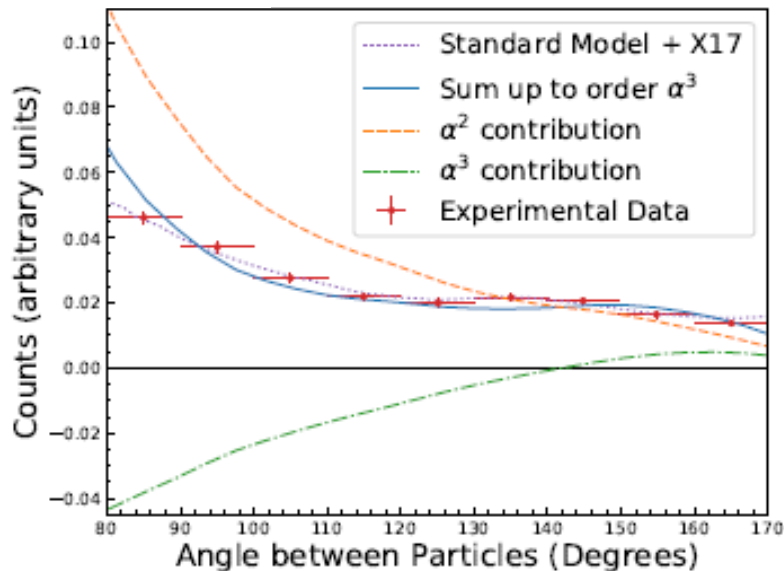


FIG. 1: Higher order QED contributions in decay of ${}^8\text{Be}$. Grey bubble corresponds to spin $1 \rightarrow 0$ transition, black bubble for spin $0 \rightarrow 0$ and white bubble for spin $1 \rightarrow 1$ transitions.

В MC моделировании использован **только аксептанс** установки ATOMKI

MC \neq GEANT



Can a protophobic vector boson explain the ATOMKI anomaly?

“We study this hypothesis by deriving an isospin relation between photon and X couplings to nucleons. ... The net result is that X production is dominated by direct transitions induced by $E1^X$ and $L1^X$ (transverse and longitudinal electric dipoles) and $C1^X$ (charge dipole) **without going through any nuclear resonance** (i.e. Bremsstrahlung radiation) with a smooth energy dependence that occurs for all proton beam energies above threshold. **This contradicts the experimental observations and invalidates the protophobic vector boson explanation.**”

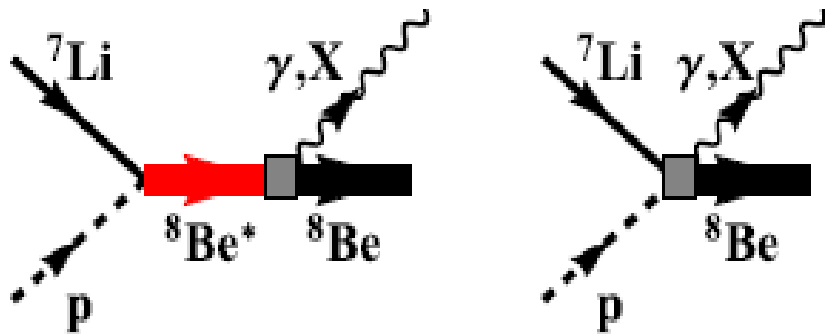


Fig. 2. The Feynman diagrams for the $M1$ and $M1^X$ (left), and $E1$ and $E1^X$ (right) transitions. In the left diagram, the intermediate ${}^8\text{Be}^*$ states are the two 1^+ resonances.

