

Наблюдение структуры в высокоимпульсных спектрах  
вторичных протонов в инклюзивном рассеянии  $^{12}\text{C}(p, p')X$   
под углами  $21^\circ$  и  $24.5^\circ$  при энергии 1 ГэВ  
(импульсные интервалы S4, S5)

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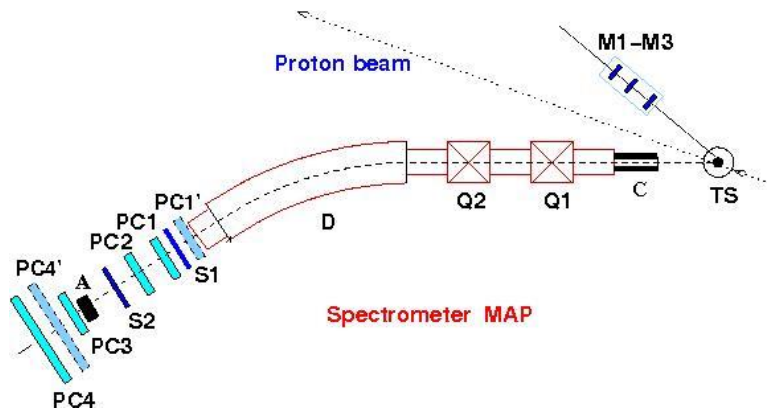
*Лаборатория малонуклонных систем*

Аннотация:

Наблюдаемая структура в импульсных интервалах s4 и s5 может быть обусловлена, в частности, квазиупругим рассеянием протонов на четырехнуклонных кластерах, подобных ядру  $^4\text{He}$ , в исследуемом ядре  $^{12}\text{C}$ .

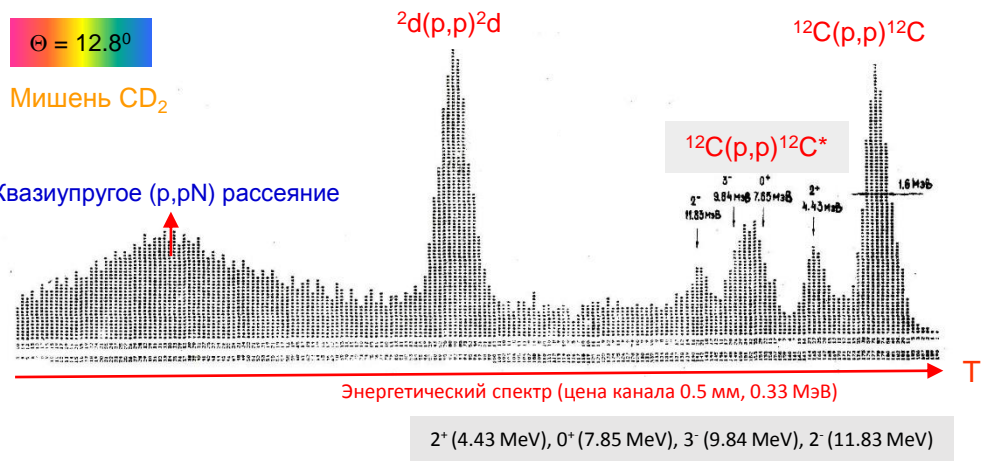
тема НИОКР 9.13. : Исследование структуры ядерной материи на малых расстояниях в квазиупругих и неупругих протон-ядерных взаимодействиях при энергии 1 ГэВ

# Experimental setup

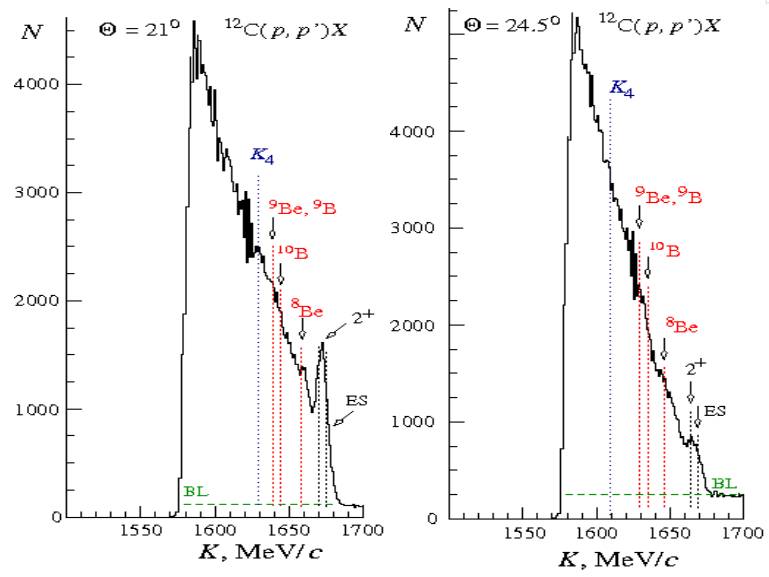


Spectrometer MAP

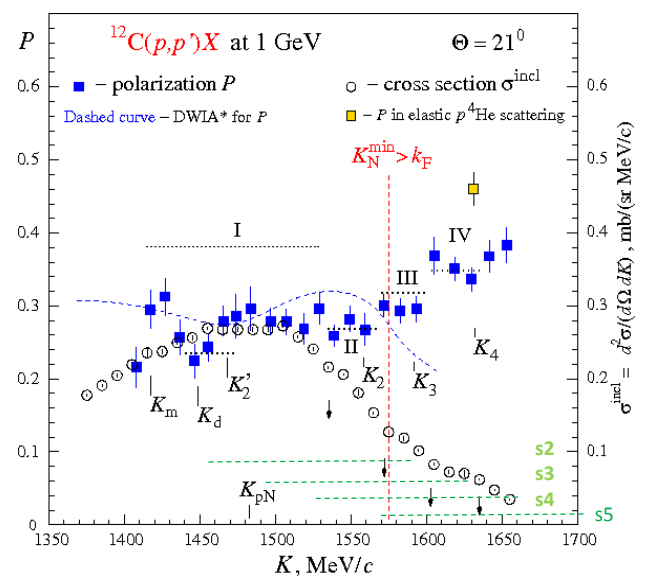
С.Л. Белостоцкий, Ю.В. Доценко, С.С. Волков, А.А. Воробьев, Л.Г. Кудин, Н.П. Куропаткин, О.В. Миклухо, В.Н. Никулин, О.Е. Прокофьев, М.А. Шуваев. Препринт ЛИЯФ № 826, 1983, с.52.



arXiv:2102.04109v1 [nucl-ex] 8 Feb 2021.



Импульсный интервал – s5, цена канала - 1 МэВ/с

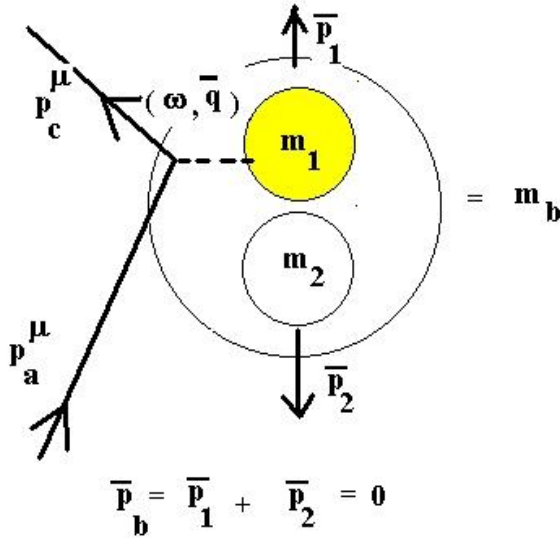


s5: 1570-1710 MeV/c; s4: 1530-1670 MeV/c; s3: 1490-1630 MeV/c; s2: 1450-1590 MeV/c.

# Кинематика реакции $^{12}\text{C}(p, p' ^4\text{He})^8\text{Be}$ (1)

## Scattering from Constituents (1-1)

$$a + b \rightarrow c + Y$$



Let's assumed that the target **b** ( $^{12}\text{C}$ ) consists of two pieces, that is, it has substructure. The incident particle, **a** (proton), scatters off component 1 ( $^4\text{He}$ ), where we assume that the whole 4 momentum lost by **a** is transferred to particle 1 ( $^4\text{He}$ ). The **c** is also proton and component 2 is residual nucleus  $^8\text{Be}$ .

$$m_b = \sqrt{m_2^2 + p_1^2} + \sqrt{m_1^2 + p_1^2} + \Delta(p_1)$$

$\Delta(0)$  is the reaction Q - value when  $p_1 = 0$ . The final state Y consists of  $m_1$  with momentum  $\vec{p}_1 + \vec{q}$ , and  $m_2$  with momentum  $-\vec{p}_1$  so that the total momentum of Y is  $p_Y = \vec{p}_1 + \vec{q} - \vec{p}_1 = \vec{q}$ . The energy of Y is

$$E_Y = \sqrt{m_2^2 + p_1^2} + \sqrt{m_1^2 + (\vec{p}_1 + \vec{q})^2}$$

thus,  $(\omega, \vec{q}) = (E_Y - m_b, p_Y)$

← For reaction  $^{12}\text{C}(p, p' ^4\text{He})^8\text{Be}$  the Q- value is -7.4 MeV  $[\Delta(0)]$ .

mass of free  $^4\text{He}$ :  
 $m(^4\text{He}) = 3727.38 \text{ MeV}$

mass of  $^8\text{Be}$ :  
 $m(^8\text{Be}) = 7454.88 \text{ MeV}$

mass of  $^{12}\text{C}$ :  
 $m(^{12}\text{C}) = 11174.87 \text{ MeV}$

We only measure the scattered proton energy, then the measurement is called an inclusive experiment.

$\omega^*(^4\text{He})$  is for elastic scattering off  $^4\text{He}$  with modified mass  $m^*(^4\text{He})$ .

$\omega(^4\text{He})$  is for elastic scattering off  $^4\text{He}$  with free mass  $m(^4\text{He})$ ;

We assume:

$$p_a^\mu - p_c^\mu = p_Y^\mu - p_b^\mu, \text{ let } q^\mu = (\omega, \vec{q}) \rightarrow$$

with

$$\omega = E_a - E_c, \text{ and, } \vec{q} = \vec{p}_a - \vec{p}_c \rightarrow$$

Таблицы:

$$P_a = k_0; \quad P_c = k_1;$$

$$q^2 = k_0^2 + k_1^2 - 2 k_0 k_1 \cos(\Theta_{\text{map}})$$

$$\omega_1 = T_0 - T_1;$$

$$Q^2 = q^2 - \omega_1^2$$

$$\omega = \omega_1 - \omega^*(^4\text{He}) [\omega(^4\text{He})]$$

На картинках:  $k_1 = K$

Кинематика реакции  $^{12}\text{C}(p, p' \ ^4\text{He})^8\text{Be}$  (2)

## Scattering from Constituents (1-2)

We can expand the equation for the energy transfer to arrive at

$Q^2 \equiv q^2 - \omega^2$ , and

$$\frac{Q^2}{2m_1\omega} = \sqrt{1 + \frac{p_1^2}{m_1^2}} - \frac{\vec{q} \cdot \vec{p}_1}{m_1\omega} - \frac{\Delta^2(p_1)}{2m_1\omega} + \frac{\Delta(p_1)}{\omega} \sqrt{1 + \frac{(\vec{p}_1 + \vec{q})^2}{m_1^2}}$$

call  $x_B = \frac{Q^2}{2m_p\omega}$  the Bjorken x value where  $m_p$  is the mass of

the proton. For elastic scattering on the proton  $x_B = 1$ .

As  $p_1 \rightarrow 0$ ,  $x = \frac{Q^2}{2m_1\omega} = 1 + \frac{\Delta(0)}{\omega} \left(1 - \frac{\Delta(0)}{2m_1}\right)$ , and  $\Delta(0) < 0$ .  $\longrightarrow$  X

The condition where x is approximately 1 is called quasi-elastic scattering. In this kinematical condition particle a loses energy and suffers a 3-momentum change consistent with scattering off an object with the mass of constituent 1. In the case of electrons scattering off a nucleus a broad peak appears at approximately  $x = 1$  when we set mass 1 equal to the proton mass (then the x value is the Bjorken x).

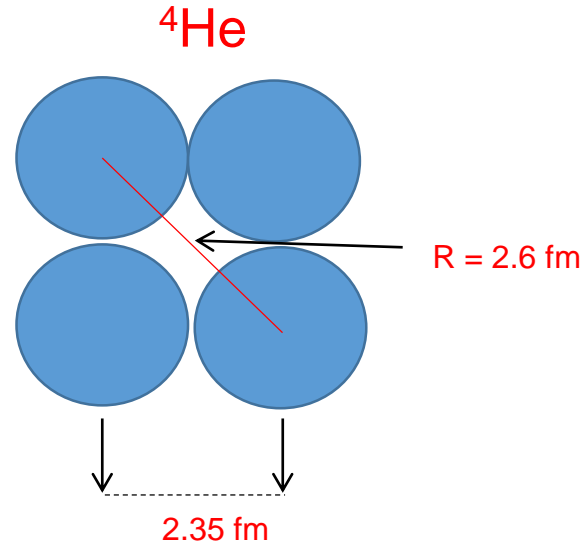
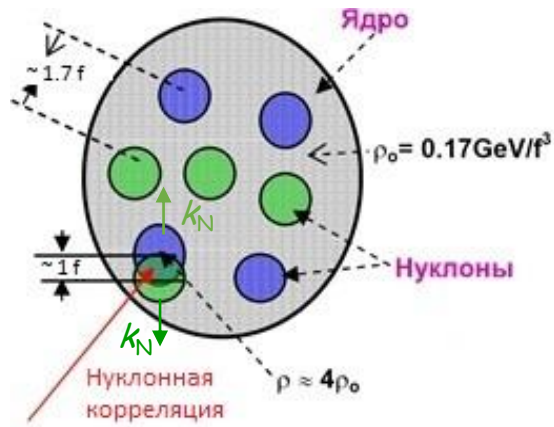
## Таблицы:

In our case:  $X = Q^2/[2\omega_1 m_{4\text{He}}]$ , where  $m_{4\text{He}}$  is mass of the  $^4\text{He}$  used in the calculations:  
 $m_{4\text{He}}$  is free mass,  $m(^4\text{He})$ , or modified mass,  $m^*(^4\text{He})$ .

We also calculated  $X^*$ :

$X^* = Q^2/[2\omega_1 m_{4\text{He}}]$ , where  $\omega_1$  is equal to  $\omega(^4\text{He})$  or  $\omega^*(^4\text{He})$ , obtained for the elastic scattering off  $^4\text{He}$  with free or modified mass.

# Длина волны де Бройля для протона и радиусы ядер



${}^4\text{He}: R_{em} = 1.67 \text{ fm}$

${}^3\text{He}: R_{em} = 2.2 \text{ fm}$

Радиус ядра:

$$R = r_0 \times A^{1/3}, \quad r_0 = 1.2 \text{ fm}$$

$$1 \text{ fm} = 10^{-13} \text{ cm}$$

${}^8\text{Be}: R = 2.4 \text{ fm}$

${}^9\text{Be}: R = 2.5 \text{ fm}$

${}^{10}\text{B}: R = 2.6 \text{ fm}$

${}^{12}\text{C}: R = 2.74 \text{ fm}$

$$\rho = (3m_N) / 4\pi r_0^3 = 2 \cdot 10^{14} \text{ g/cm}^3$$

Комптоновская длина волны протона,  $h/mc$ :  $\lambda = 1.32 \text{ фм}$

Комптоновская длина волны электрона,  $h/mc$ :  $\lambda = 2400 \text{ фм}$

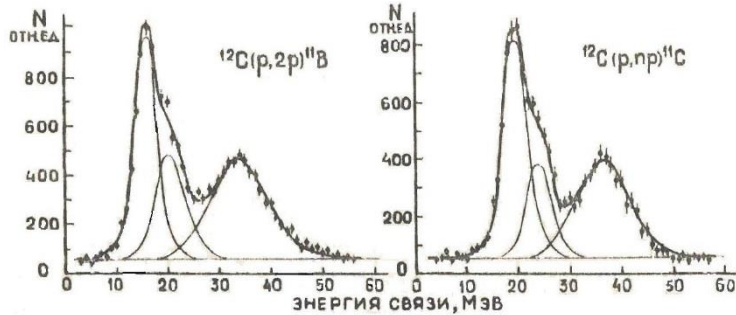
Длина волны де Бройля:  $\lambda_B = \lambda / [2T/mc^2 - (T/mc^2)^2]^{0.5}$

$\lambda_B = 0.73 \text{ fm}$  for proton with 1 GeV energy

$\lambda_B = 0.90 \text{ fm}$  for proton with 0.8 GeV energy

$\lambda_B = 1.75 \text{ fm}$  for proton with 230 MeV energy

Proton: JLAB:  $R_{em} = 0,831 \pm 0,007 \pm 0.012 \text{ фм}$ , 2019



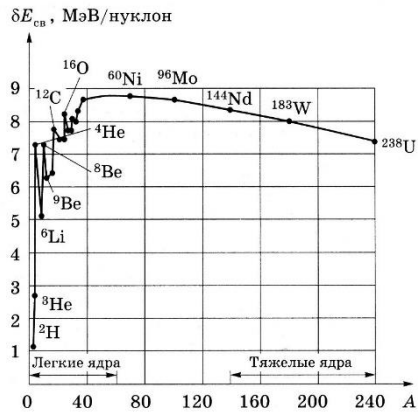
Среднеквадратичные радиусы распределения плотности протонов, нейтронов и материи

	$\langle r_p^2 \rangle^{1/2}$ , Фм			(e.A)	$\langle r_n^2 \rangle^{1/2}$ , Фм			$\langle r_m^2 \rangle^{1/2}$ , Фм	
	Sk II	Sk III	Sk 7		Sk II	Sk III	Sk 7	Sk 7	(p.A)
<sup>12</sup> C	2.67	2.66	2.60	2.46 ÷ 2.49	2.65	2.64	2.59	2.59	2.52(8)
<sup>11</sup> B	2.55	2.51	2.47	2.42 ÷ 2.46	2.61	2.57	2.54	2.50	2.49(2)
<sup>10</sup> B	2.62	2.56	2.56	2.45(5)	2.61	2.56	2.55	2.55	
<sup>9</sup> Be	2.52	2.46	2.48	2.46 ÷ 2.52	2.66	2.61	2.64	2.57	2.68(2)
<sup>7</sup> Li	2.36	2.28	2.34	2.41(5)	2.53	2.42	2.53	2.45	
<sup>6</sup> Li	2.38	2.30	2.37	2.50(10)	2.36	2.29	2.35	2.36	2.50(2)

(e.A), (p.A) - электрон-ядерное и протон-ядерное рассеяния.

Энергии одночастичных состояний (МэВ)

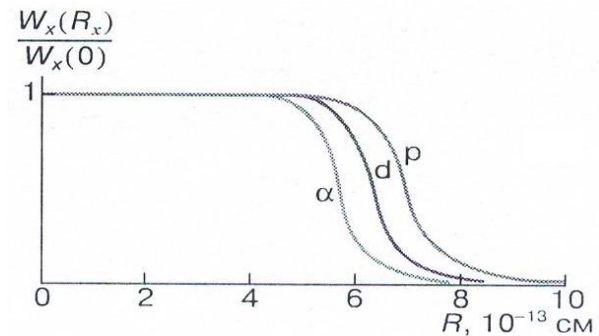
	$e_p$				$e_n$				
	$\Omega, \pi$	экс.	S7	SII	SIII	экс.	S7	SII	SIII
<sup>12</sup> C	1/2 <sup>-</sup>	16.1(2)	16.4	16.3	16.6	19.0(2)	19.3	19.5	19.5
	3/2 <sup>-</sup>	20.4(4)	20.3	19.8	20.5	23.3(3)	23.3	23.1	23.5
	1/2 <sup>+</sup>	34.0(8)	35.9	36.9	31.9	36.3(6)	38.8	40.3	34.9
<sup>11</sup> B	3/2 <sup>-</sup>	11.7(4)	11.8	12.3	13.3	11.5(5)	10.7	11.9	12.2
	1/2 <sup>-</sup>	17.5(4)	17.6	17.7	17.8	17.2(5)	17.4	17.7	17.5
	1/2 <sup>+</sup>	33.2(9)	34.7	35.9	34.7	33.9(8)	33.7	35.6	30.4
<sup>10</sup> B	3/2 <sup>-</sup>	7.3(3)	7.5	8.3	9.7	9.2(4)	9.7	10.6	11.7
	1/2 <sup>-</sup>	17.5(3)	17.9	17.3	17.3	20.5(5)	20.4	21.1	20.9
	1/2 <sup>+</sup>	31.8(8)	31.4	32.7	28.7	32.2(8)	33.9	35.9	31.4
<sup>9</sup> Be	3/2 <sup>-</sup>					2.0(2)	6.1	7.2	8.4
	1/2 <sup>-</sup>	17.1(3)	17.0	16.7	17.6	18.1(5)	18.2	18.6	18.6
	1/2 <sup>+</sup>	27.7(5)	31.1	32.6	29.4	29.2(8)	30.1	32.2	28.5
<sup>7</sup> Li	1/2 <sup>-</sup>	10.3(3)	10.3	10.0	10.6	8.0(6)	8.0	8.1	8.2
	1/2 <sup>+</sup>	23.2(3)	25.5	27.6	25.5	26.0(6)	23.0	25.7	22.8
<sup>6</sup> Li	1/2 <sup>-</sup>	4.9(2)	4.8	4.9	6.6	6.0(3)	6.1	6.6	8.0
	1/2 <sup>+</sup>	21.9(8)	20.6	22.9	21.1	23.7(4)	22.1	24.8	22.6



Ядра <sup>4</sup>He и <sup>8</sup>Be имеют одинаковую энергию связи 7.25 МэВ на нуклон.

С.Г. Кадменский, «Кластеры в ядрах»

Объемное распределение протонов и кластеров в ядре <sup>208</sup>Pb



$$\Theta = 24.5^{\circ}$$

Setting - 4

Kinematics for the reaction  $^{12}\text{C}(p, p\ ^4\text{He})^8\text{Be}$  at an angle of  $24.5^\circ$ , setting-4

$$T_0 = 998.2 \text{ MeV}, k_0 = 1693.98 \text{ MeV}/c$$

1. Masses of free  $^4\text{He}$ ,  $^8\text{Be}$  and  $^{12}\text{C}$ :

$$m(^4\text{He}) = 3727.38 \text{ MeV}; m(^8\text{Be}) = 7454.88 \text{ MeV}. m(^{12}\text{C}) = 11174.87 \text{ MeV};$$

$$Q_{\text{map}} = 24.5^0, Q\text{-value} = -7.4 \text{ MeV}; \text{Theta}2=71.02^\circ$$

$$k_1 = 1609.30 \text{ MeV}/c, k_2 = 705.77 \text{ MeV}/c;$$

$$T_1 = 924.57 \text{ MeV}, T_2 = 66.23 \text{ MeV}$$

$$\omega_1 = 73.63 \text{ MeV}; q = 705.75 \text{ MeV}/c (Q=701.90); \omega(^4\text{He}) = 66.39 \text{ MeV};$$

$$\omega = \omega_1 - \omega(^4\text{He}) = 7.24 \text{ MeV}$$

$$X = Q^2/[2\omega_1 m(^4\text{He})] \approx 0.898 \{ \omega_1 \rightarrow \omega(^4\text{He}), X^* \approx 0.9960 \}$$

2. Mass of  $^4\text{He}$  is less than the free one (10%):

$$m(^4\text{He}) = 3354.64 \text{ MeV}$$

$$Q_{\text{map}} = 24.5^0, Q\text{-value} = -7.4 \text{ MeV}; \text{Theta}2=70.36^\circ$$

$$k_1 = 1601.13 (1601) \text{ MeV}/c, k_2 = 705.13 \text{ MeV}/c;$$

$$T_1 = 917.52 \text{ MeV}, T_2 = 73.28 \text{ MeV};$$

$$\omega_1 = 80.68 \text{ MeV}; q = 705.01 \text{ MeV}/c (Q=700.38); \omega(^4\text{He}) = 73.44 \text{ MeV};$$

$$\omega = \omega_1 - \omega(^4\text{He}) = 7.24 \text{ MeV}$$

$$X = Q^2/[2\omega_1 m(^4\text{He})] \approx 0.906 \{ \omega_1 \rightarrow \omega(^4\text{He}), X^* \approx 0.9953 \}$$

3. Mass of  $^4\text{He}$  is less than the free one (7.68%):

$$m(^4\text{He}) = 3441.01 \text{ MeV}$$

$$Q_{\text{map}} = 24.5^0, Q\text{-value} = -7.4 \text{ MeV}; \text{Theta}2=70.52^\circ$$

$$k_1 = 1603.17 (1603) \text{ MeV}/c, k_2 = 705.23 \text{ MeV}/c;$$

$$T_1 = 919.28 \text{ MeV}, T_2 = 71.52 \text{ MeV};$$

$$\omega_1 = 78.92 \text{ MeV}; q = 705.19 \text{ MeV}/c (Q=700.76); \omega(^4\text{He}) = 71.67 \text{ MeV};$$

$$\omega = \omega_1 - \omega(^4\text{He}) = 7.25 \text{ MeV}$$

$$X = Q^2/[2\omega_1 m(^4\text{He})] \approx 0.904 \{ \omega_1 \rightarrow \omega(^4\text{He}), X^* \approx 0.9954 \}$$

4. Mass of  $^4\text{He}$  is less than the free one (7.68%):

$$m(^4\text{He}) = 3441.01 \text{ MeV};$$

$$Q_{\text{map}} = 24.514^0, Q\text{-value} = -(7.4+3.6) = -11 \text{ MeV}; \text{Theta}2=70.18^\circ$$

$$k_1 = 1598.993 (1599) \text{ MeV}/c, k_2 = 705.23 \text{ MeV}/c;$$

$$T_1 = 915.68 \text{ MeV}, T_2 = 71.52 \text{ MeV};$$

$$\omega_1 = 82.52 \text{ MeV}; q = 705.23 \text{ MeV}/c (Q=700.785); \omega(^4\text{He}) = 71.75 \text{ MeV};$$

$$\omega = \omega_1 - \omega(^4\text{He}) = 10.77 \text{ MeV}$$

$$X = Q^2/[2\omega_1 m(^4\text{He})] \approx 0.865 \{ \omega_1 \rightarrow \omega(^4\text{He}), X^* \approx 0.9948 \}$$

5. Mass of  $^4\text{He}$  is less than the free one (7.68%):

$$m(^4\text{He}) = 3441.01 \text{ MeV};$$

$$Q_{\text{map}} = 24.537^0, Q\text{-value} = -(7.397+10.92) = -18.32 \text{ MeV}; \text{Theta}2=70.18^\circ$$

$$k_1 = 1590.5 (1590.5) \text{ MeV}/c, k_2 = 705.23 \text{ MeV}/c;$$

$$T_1 = 908.36 \text{ MeV}, T_2 = 71.52 \text{ MeV};$$

$$\omega_1 = 89.84 \text{ MeV}; q = 705.23 \text{ MeV}/c (Q=699.484); \omega(^4\text{He}) = 71.88 \text{ MeV};$$

$$\omega = \omega_1 - \omega(^4\text{He}) = 17.96 \text{ MeV}$$

$$X = Q^2/[2\omega_1 m(^4\text{He})] \approx 0.791 \{ \omega_1 \rightarrow \omega(^4\text{He}), X^* \approx 0.9886 \}$$



## Kinematics for the reaction $^{12}\text{C}(p, p\ ^8\text{Be})^4\text{He}$ at an angle of $24.5^\circ$ , setting-4

$$T_0 = 998.2 \text{ MeV} \quad (k_0 = 1693.98 \text{ MeV}/c)$$

### 1. Masses of free $^4\text{He}$ and $^8\text{Be}$ :

$$m(^4\text{He}) = 3727.38 \text{ MeV}; \quad m(^8\text{Be}) = 7454.88 \text{ MeV}; \quad m(^{12}\text{C}) = 11174.87 \text{ MeV};$$

$$Q_{\text{map}} = 24.5^\circ, \quad Q\text{-value} = -7.4 \text{ MeV};$$

$$k_1 = 1646.77 \text{ MeV}/c, \quad k_2 = 710.35 \text{ MeV}/c;$$

$$T_1 = 957.04 \text{ MeV}, \quad T_2 = 33.77 \text{ MeV}.$$

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### 2. Mass of $^4\text{He}$ is less than the free one (10%):

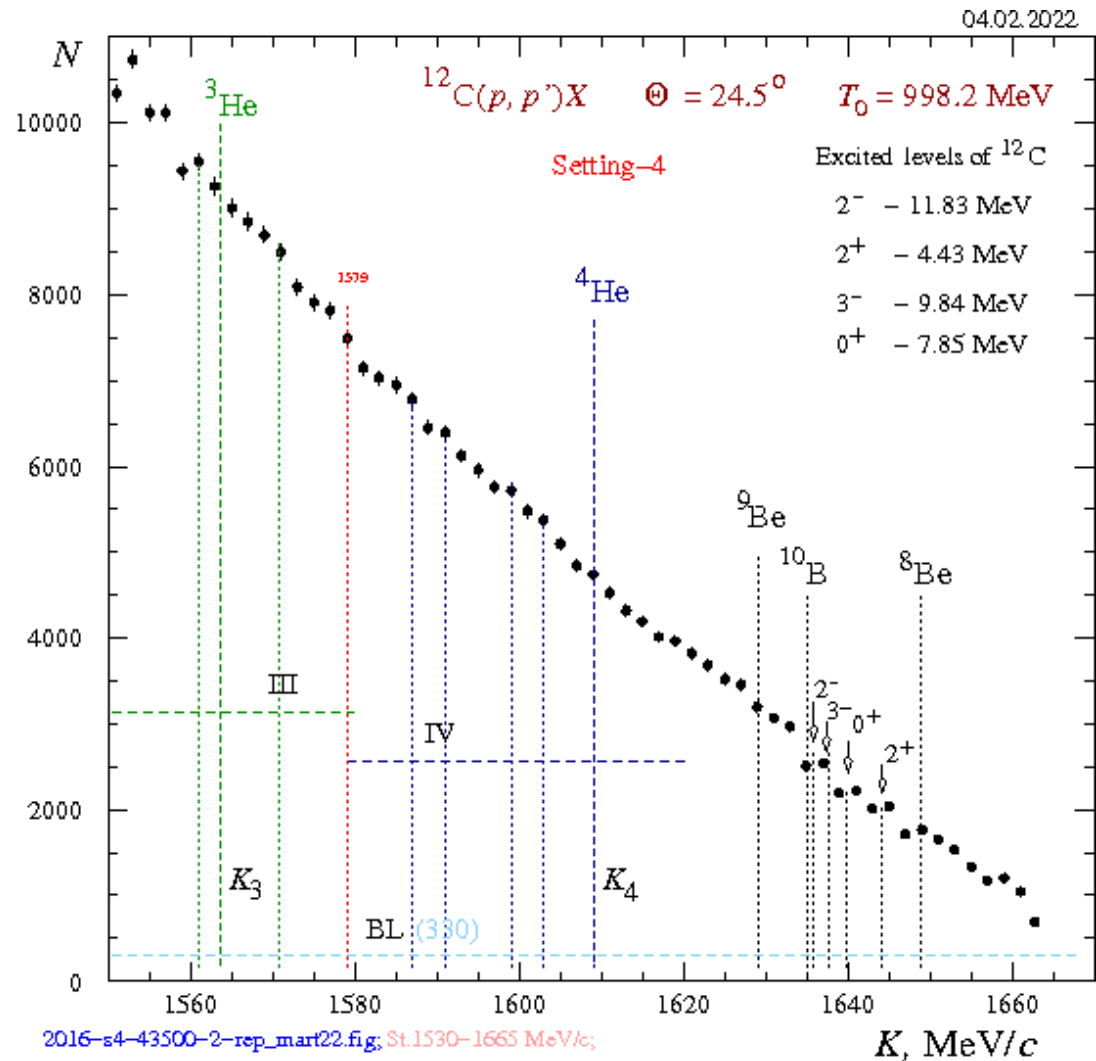
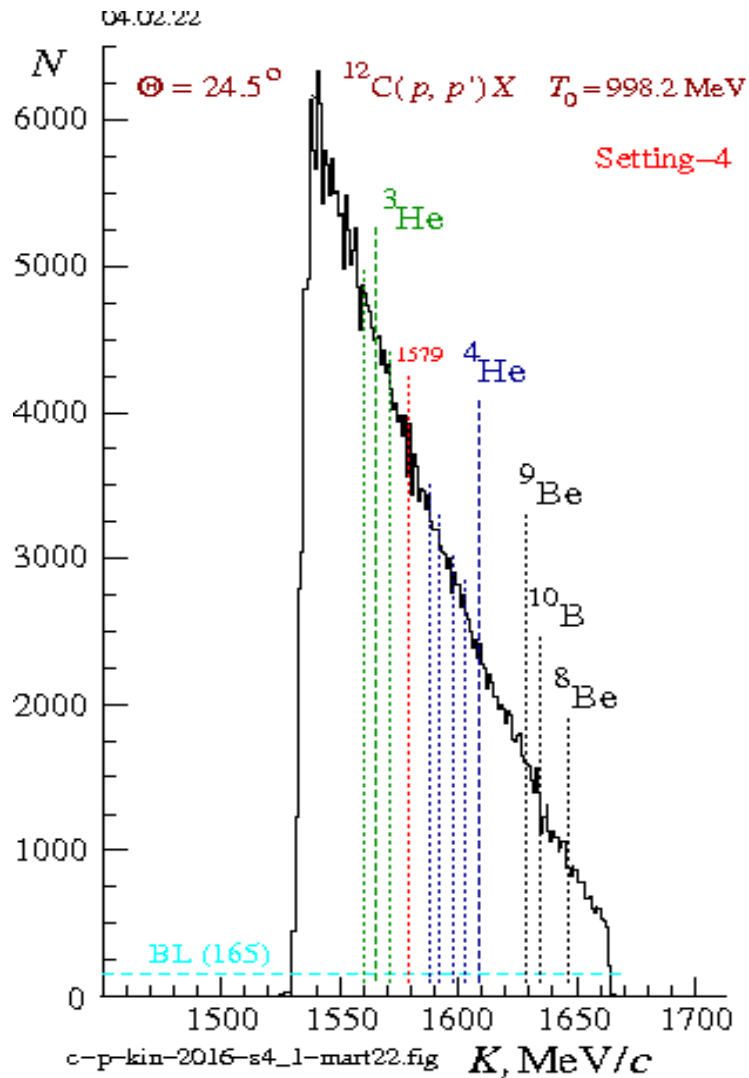
$m(^4\text{He}) = 3354.64 \text{ MeV}$ ; mass of  $^8\text{Be} = 7827.62 \text{ MeV}$  is more than free value, so that the sum of the masses is not changed due to the modification.

$$Q_{\text{map}} = 24.5^\circ, \quad Q\text{-value} = -7.4 \text{ MeV};$$

$$k_1 = 1648.58 \text{ MeV}/c, \quad k_2 = 710.60 \text{ MeV}/c;$$

$$T_1 = 958.61 \text{ MeV}, \quad T_2 = 32.19 \text{ MeV}.$$

Спектры протонов, рассеянных под углом  $24.5^\circ$  в импульсном интервале - 4 с шириной канала 1 и 2 МэВ/с

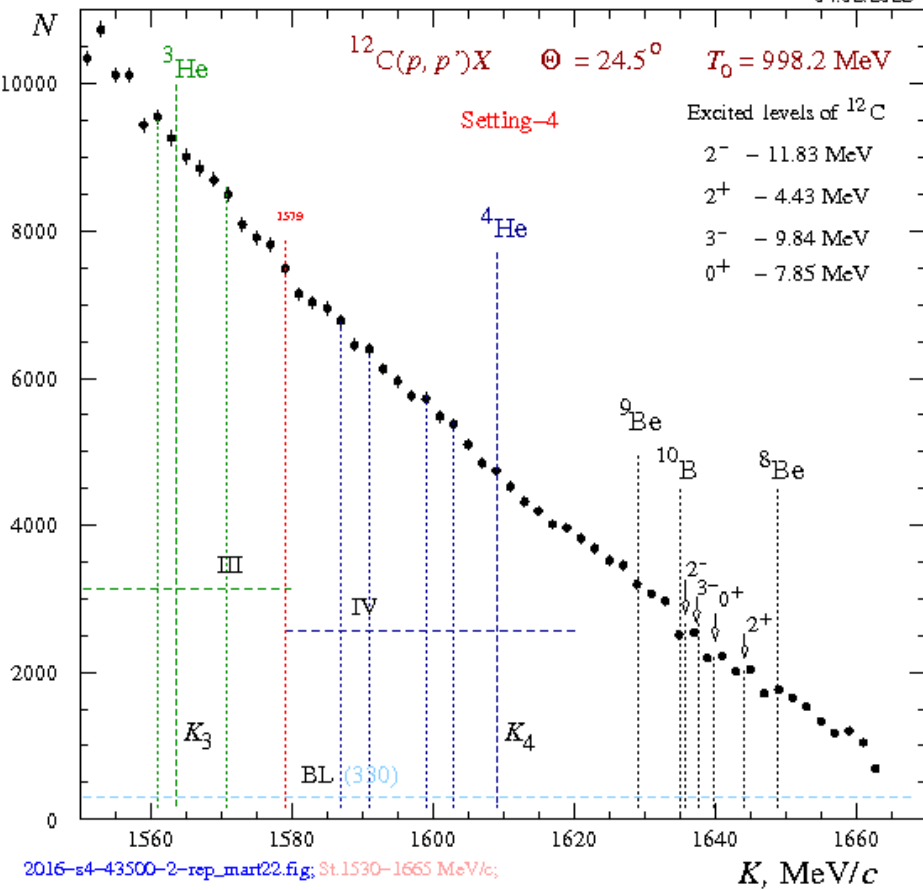


Импульсный интервал - 4, цена канала 1 МэВ/с

Импульсный интервал - 4, цена канала 2 МэВ/с

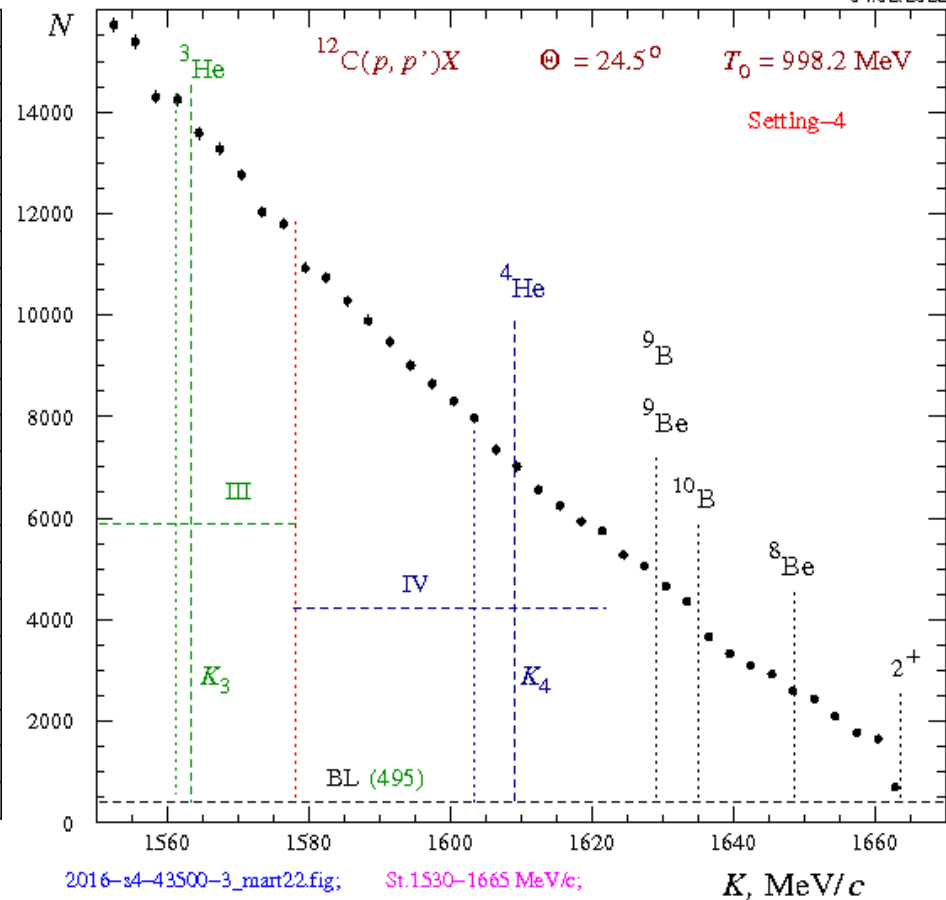
Спектры протонов, рассеянных под углом  $24.5^\circ$  в импульсном интервале - 4 с шириной канала 2 и 3 МэВ/с

04.02.2022

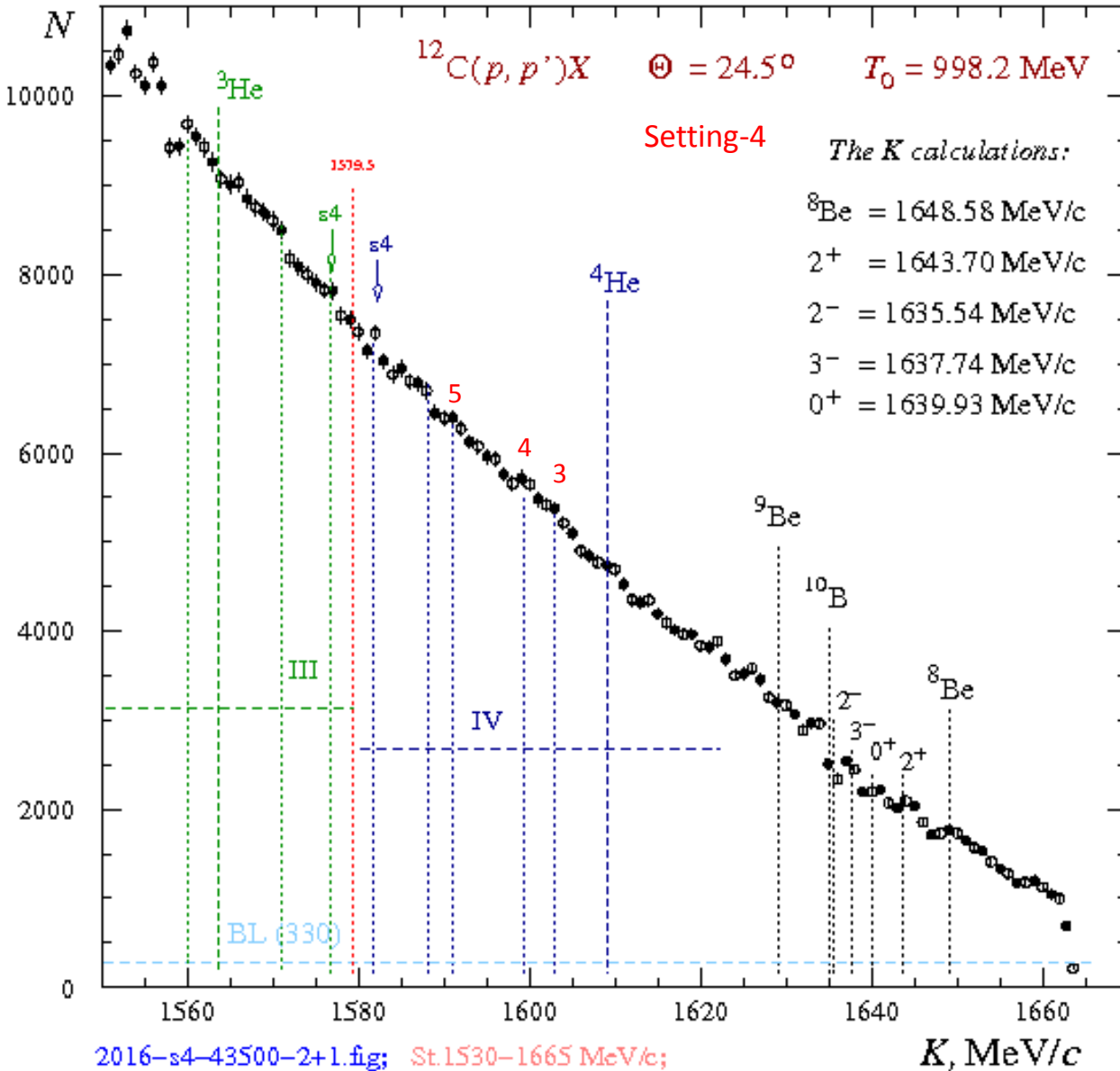


Импульсный интервал - 4, цена канала 2 МэВ/с

04.02.2022



Импульсный интервал - 4, цена канала 3 МэВ/с



3-5. Mass of  $^4\text{He}$  is less than the free one (7.68%):  
 $m(^4\text{He}) = 3441.01 \text{ MeV}$

3. Q-value = -7.4 MeV     $k_1 = 1603 \text{ MeV/c}$   
 $T_1 = 919.28 \text{ MeV}$ ,  $T_2 = 71.52 \text{ MeV}$ ;  
 $\omega_1 = 78.92 \text{ MeV}$ ;  $q = 705.19 \text{ MeV/c}$  ( $Q=700.76$ );  
 $\omega(^4\text{He}) = 71.67 \text{ MeV}$ ;     $\omega = \omega_1 - \omega(^4\text{He}) = 7.25 \text{ MeV}$

$X = Q^2/[2\omega_1 m(^4\text{He})] \approx 0.904$  { $\omega_1 \rightarrow \omega(^4\text{He})$ ,  $X^* \approx 0.9954$ }

4. Q-value = -(7.4+3.6) = -11 MeV;     $k_1 = 1599 \text{ MeV/c}$   
 $T_1 = 915.68 \text{ MeV}$ ,  $T_2 = 71.52 \text{ MeV}$ ;  
 $\omega_1 = 82.52 \text{ MeV}$ ;  $q = 705.23 \text{ MeV/c}$  ( $Q=700.785$ );  
 $\omega(^4\text{He}) = 71.75 \text{ MeV}$ ;     $\omega = \omega_1 - \omega(^4\text{He}) = 10.8 \text{ MeV}$

$X = Q^2/[2\omega_1 m(^4\text{He})] \approx 0.865$  { $\omega_1 \rightarrow \omega(^4\text{He})$ ,  $X^* \approx 0.9948$ }

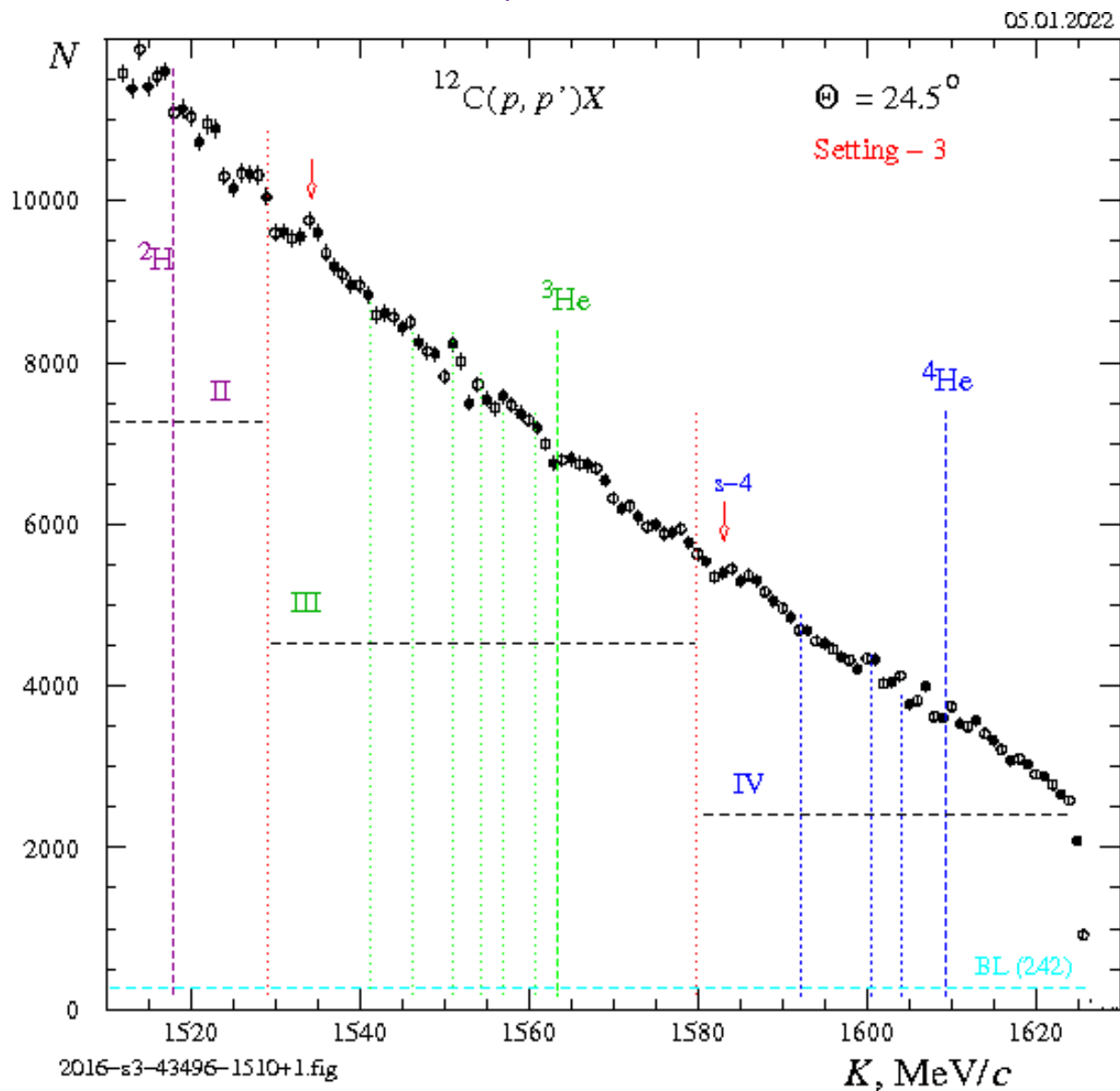
5. Q-value = -(7.4+10.9) = -18.3 MeV;  $k_1 = 1590.5 \text{ MeV/c}$   
 $T_1 = 908.36 \text{ MeV}$ ,  $T_2 = 71.52 \text{ MeV}$ ;  
 $\omega_1 = 89.84 \text{ MeV}$ ;  $q = 705.23 \text{ MeV/c}$  ( $Q=699.48$ );  
 $\omega(^4\text{He}) = 71.88 \text{ MeV}$ ;     $\omega = \omega_1 - \omega(^4\text{He}) = 18 \text{ MeV}$

$X = Q^2/[2\omega_1 m(^4\text{He})] \approx 0.791$  { $\omega_1 \rightarrow \omega(^4\text{He})$ ,  $X^* \approx 0.9886$ }

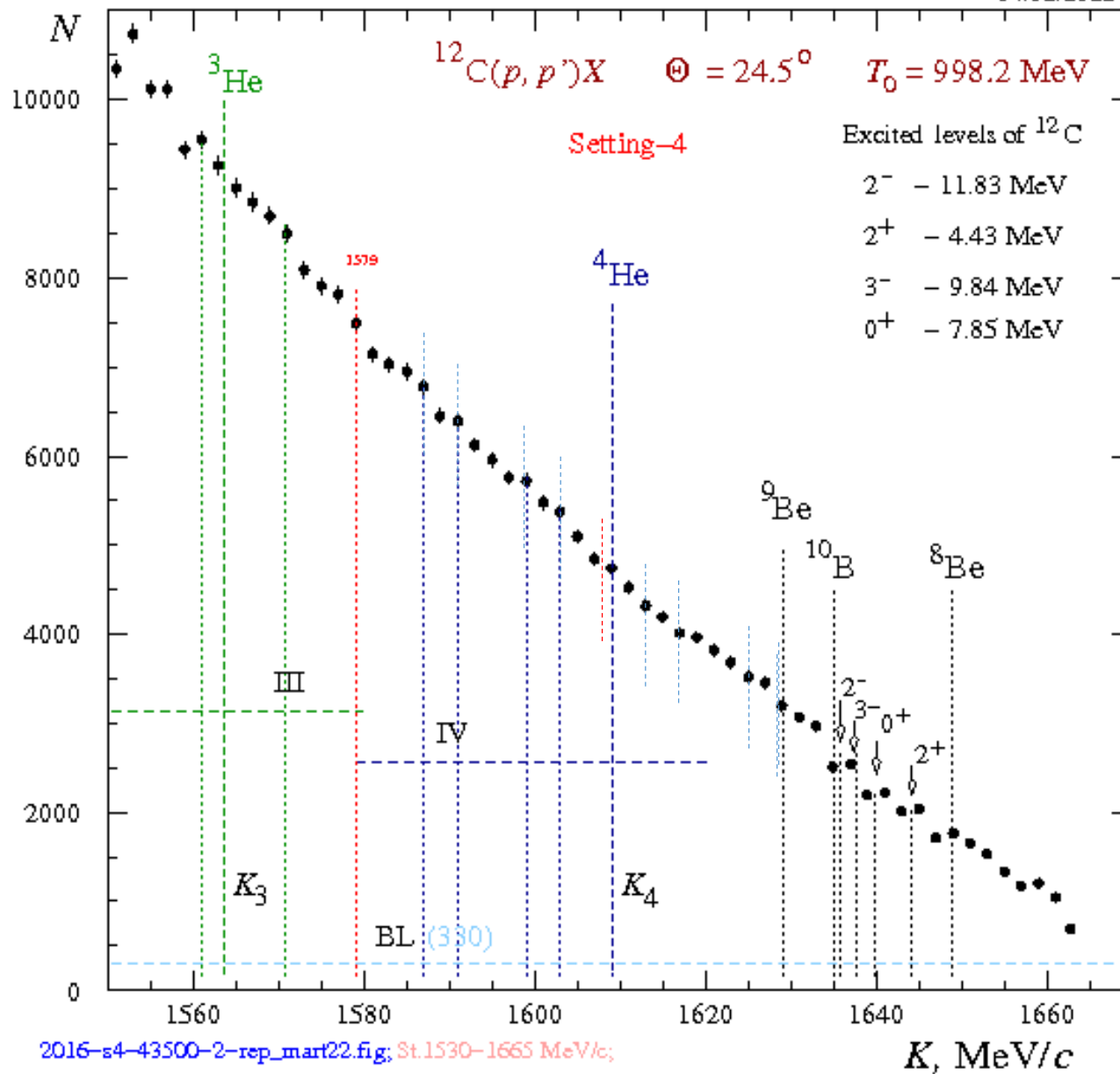
Видим узкий пик при  $K = 1582 \text{ МэВ/с}$ ,  
 меченный стрелкой s4 !

Этот пик проявляется также в интервале s3  
 при  $K = 1583 \text{ МэВ/с}$ .

Спектр протонов, рассеянных под углом  $24.5^\circ$  в импульсном интервале - 3  
с шириной канала 2 МэВ/с



04.02.2022



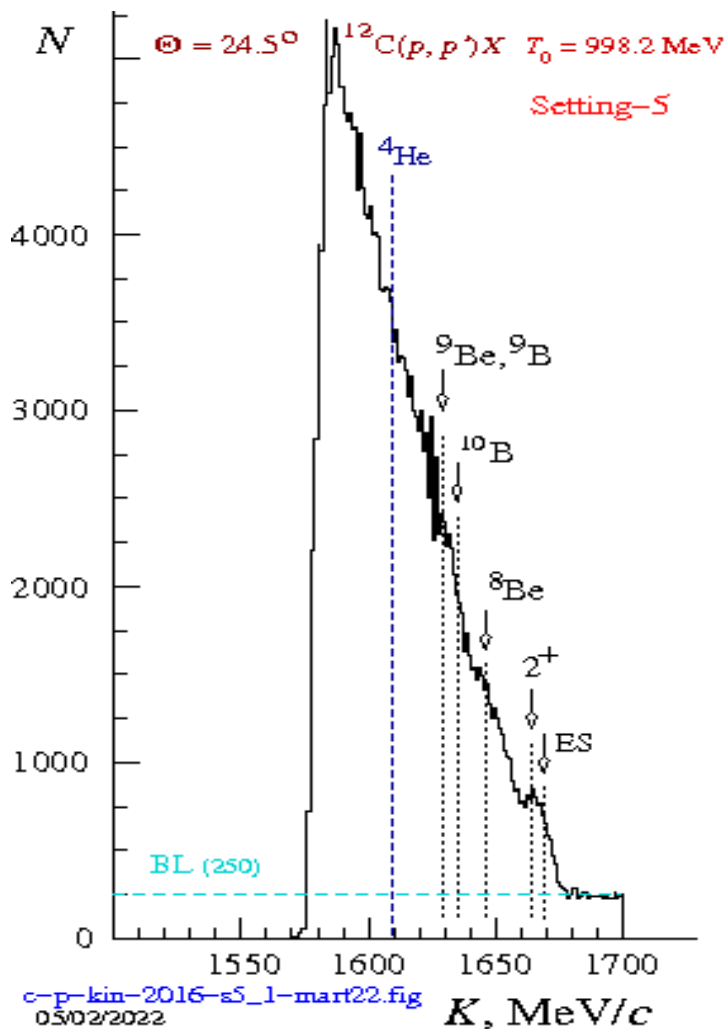
2016-s4-43500-2-rep\_mart22.fig; St.1530-1665 MeV/c;

$$\theta = 24.5^{\circ}$$

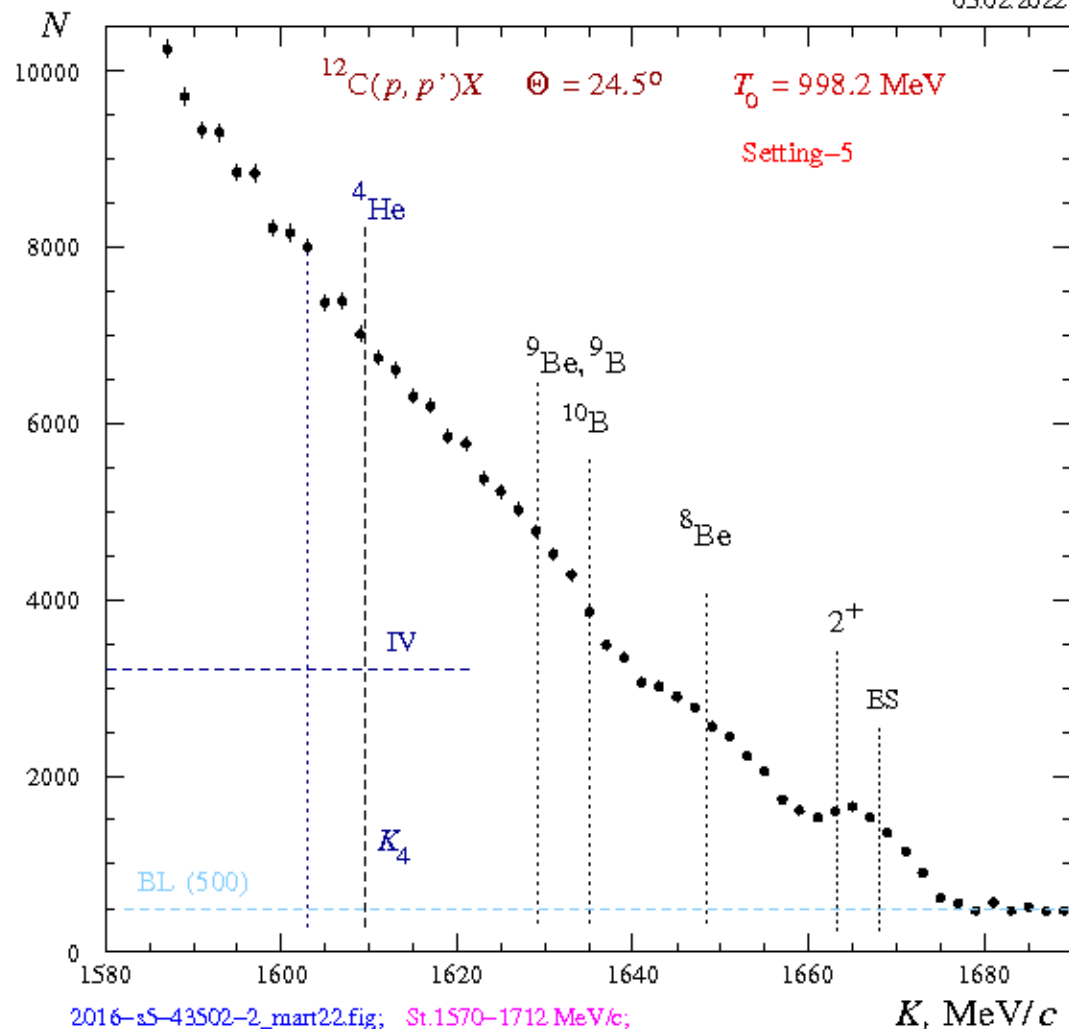
Setting - 5

Спектры протонов, рассеянных под углом  $24.5^\circ$  в импульсном интервале - 5  
с шириной канала 1 и 2 МэВ/с

05.02.2022



Импульсный интервал – 5, цена канала 1 МэВ/с

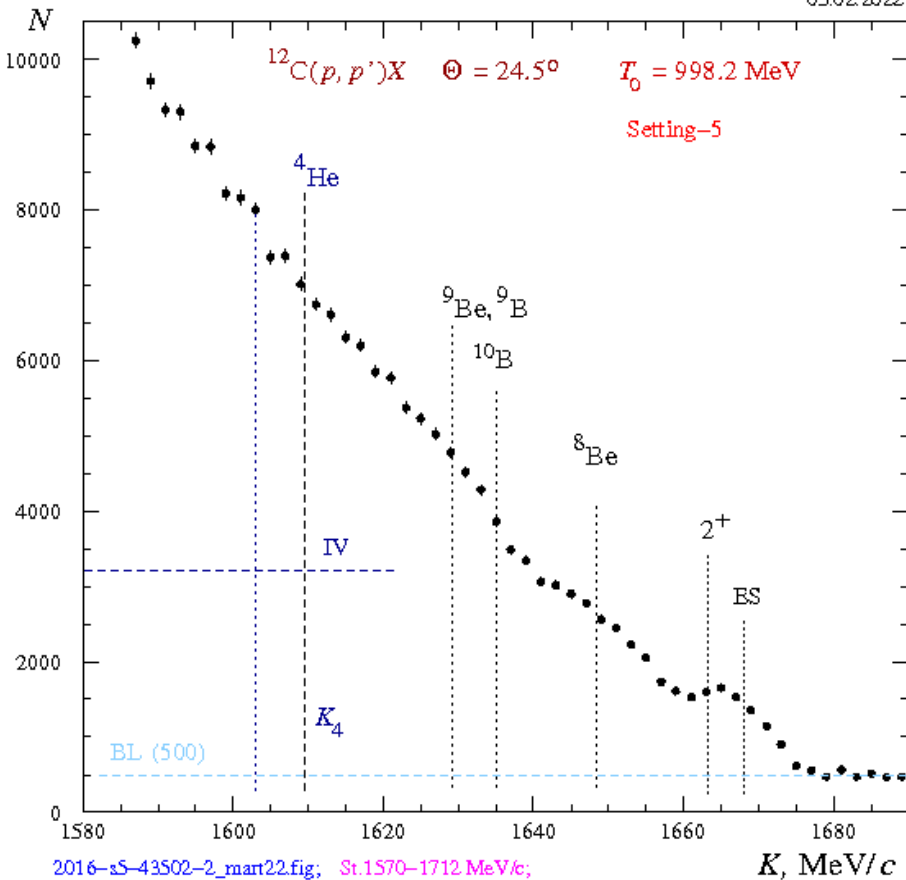


Импульсный интервал – 5, цена канала 2 МэВ/с

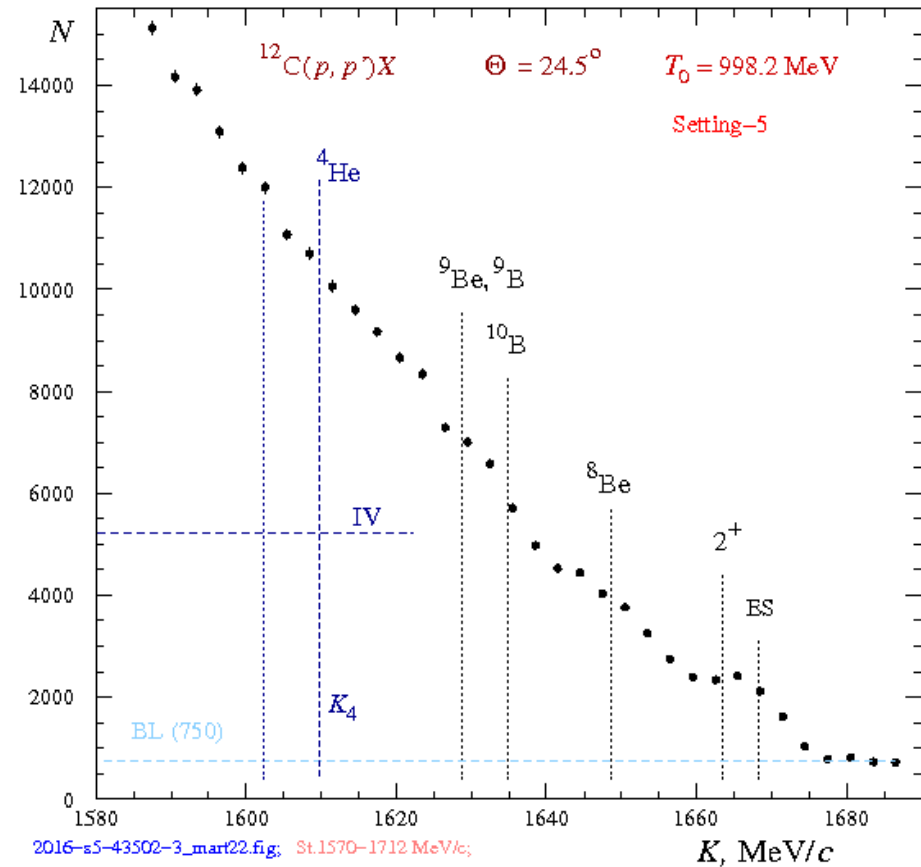


## Спектры протонов, рассеянных под углом $24.5^\circ$ в импульсном интервале - 5 с шириной канала 2 и 3 МэВ/с

05.02.2022



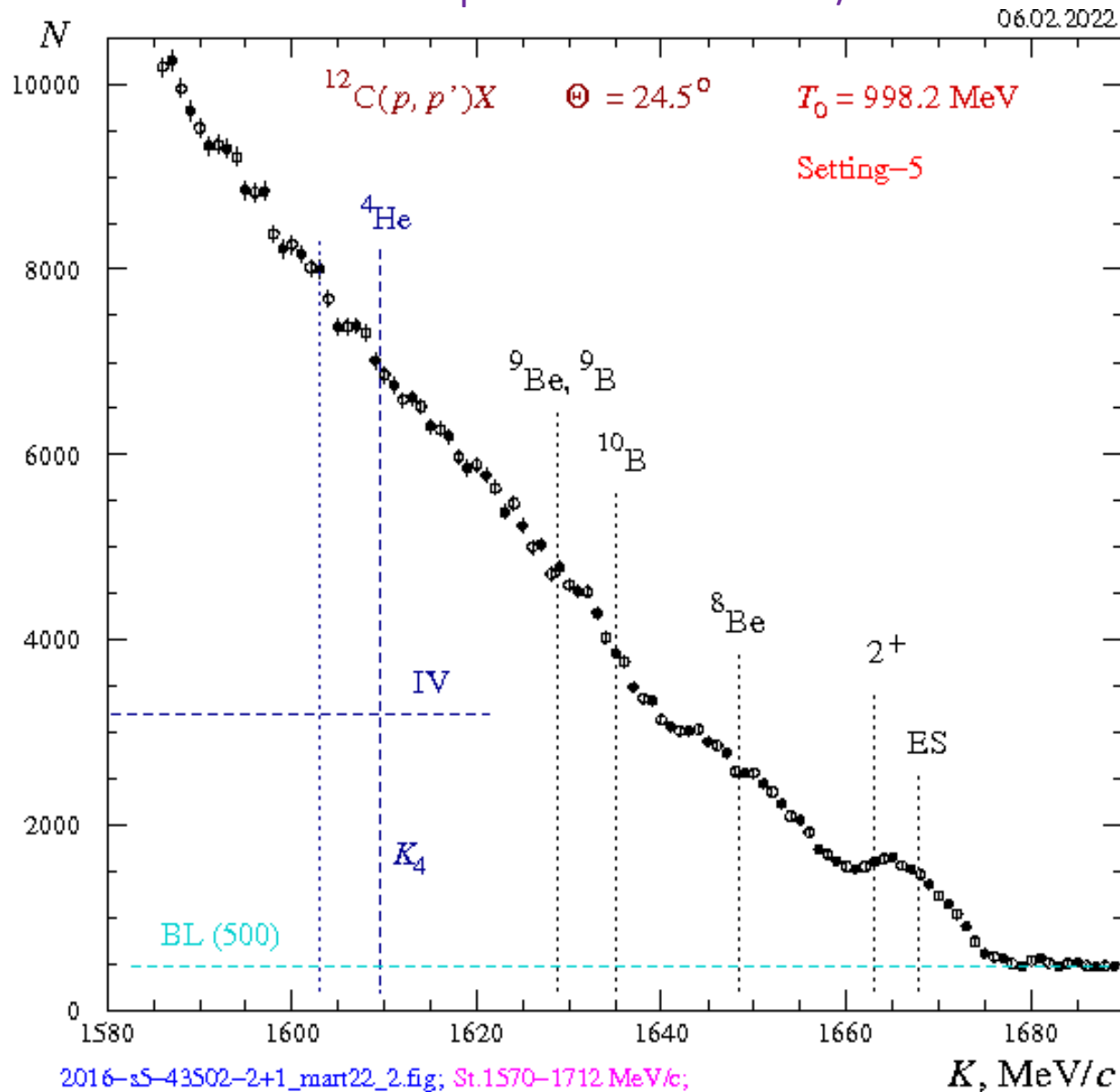
05.02.2022



Импульсный интервал – 5, цена канала 2 МэВ/с

Импульсный интервал – 5, цена канала 3 МэВ/с

Спектр протонов, рассеянных под углом  $24.5^\circ$  в импульсном интервале - 5 с шириной канала 2 МэВ/с



$$\theta = 21^{\circ}$$

Setting - 4

$$T_0 = 998.6 \text{ MeV}, k_0 = 1694.44 \text{ MeV/c}$$

**1. Masses of free  $^4\text{He}$ ,  $^8\text{Be}$  and  $^{12}\text{C}$ :**

$$m(^4\text{He}) = 3727.38 \text{ MeV}; m(^8\text{Be}) = 7454.88 \text{ MeV} \text{ and } m(^{12}\text{C}) = 11174.87 \text{ MeV};$$

$$Q_{\text{map}} = 21^\circ, Q\text{-value} = -7.397 \text{ MeV};$$

$$k_1 = 1629.17 \text{ MeV/c}, k_2 = 609.70 \text{ MeV/c};$$

$$T_1 = 941.77 \text{ MeV}, T_2 = 49.43 \text{ MeV}.$$

$$\omega_1 = 56.83 \text{ MeV}; q = 609.07 \text{ MeV/c } (Q=606.41); \omega(^4\text{He}) = 49.55 \text{ MeV};$$

$$\omega = \omega_1 - \omega(^4\text{He}) = 7.28 \text{ MeV}$$

$$X = Q^2/[2\omega_1 m(^4\text{He})] \approx 0.868 \{ \omega_1 \rightarrow \omega(^4\text{He}), X^* \approx 0.9955 \}$$

**2. Mass of  $^4\text{He}$  is less than the free one (10%):**

$$m(^4\text{He}) = 3354.64 \text{ MeV}$$

$$Q_{\text{map}} = 21^\circ, Q\text{-value} = -7.397 \text{ MeV};$$

$$k_1 = 1623.02 \text{ (1623) MeV/c}, k_2 = 608.625 \text{ MeV/c};$$

$$T_1 = 936.44 \text{ MeV}, T_2 = 54.76 \text{ MeV};$$

$$\omega_1 = 62.16 \text{ MeV}; q = 608.62 \text{ MeV/c } (Q=605.44); \omega(^4\text{He}) = 54.88 \text{ MeV};$$

$$\omega = \omega_1 - \omega(^4\text{He}) = 7.28 \text{ MeV}$$

$$X = Q^2/[2\omega_1 m(^4\text{He})] \approx 0.879 \{ \omega_1 \rightarrow \omega(^4\text{He}), X^* \approx 0.9956 \}$$

**3. Mass of  $^4\text{He}$  is less than the free one (11.66%):**

$$m(^4\text{He}) = 3292.82 \text{ MeV};$$

$$Q_{\text{map}} = 21^\circ, Q\text{-value} = -7.4 \text{ MeV}; \text{ Theta}2=72.77^\circ$$

$$k_1 = 1621.87 \text{ (1622) MeV/c}, k_2 = 608.55 \text{ MeV/c};$$

$$T_1 = 935.44 \text{ MeV}, T_2 = 55.76 \text{ MeV};$$

$$\omega_1 = 63.16 \text{ MeV}; q = 608.55 \text{ MeV/c } (Q=605.26); \omega(^4\text{He}) = 55.87 \text{ MeV};$$

$$\omega = \omega_1 - \omega(^4\text{He}) = 7.29 \text{ MeV}$$

$$X = Q^2/[2\omega_1 m(^4\text{He})] \approx 0.881 \{ \omega_1 \rightarrow \omega(^4\text{He}), X^* \approx 0.9960 \}$$

**4. Mass of  $^4\text{He}$  is less than the free one (11.66%):**

$$m(^4\text{He}) = 3292.82 \text{ MeV};$$

$$Q_{\text{map}} = 21.0106^\circ, Q\text{-value} = -(7.4+4.2) = -11.6 \text{ MeV}; \text{ Theta}2=72.31^\circ$$

$$k_1 = 1617.01 \text{ (1617) MeV/c}, k_2 = 608.55 \text{ MeV/c};$$

$$T_1 = 931.24 \text{ MeV}, T_2 = 55.76 \text{ MeV};$$

$$\omega_1 = 67.36 \text{ MeV}; q = 608.53 \text{ MeV/c } (Q=604.79); \omega(^4\text{He}) = 55.93 \text{ MeV};$$

$$\omega = \omega_1 - \omega(^4\text{He}) = 11.43 \text{ MeV}$$

$$X = Q^2/[2\omega_1 m(^4\text{He})] \approx 0.825 \{ \omega_1 \rightarrow \omega(^4\text{He}), X^* \approx 0.9936 \}$$

**5. Mass of  $^4\text{He}$  is less than the free one (11.66%):**

$$m(^4\text{He}) = 3292.82 \text{ MeV};$$

$$Q_{\text{map}} = 21.027^\circ, Q\text{-value} = -(7.397+11.993) = -19.39 \text{ MeV}; \text{ Theta}2=71.46^\circ$$

$$k_1 = 1607.996 \text{ (1608) MeV/c}, k_2 = 608.55 \text{ MeV/c};$$

$$T_1 = 923.45 \text{ MeV}, T_2 = 55.76 \text{ MeV};$$

$$\omega_1 = 75.15 \text{ MeV}; q = 608.55 \text{ MeV/c } (Q=603.89); \omega(^4\text{He}) = 56.01 \text{ MeV};$$

$$\omega = \omega_1 - \omega(^4\text{He}) = 19.14 \text{ MeV}$$

$$X = Q^2/[2\omega_1 m(^4\text{He})] \approx 0.737 \{ \omega_1 \rightarrow \omega(^4\text{He}), X^* \approx 0.9889 \}$$

**6. Mass of  $^4\text{He}$  is less than the free one (11.66%):**

$$m(^4\text{He}) = 3292.82 \text{ MeV};$$

$$Q_{\text{map}} = 21.0202^\circ, Q\text{-value} = -(7.397+8.533) = -15.93 \text{ MeV}; \text{ Theta}2=71.84^\circ$$

$$k_1 = 1612.001 \text{ (1612) MeV/c}, k_2 = 608.55 \text{ MeV/c};$$

$$T_1 = 926.91 \text{ MeV}, T_2 = 55.76 \text{ MeV};$$

$$\omega_1 = 71.69 \text{ MeV}; q = 608.55 \text{ MeV/c } (Q=604.31); \omega(^4\text{He}) = 55.97 \text{ MeV};$$

$$\omega = \omega_1 - \omega(^4\text{He}) = 15.72 \text{ MeV}$$

$$X = Q^2/[2\omega_1 m(^4\text{He})] \approx 0.774 \{ \omega_1 \rightarrow \omega(^4\text{He}), X^* \approx 0.9914 \}$$

## Kinematics for the reaction $^{12}\text{C}(p, p \ ^8\text{Be})^4\text{He}$ at an angle of $21^\circ$ , setting - 4

$$T_0 = 998.6 \text{ MeV} \quad (k_0 = 1694.44 \text{ MeV}/c)$$

### 1. Masses of free $^4\text{He}$ and $^8\text{Be}$ :

$$m(^4\text{He}) = 3727.38 \text{ MeV}; \quad m(^8\text{Be}) = 7454.88 \text{ MeV}; \quad m(^{12}\text{C}) = 11174.87 \text{ MeV};$$

$$Q_{\text{map}} = 21^0, \quad Q\text{-value} = -7.4 \text{ MeV};$$

$$k_1 = 1657.23 \text{ MeV}/c, \quad k_2 = 611.89 \text{ MeV}/c;$$

$$T_1 = 966.13 \text{ MeV}, \quad T_2 = 25.07 \text{ MeV}.$$

---

### 2. Mass of $^4\text{He}$ is less than the free one (**11.6585%**):

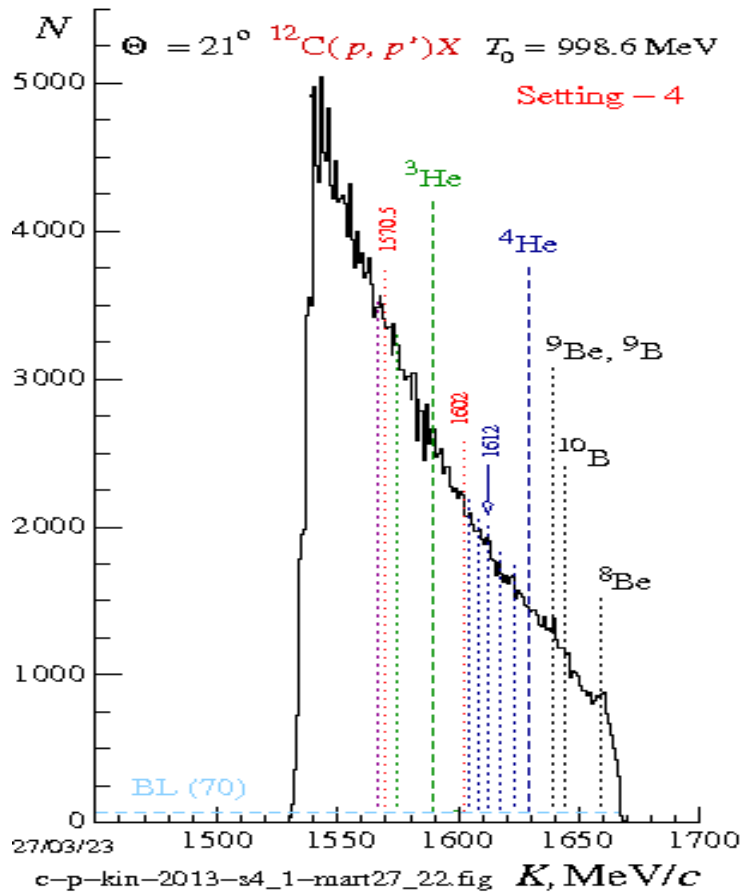
$m^*(^4\text{He}) = 3292.822 \text{ MeV}$ ; mass of  $^8\text{Be} = 7889.441 \text{ MeV}$  is more than free value, so that the sum of the masses is not changed due to the modification.

$$Q_{\text{map}} = 21^0, \quad Q\text{-value} = -7.4 \text{ MeV};$$

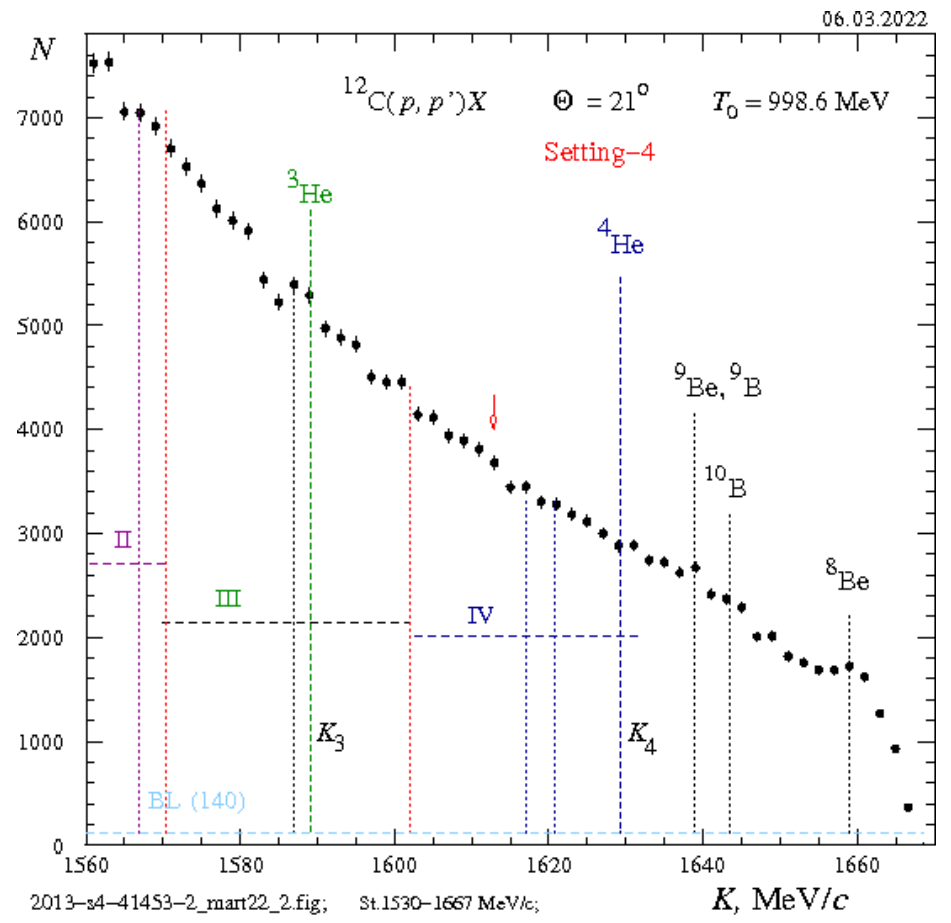
$$k_1 = 1658.79 \text{ MeV}/c, \quad k_2 = 612.08 \text{ MeV}/c;$$

$$T_1 = 967.50 \text{ MeV}, \quad T_2 = 23.71 \text{ MeV}.$$

Спектры протонов, рассеянных под углом  $21^\circ$  в импульсном интервале - 4 с шириной канала 1 и 2 МэВ/с

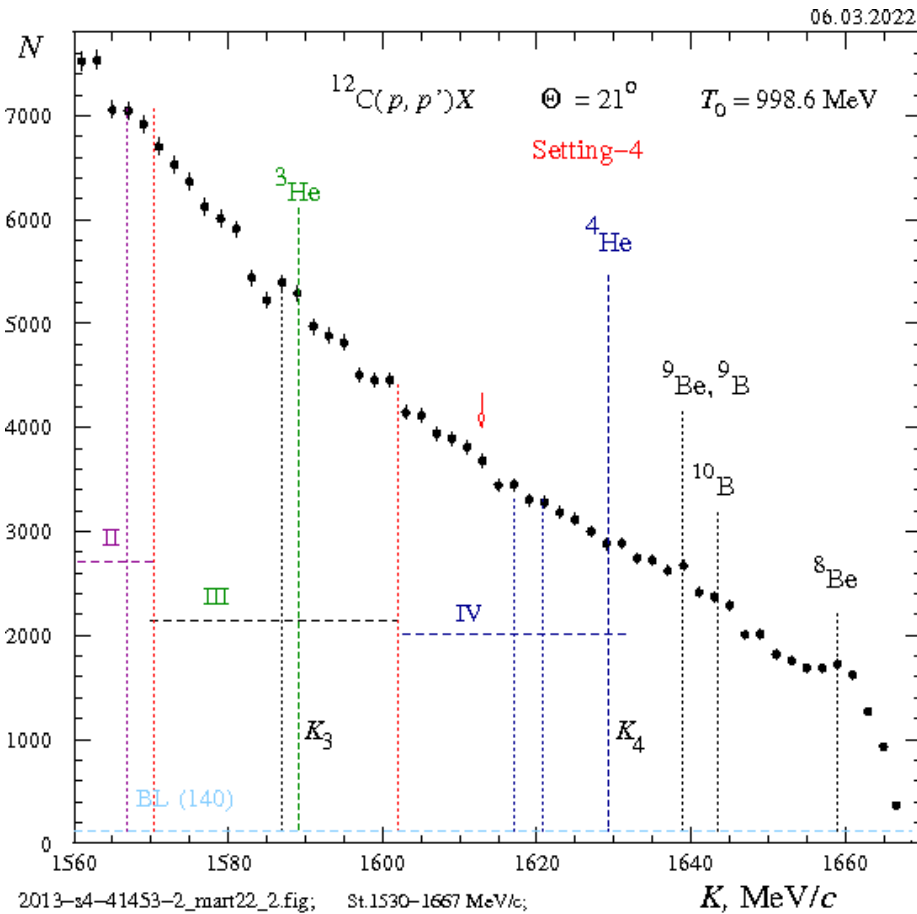


Импульсный интервал - 4, цена канала 1 МэВ/с

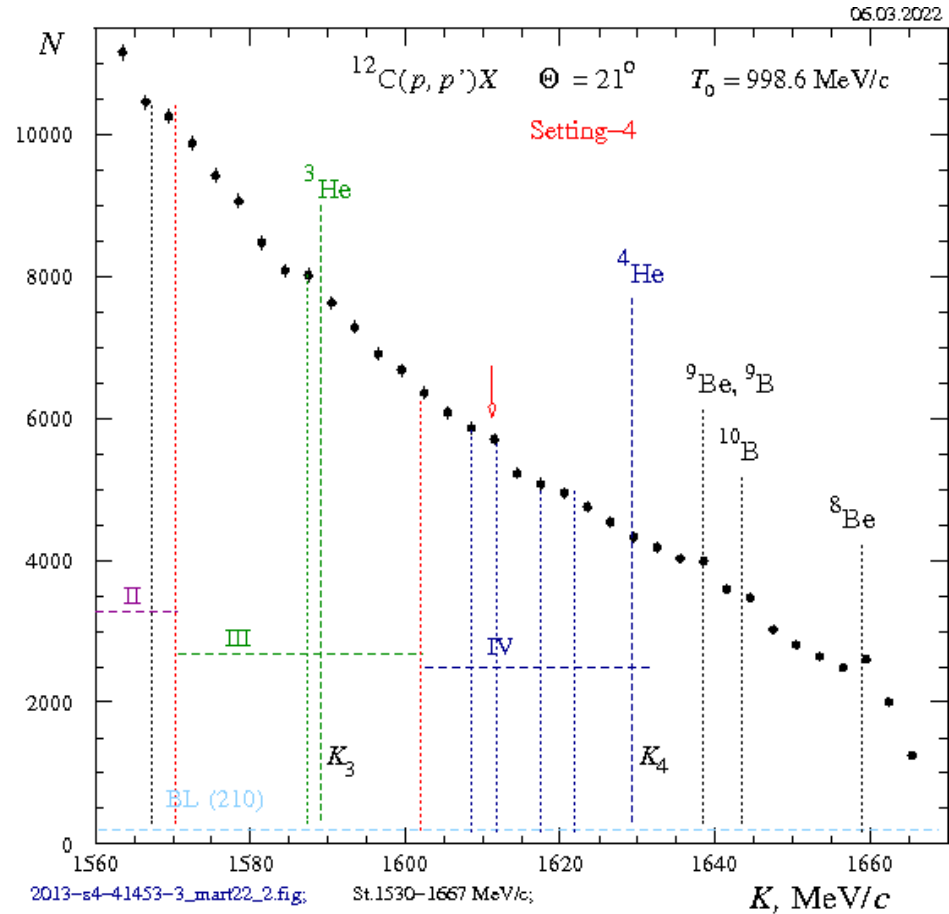


Импульсный интервал - 4, цена канала 2 МэВ/с

Спектры протонов, рассеянных под углом  $21^\circ$  в импульсном интервале - 4  
с шириной канала 2 и 3 МэВ/с



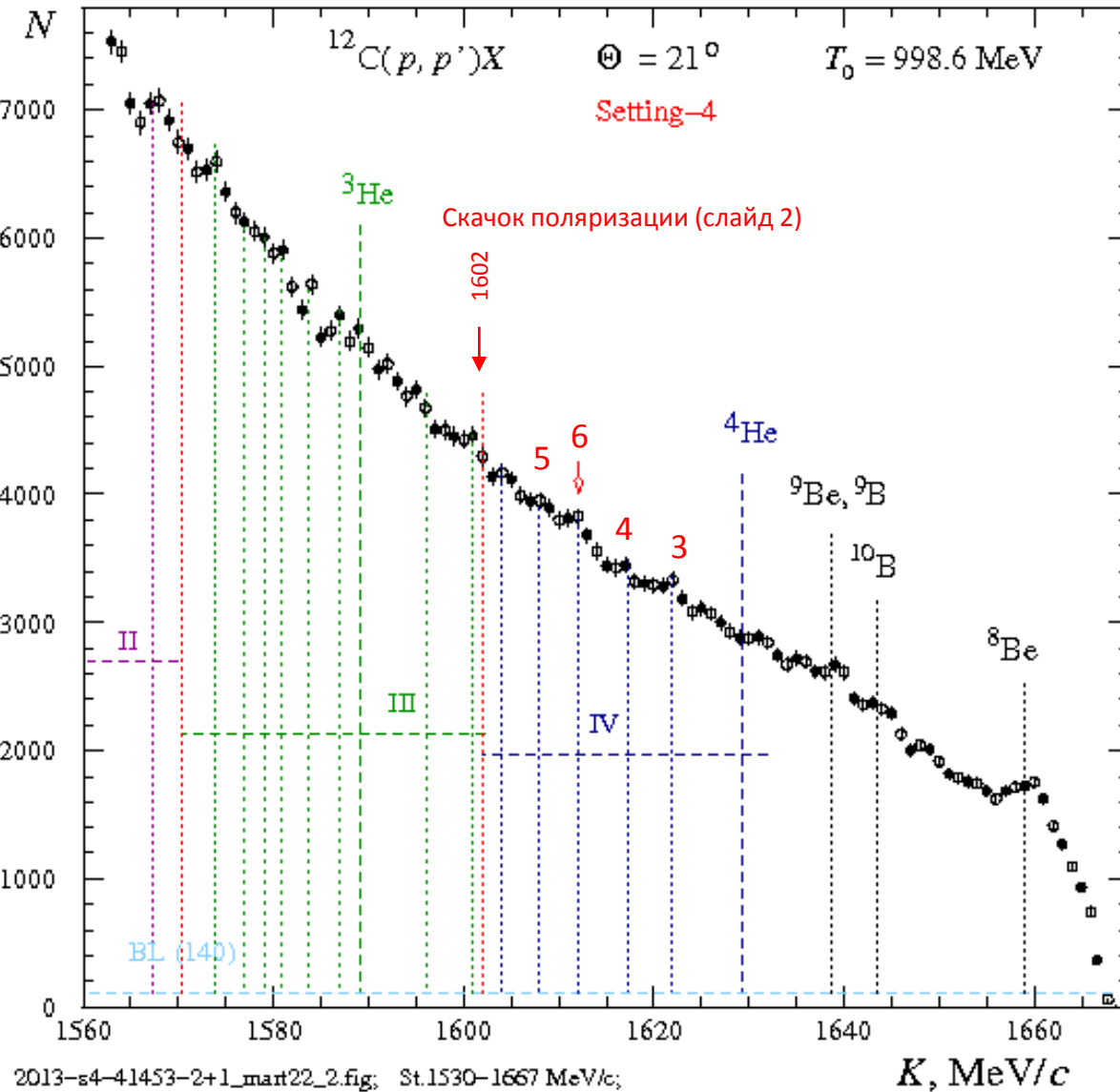
Импульсный интервал - 4, цена канала 2 МэВ/с



Импульсный интервал - 4, цена канала 3 МэВ/с

Спектр протонов, рассеянных под углом  $21^\circ$  в импульсном интервале - 4  
с шириной канала 2 МэВ/с

06.03.2022



3-6. Mass of  $^4\text{He}$  is less than the free one (11.66%):  
 $m^*(^4\text{He}) = 3292.82$  MeV

3. Q-value = - 7.4 MeV  $k_1 = 1622$  MeV/c  
 $T_1 = 935.44$  MeV,  $T_2 = 55.76$  MeV;  
 $\omega_1 = 63.16$  MeV;  $q = 608.55$  MeV/c ( $Q=605.26$ );  
 $\omega^*(^4\text{He}) = 55.87$  MeV;  $\omega = \omega_1 - \omega^*(^4\text{He}) = 7.3$  MeV  
 $X = Q^2/[2\omega_1 m^*(^4\text{He})] \approx 0.881 \{\omega_1 \rightarrow \omega^*(^4\text{He}), X^* \approx 0.9960\}$

4. Q-value = - (7.4+4.2) = - 11.6 MeV;  $k_1 = 1617$  MeV/c  
 $T_1 = 931.24$  MeV,  $T_2 = 55.76$  MeV;  
 $\omega_1 = 67.36$  MeV;  $q = 608.53$  MeV/c ( $Q=604.79$ );  
 $\omega^*(^4\text{He}) = 55.93$  MeV;  $\omega = \omega_1 - \omega^*(^4\text{He}) = 11.4$  MeV  
 $X = Q^2/[2\omega_1 m^*(^4\text{He})] \approx 0.825 \{\omega_1 \rightarrow \omega^*(^4\text{He}), X^* \approx 0.9936\}$

5. Q-value = - (7.4+12.0) = - 19.4 MeV;  $k_1 = 1608$  MeV/c  
 $T_1 = 923.45$  MeV,  $T_2 = 55.76$  MeV;  
 $\omega_1 = 75.15$  MeV;  $q = 608.55$  MeV/c ( $Q=603.89$ );  
 $\omega^*(^4\text{He}) = 56.01$  MeV;  $\omega = \omega_1 - \omega^*(^4\text{He}) = 19.1$  MeV  
 $X = Q^2/[2\omega_1 m^*(^4\text{He})] \approx 0.737 \{\omega_1 \rightarrow \omega^*(^4\text{He}), X^* \approx 0.9889\}$

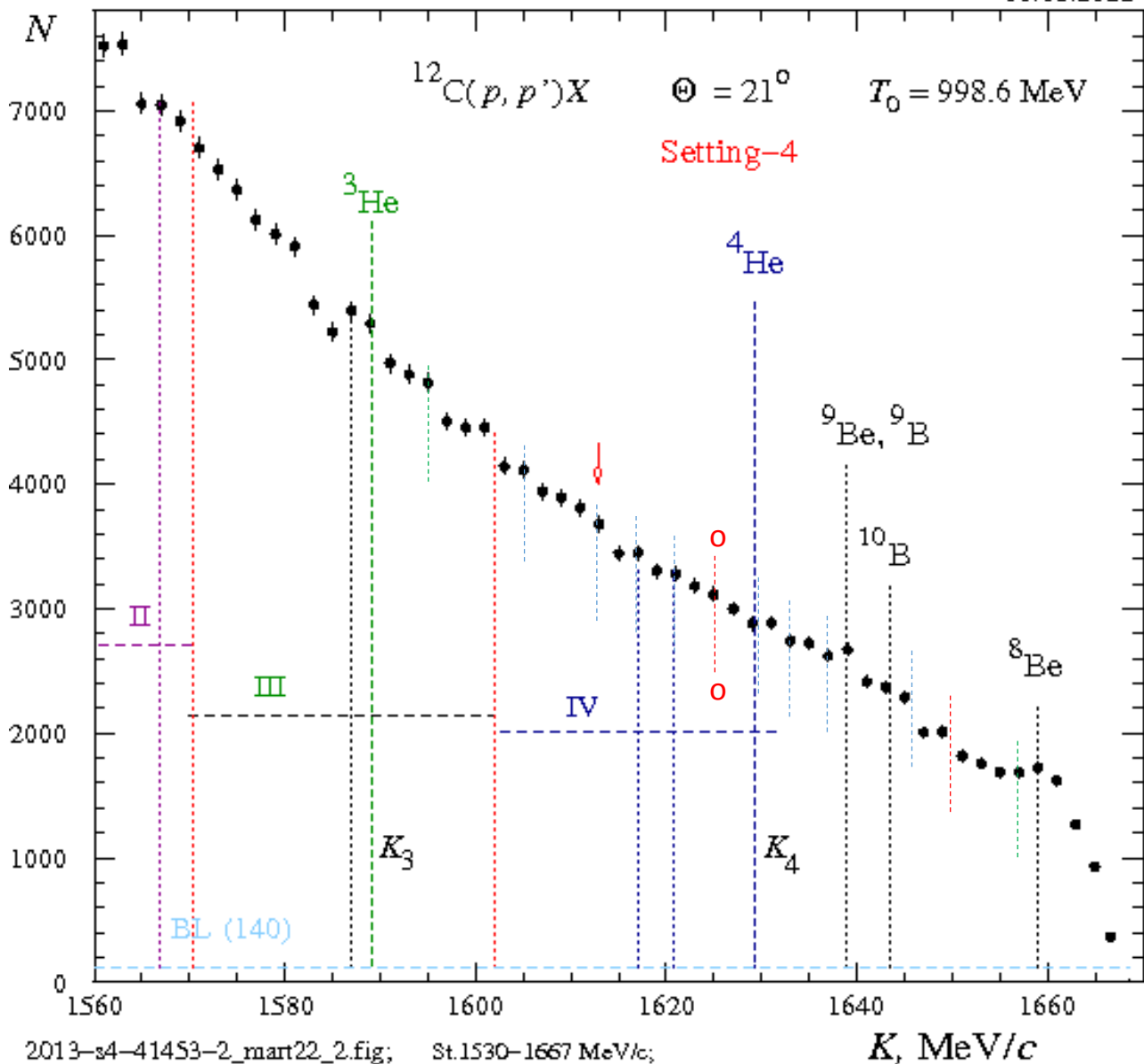
6. Q-value = - (7.4+8.53) = - 15.93 MeV;  $k_1 = 1612$  MeV/c  
 $T_1 = 926.91$  MeV,  $T_2 = 55.76$  MeV;  
 $\omega_1 = 71.69$  MeV;  $q = 608.55$  MeV/c ( $Q=604.31$ );  
 $\omega^*(^4\text{He}) = 55.97$  MeV;  $\omega = \omega_1 - \omega^*(^4\text{He}) = 15.7$  MeV  
 $X = Q^2/[2\omega_1 m^*(^4\text{He})] \approx 0.774 \{\omega_1 \rightarrow \omega^*(^4\text{He}), X^* \approx 0.9914\}$

Наблюдаем пик (6) при  
 $K = k_1 = 1612$  МэВ/с !!!

Этот пик виден и в интервале 5  
при  $K = k_1 = 1612$  МэВ/с.



06.03.2022

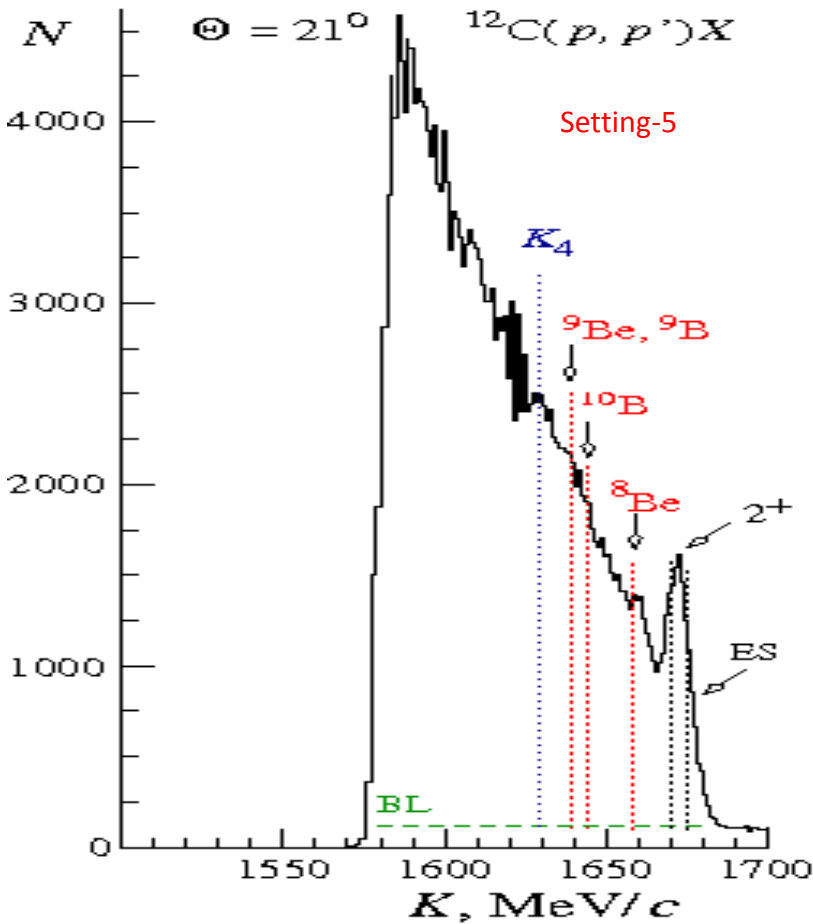


Наблюдается симметрия относительно отрезка красной штриховой линии о--о !!!!

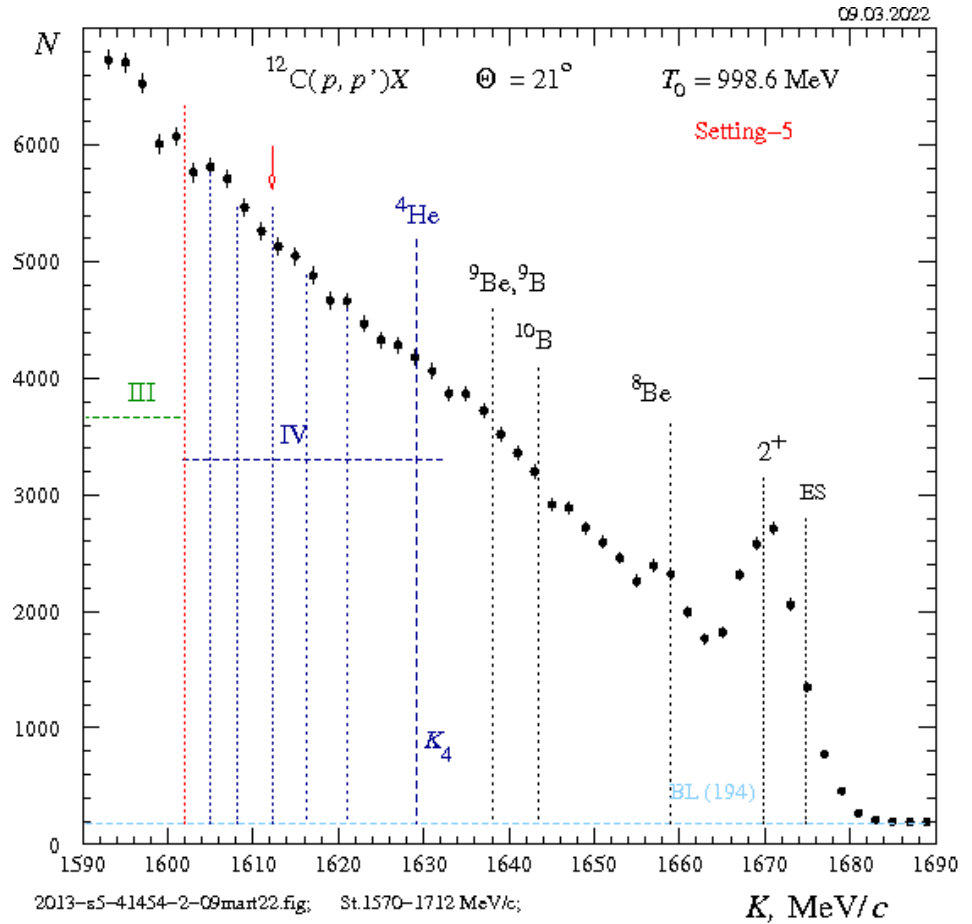
$$\theta = 21^0$$

Setting - 5

Спектры протонов, рассеянных под углом  $21^\circ$  в импульсном интервале - 5 с шириной канала 1 и 2 МэВ/с

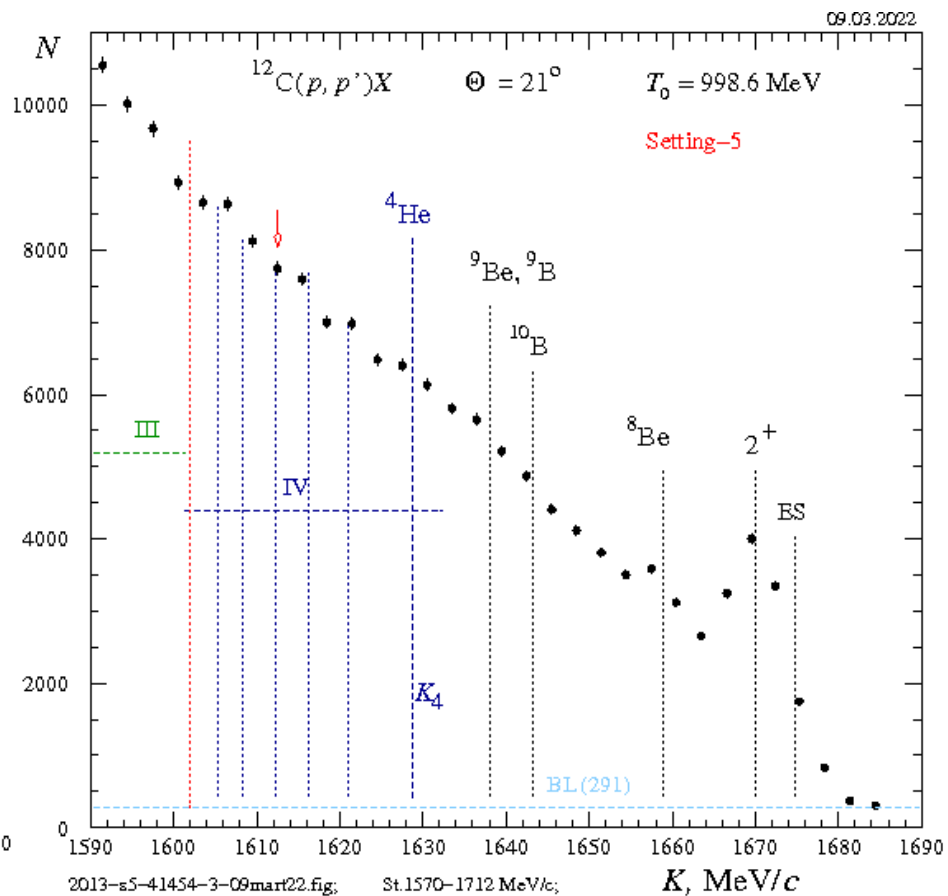
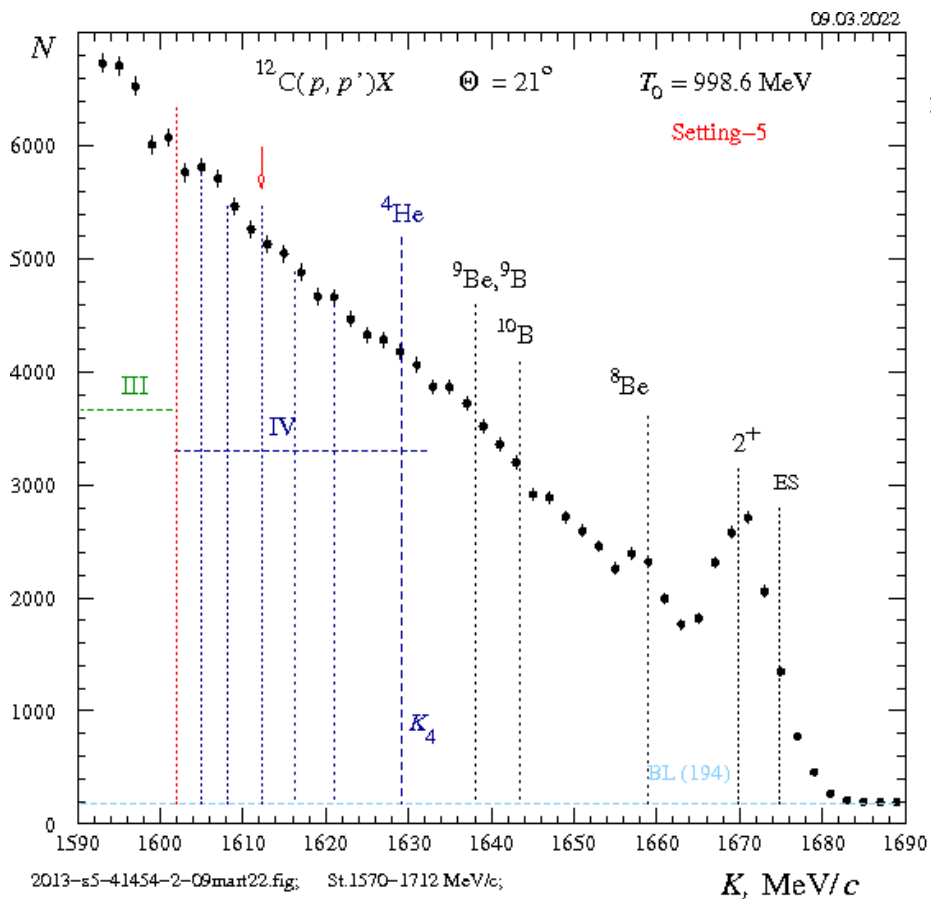


Импульсный интервал - 5, цена канала 1 МэВ/с



Импульсный интервал - 5, цена канала 2 МэВ/с

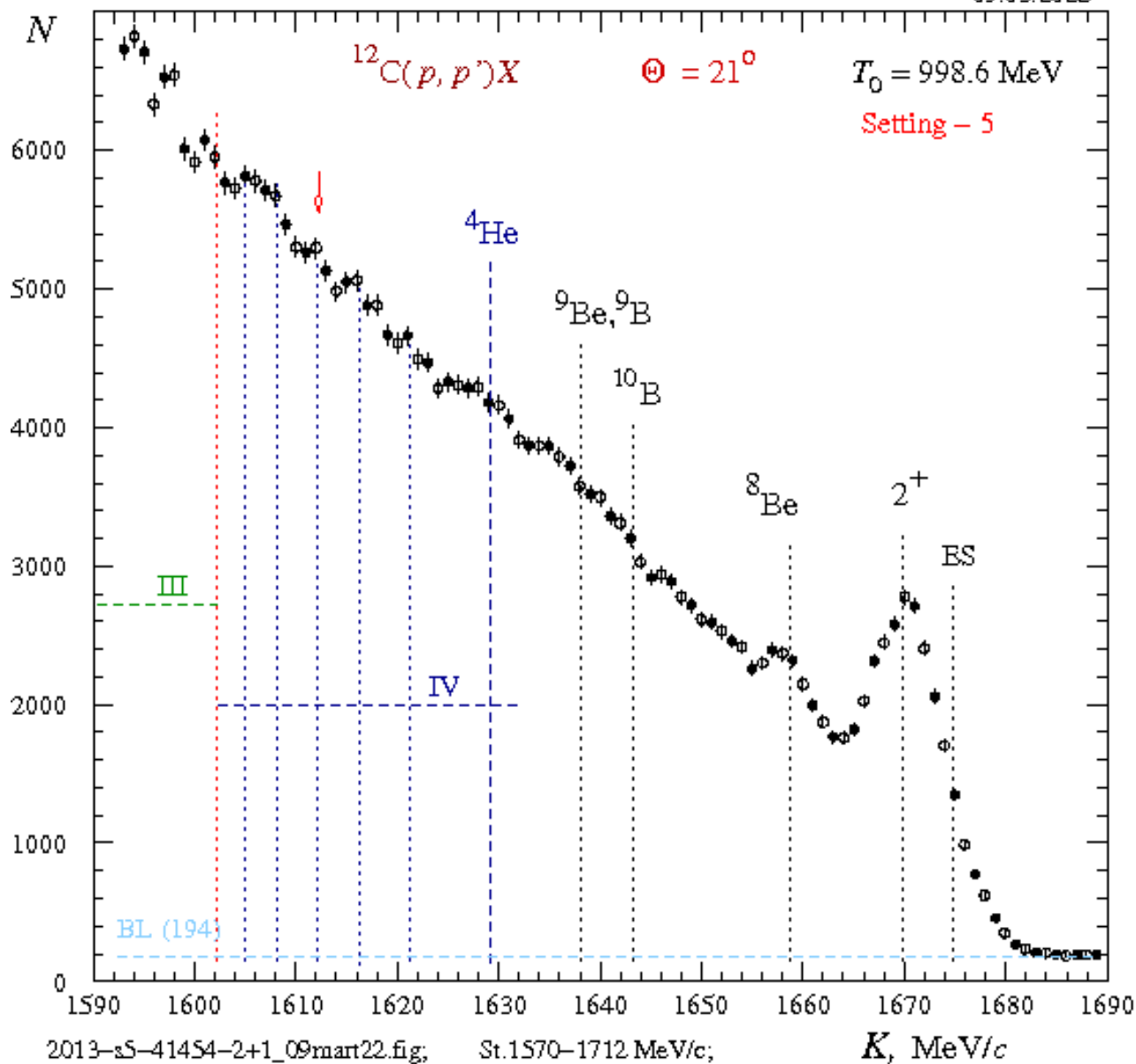
# Спектры протонов, рассеянных под углом $21^\circ$ в импульсном интервале - 5 с шириной канала 2 и 3 МэВ/с



Импульсный интервал – 5, цена канала 2 МэВ/с

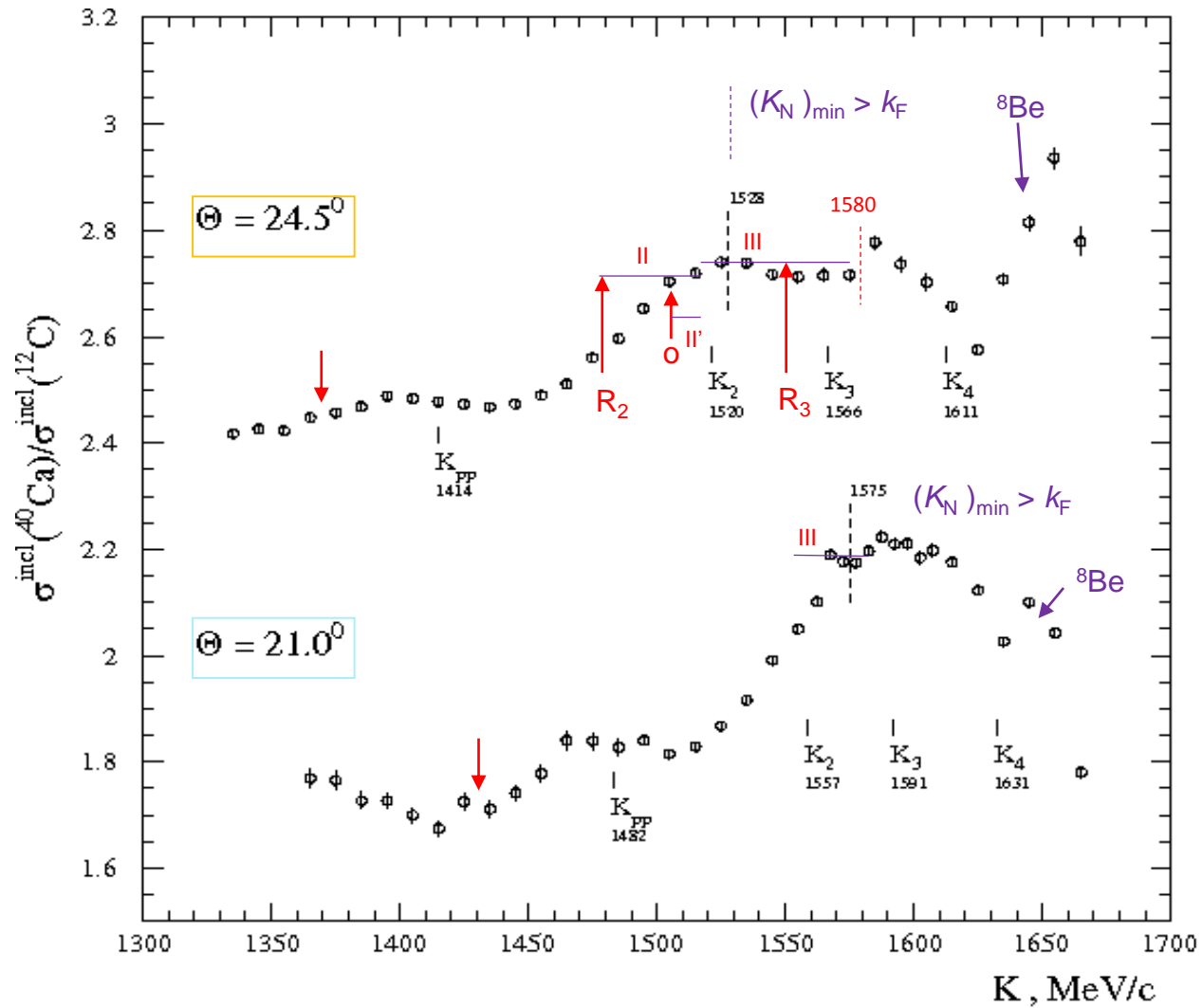
Импульсный интервал – 5, цена канала 3 МэВ/с

09.03.2022



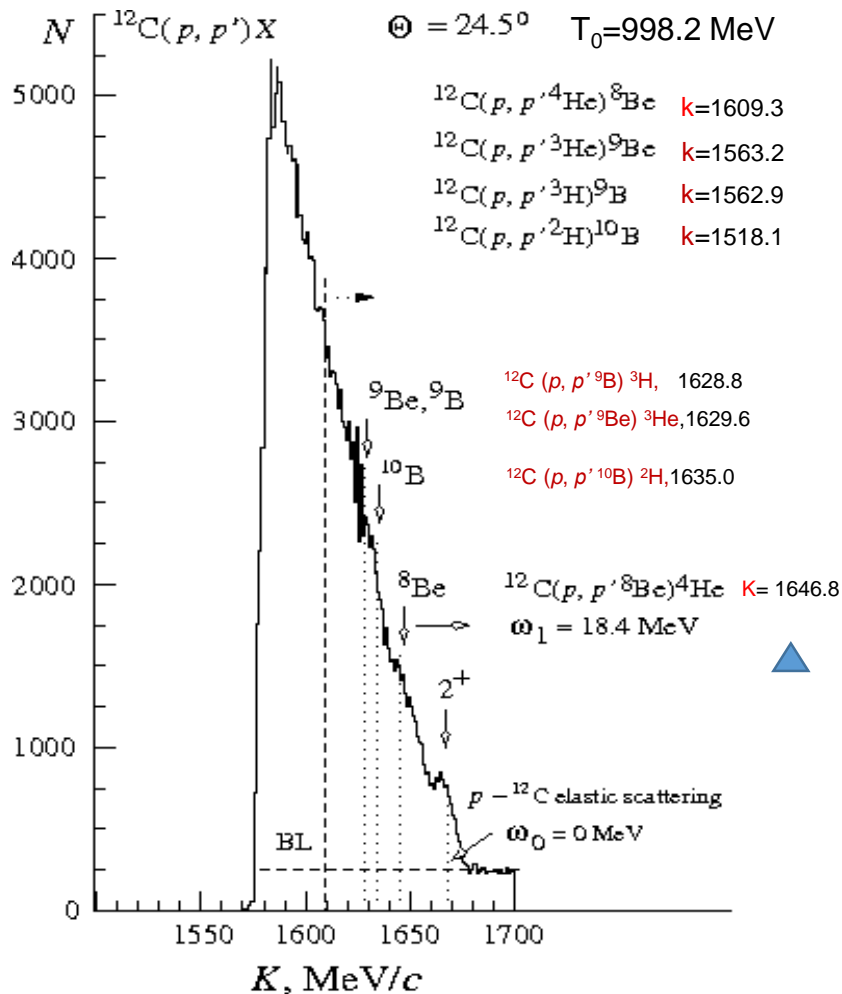
Спасибо за внимание

Отношение дифференциальных сечений рассеяния на ядрах  $^{40}\text{Ca}$  и  $^{12}\text{C}$  под углами  $24.5^\circ$  и  $21^\circ$



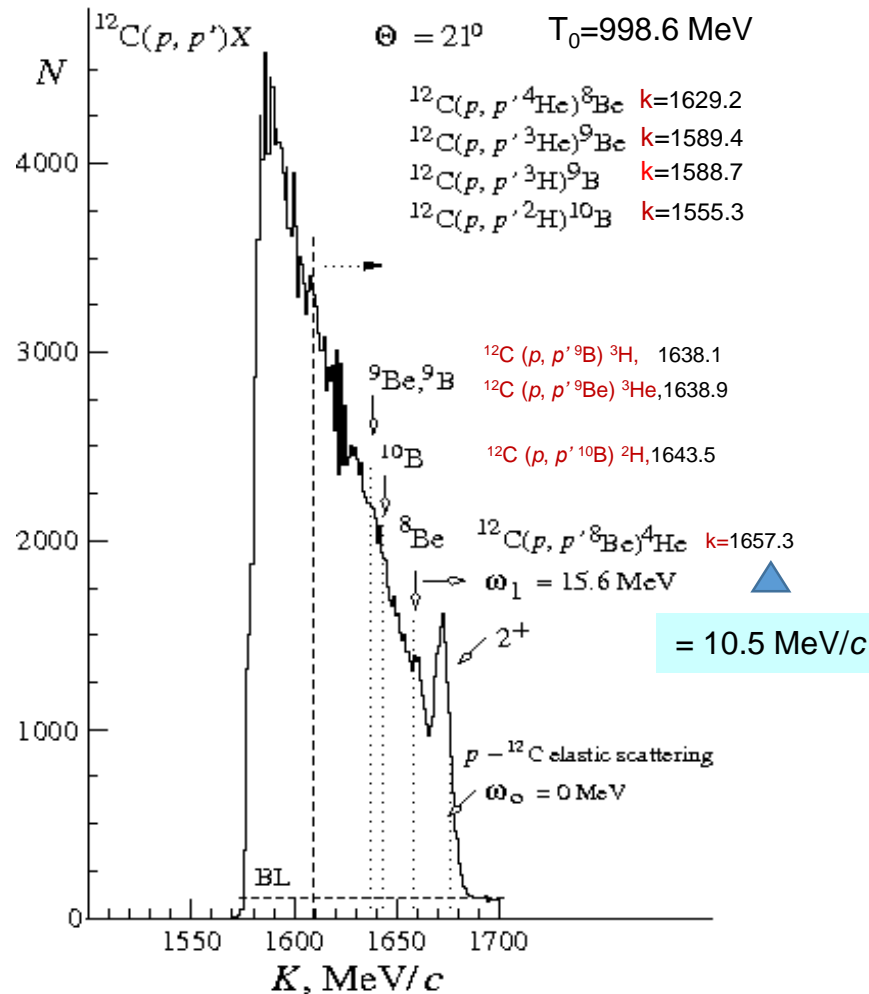
Импульсные спектры вторичных протонов в инклюзивной реакции ( $p, p'$ ) с ядром  $^{12}\text{C}$ , измеренные при углах рассеяния  $24.5^\circ$  и  $21^\circ$ .

O.V. Miklukho et al., arXiv:2102.04109v1 [nucl-ex] 8 Feb 2021



$1^+$   $^{12}\text{C}(p, p')^{12}\text{C}^*$ ,  $k=1651.1$  MeV/c

$2^+$   $^{12}\text{C}(p, p')^{12}\text{C}^*$ ,  $k=1663$  MeV/c; ES:  $k=1667.9$  MeV/c



$2^+$   $^{12}\text{C}(p, p')^{12}\text{C}^*$ ,  $k=1670.2$  MeV/c; ES:  $k=1675.1$  MeV/c

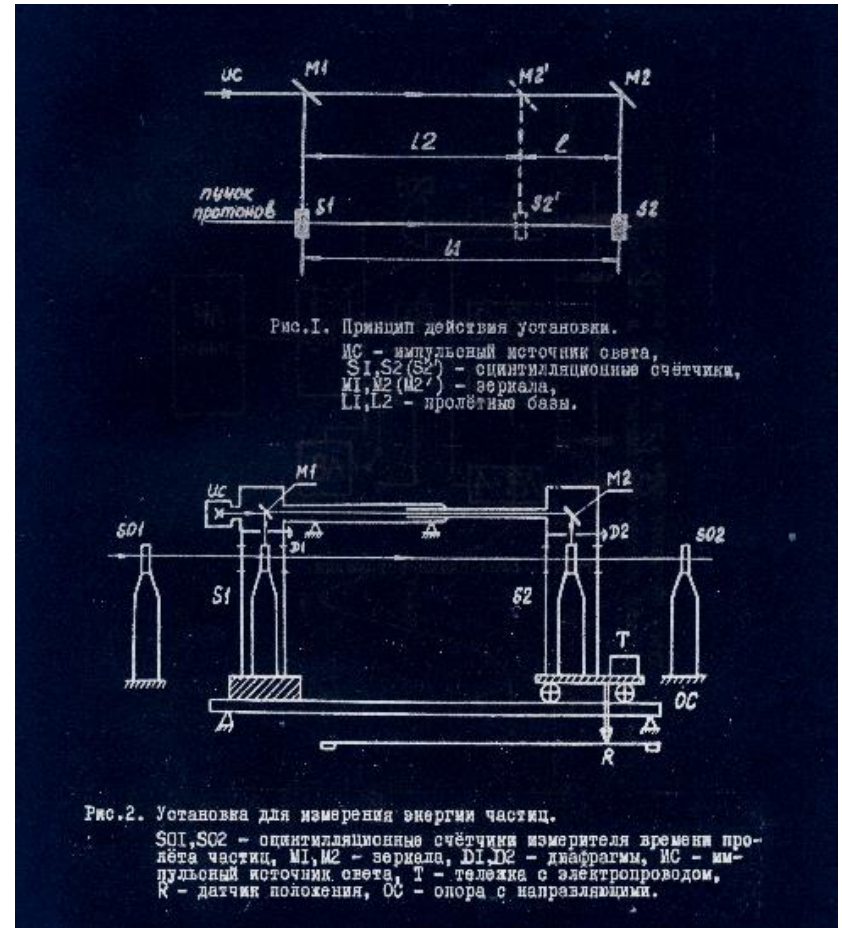
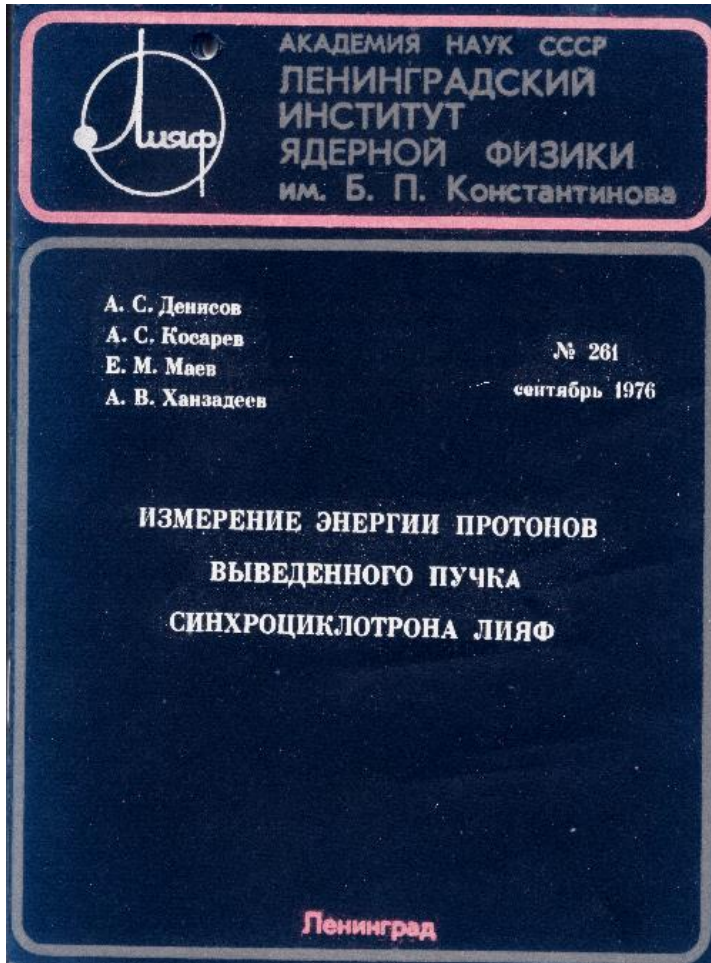
$1^+$   $^{12}\text{C}(p, p')^{12}\text{C}^*$ ,  $k=1658.2$  MeV/c = 7.1 MeV/c



Препринт – ЛИЯФ № 261, 1976

А.С. Денисов, А.С. Косарев, Е.М. Маев, А.В. Ханзадеев

Измерение энергии протонов выведенного пучка синхроциклотрона ЛИЯФ



$$T_{\text{beam}} = 997.5 \pm 5.0 \text{ МэВ}$$

END