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Grupo de Física Nuclear Experimental

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Precise characterization of the β^+ decay of ^{8}B to ^{8}Be

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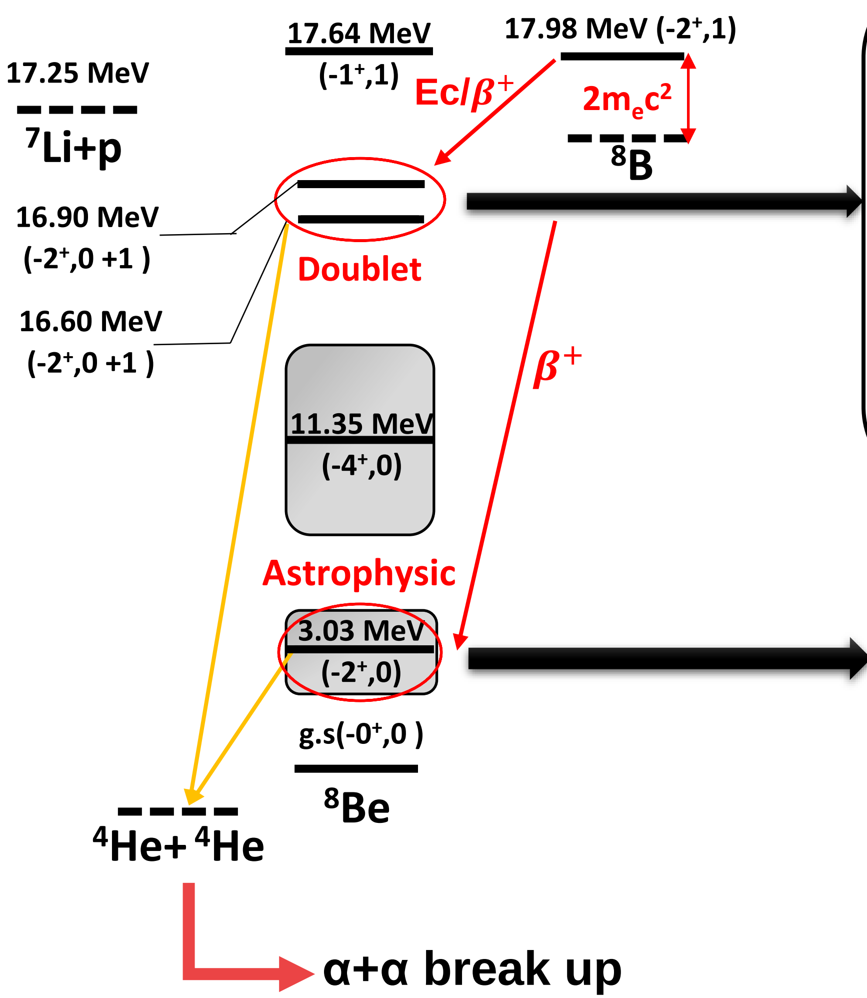
ISOLDE WORKSHOP (November-2023)

The β^{+} decay of ^{8}B to ^{8}Be is of interest for astrophysics and nuclear structure

Decay scheme



The 16.6 and 16.9 MeV levels of ^{8}Be are considered to form a fully mixed 2^{+} *isospin doublet* ($^{7}Li \otimes p$; $^{7}Be \otimes n$)

E. Matt, et al. Physi... s,
9(2):17...

...nD Thesis
(UCM, De... ment of Physics, Sep. 2020)

Main Focus

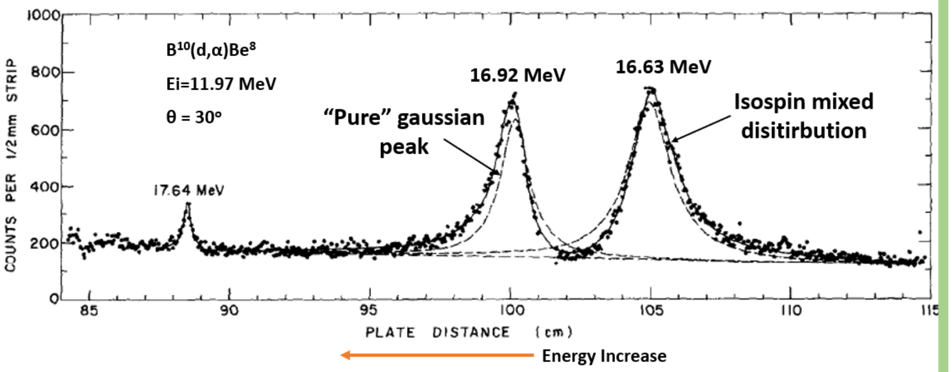
Source of high-energy solar neutrinos above 2 MeV

Main contributor to what was known as the *"solar neutrino problem"*

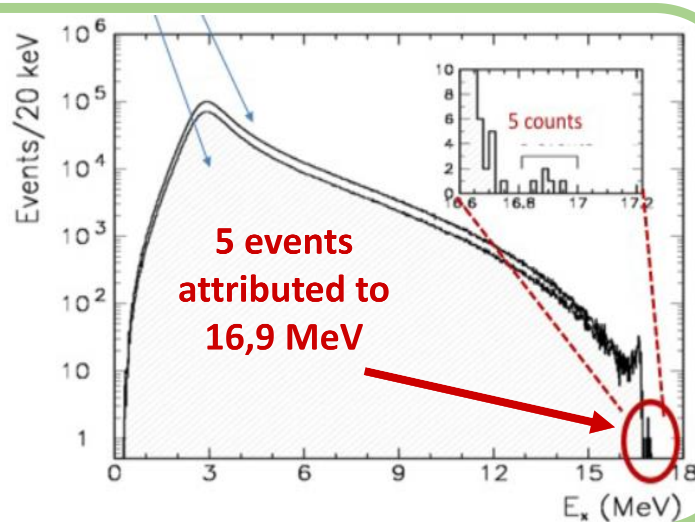
JYFL08

O Kirsebom. Phys. Rev. C, 83(6):065802–065822, 2011.

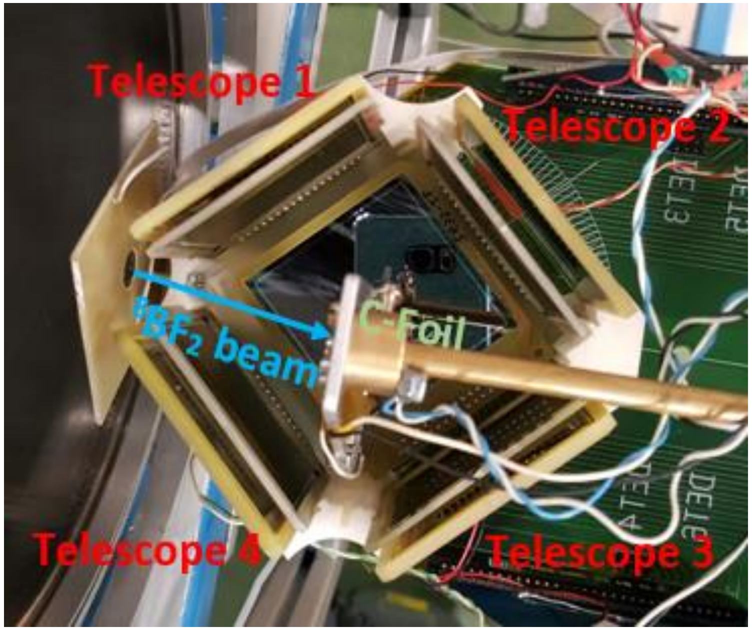
- ✓ The 16,6 MeV and 16,9 MeV have been observed through reaction experiments.
- ✓ The line shape can only be explained by assuming an equal isospin mixture.(W.D. Callender and C.P.Brown, Physical Review 2 (1970))
- ✓ Isospin mixture can be determined through the Fermi (F) and Gamow-Teller (GT) feeding to the levels.
- ✓ The β^+ decay is sensible to B_F and B_{GT}, but has a problem: statistics.



- The 3 MeV level takes most of the β-feeding, (>88%).
- 16,6 MeV : observed by several groups in EC/β^+-decay studies (*E. Matt et al., Physics Letters 9 (1964) 174. +C.P. Browne et al., Physics letters 23 (1966) 371*).
- 16,9 MeV : first hinted at the JYFL08 experiment (*O. Kirsebom et al., Phys. Rev. C 83 (2011) 065802.*),



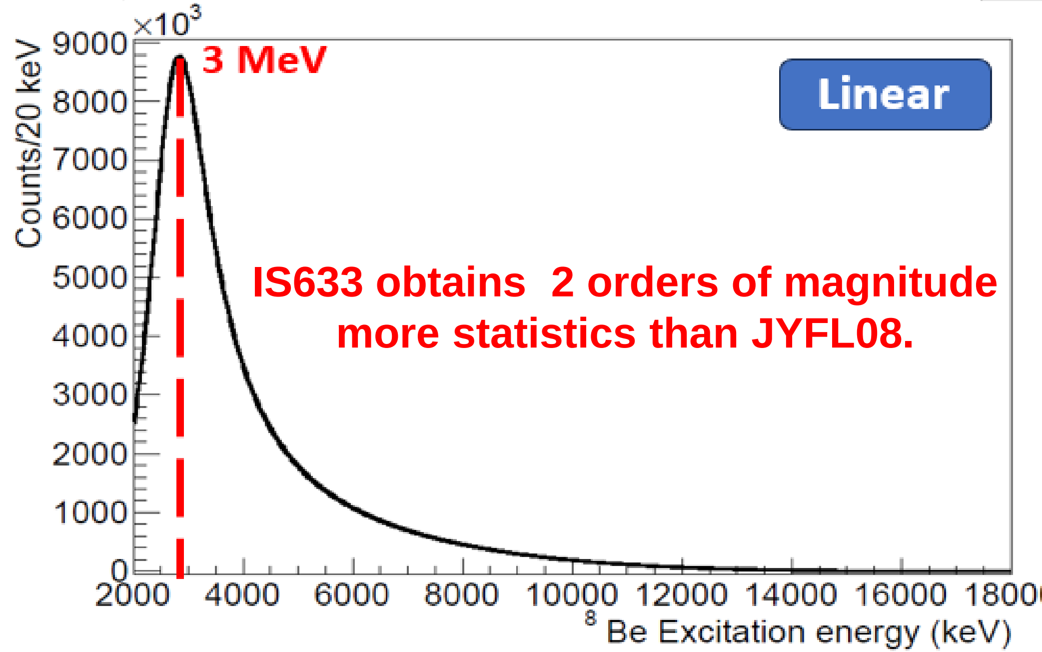
Experiment IS633 was designed to improve on the previous result

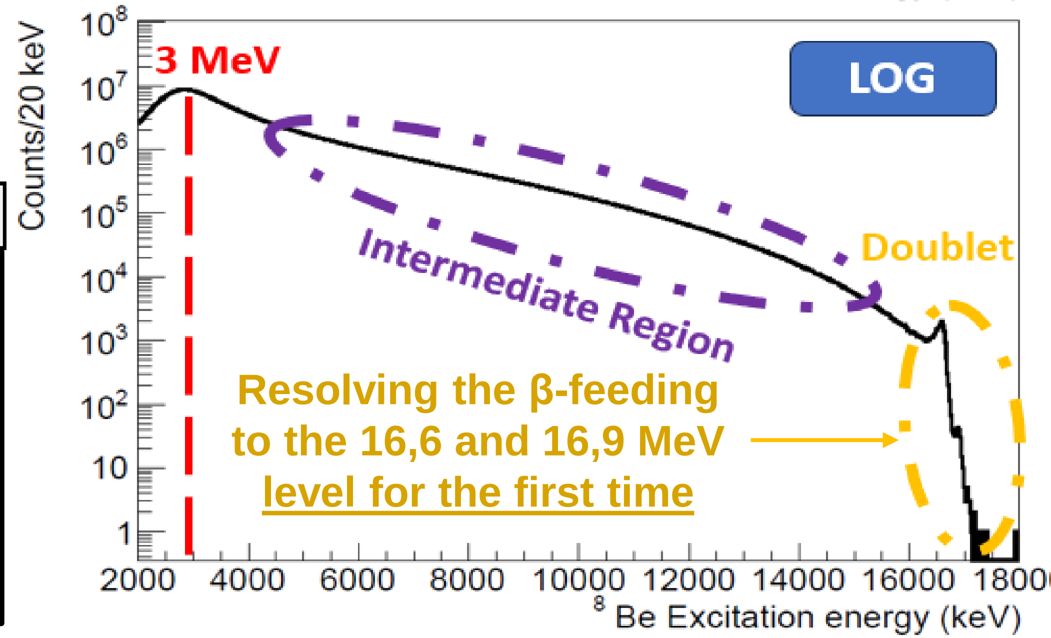


- 4 Si △E-E **telescopes** DSSD + PAD
- stop α: 1-9 MeV -- 60μm (U6 & U2)
- stop α: 1-7 MeV -- 40μm-- 40μm (U3 & U4)
- (low β-response)

Our experiment follows a four-step technique

1. **^{8}B nucleus is implanted in a ^{12}C foil**
2. **The β^+ decay of ^{8}B ($T_{1/2} = 771.17(94)$ ms) populates states of ^{8}Be**
3. **^{8}Be is unbound → α–α break up**
4. **Reconstruction of the $\alpha-\alpha$ coincidence spectrum through a system of four telescopes**





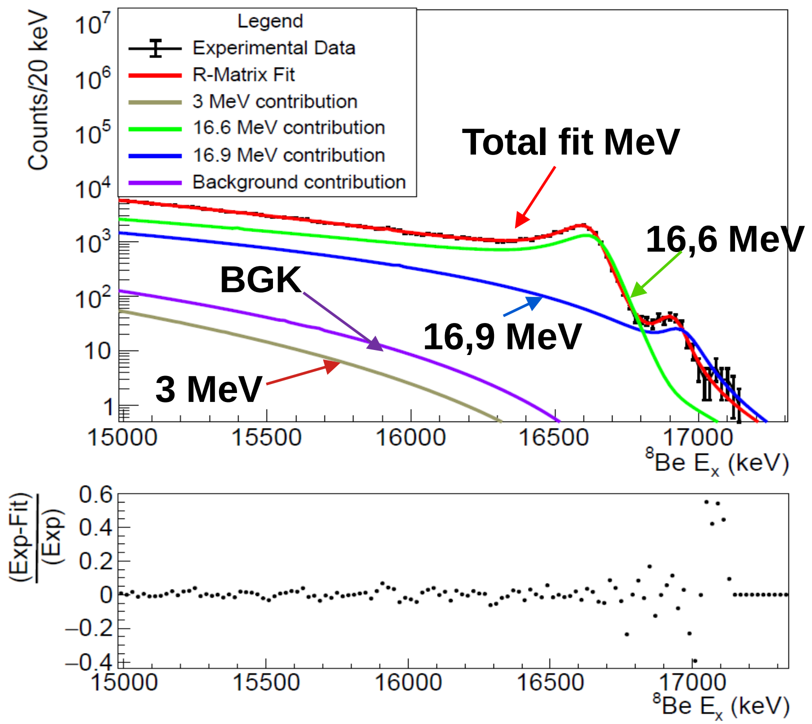
Our objective is to extract B_F B_{GT} and Γ from the spectrum.

Levels fed through β^+/EC are to broad to be fitted with a simple function (Landau, Gauss, …)

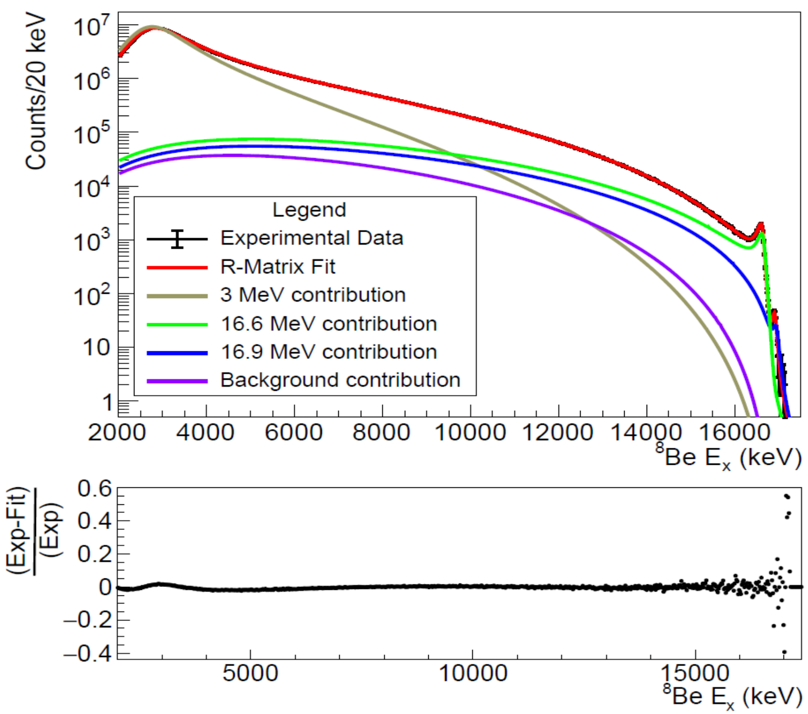
Instead a 4 level R-Matrix algorithm was used $R_{c'c} = \sum_\lambda \frac{\gamma_{\lambda c'}\gamma_{\lambda c}}{E_\lambda - E}$

- 3 MeV → Dominant
- 16,6 MeV, 16,9 MeV → Main decay
- BKG → Level tails

Local 2⁺ doublet fit



Global fit



The contribution of the broad 3 MeV state does not influence in the region of the 2⁺ doublet.

The global fit includes the contributions of the 3 MeV and Intermediate region.

There is a **discrepancy** between the **Decay Width ($\Gamma_{\alpha\alpha}$) obtained through our R-Matrix** and those of the **adopted published values [Tilley (2004)]**

We have performed **two types of cross-checks** to find the reason for this discrepancy

Parameters		Tilley (2004))	Global Fit	Local 2+ Fit
r_0 (fm)		1.35	1.35	1.35
2_0^+	E(keV)	3030 (30)	3036	
	B_F		0	
	B_{GT}		0,011485	
	$\Gamma_{\alpha\alpha}$(keV)	1513(15)	1883,1	
2_1^+	E(keV)	16626(3)	16623	16632(70)
	B_F		1,282	0.32
	B_{GT}		0,572277	1.17
	$\Gamma_{\alpha\alpha}$(keV)	108.1(5)	114,67	129.5
2_2^+	E(keV)	16922	16913	16919(20)
	B_F		0,39353	1.44(79)
	B_{GT}		1,046	0.35(49)
	$\Gamma_{\alpha\alpha}$(keV)	74.0(4)	99,179	108(13)
2_{BKG}^+	E(keV)		37000	
	B_F		0	
	B_{GT}		0,093286	
	$\Gamma_{\alpha\alpha}$(keV)		12116	

Beyond Wigner limit

Consistency tests of our fits

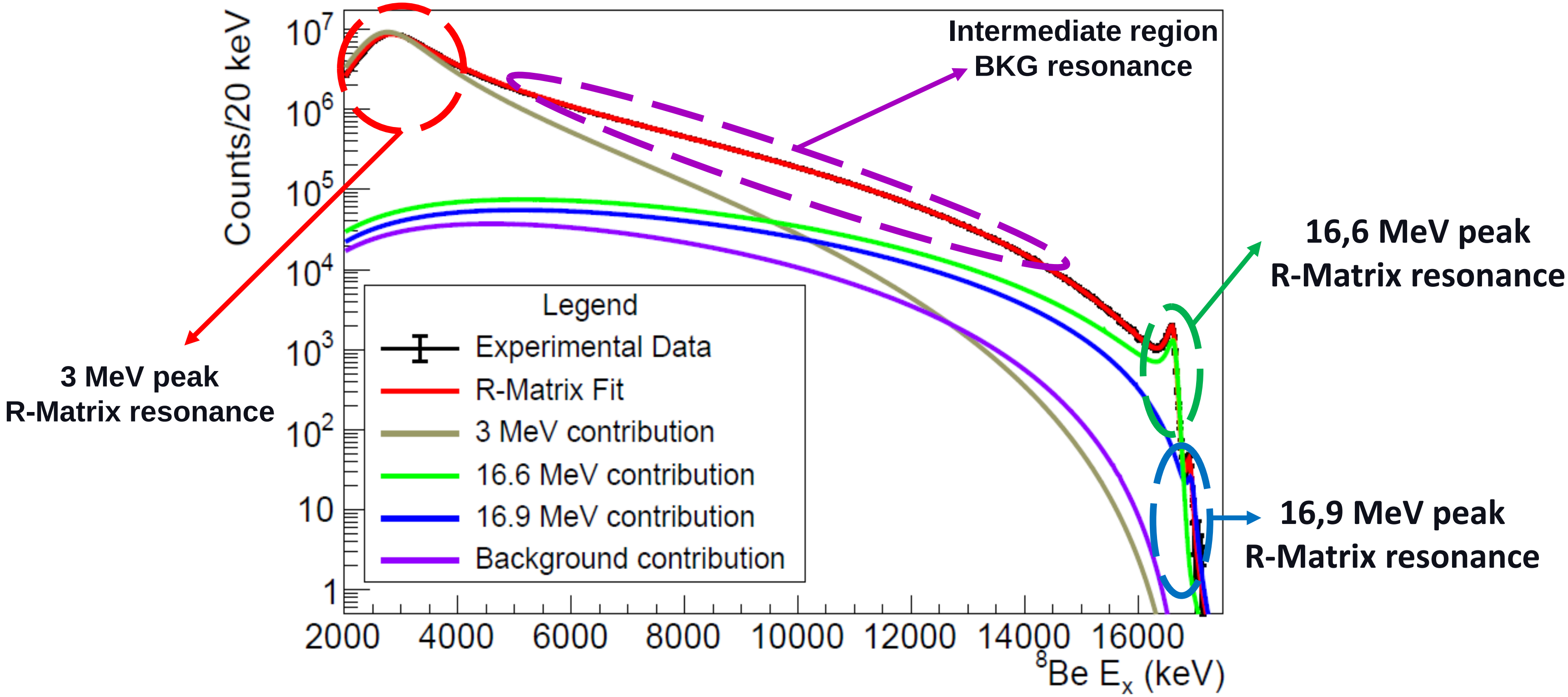
All consistency checks indicate that the R-Matrix converges to $\Gamma_{\alpha\alpha}$(3 keV)~1890

Local fits

Local fits to the 3MeV region produce results in agreement with published values.

Local fits produce results in agreement with the literature → global fits don´t

The problem appears in the intermediate region (BKG level) → distortion of the 3 MeV resonance



- **R-Matrix decomposes the spectrum in resonant levels.**
- **For an excitation to continuum, a virtual resonance must be used.**
- **This only works if the continuum is close to the resonant levels.**
- **But if that is not the case R-Matrix will not work.**

R-Matrix can not fit the whole spectrum due to the intermediate (not resonant) region.

Assuming 16,9 and 16,6 can be expressed as a mixture of two states with well defined isospin.

$$|16{,}6\rangle = \alpha|T=0\rangle + \beta|T=1\rangle$$

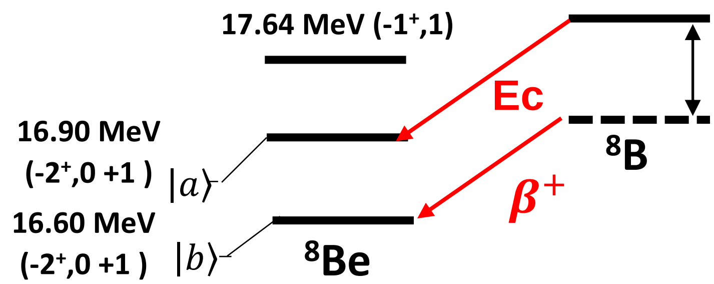
$$|16{,}9\rangle = \beta|T=0\rangle - \alpha|T=1\rangle$$

$$\alpha^2 + \beta^2 = 1$$

mixing coeficients

If the states are completely mixed : ${\alpha^2}/{\beta^2} = 1$

$M_{0,GT} >>> M_{1,GT} = 0$ Asumed due to S.M calculations



How can we find α^2/β^2 ?

Method 1

$$\frac{\alpha^2}{\beta^2} = \frac{B_{16.9,F}}{B_{16.6,F}}$$

Method 2

$$\frac{\alpha^2}{\beta^2} = \frac{B_{16.6,GT}}{B_{16.9,GT}}$$

Method 3

$$\alpha^2 = \frac{\Gamma_{16.6}}{\Gamma_0} = \frac{\Gamma_{16.6}}{\Gamma_{16.6} + \Gamma_{16.9}}$$

$$\beta^2 = \frac{\Gamma_{16.9}}{\Gamma_0} = \frac{\Gamma_{16.9}}{\Gamma_{16.6} + \Gamma_{16.9}}$$

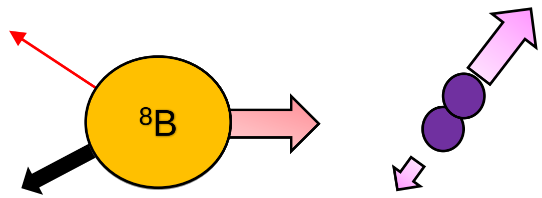
	Isospin coefficient ratio (α^2/β^2)	
Method	Local 2^+ doublet Fit	Global Fit
B_F	5(12)	1,71(48)
B_{GT}	3(5)	1,73(42)
Γ	1,20(14)	1,22(13)

The results form the Fermi and GT feeding are inconsistent between local and global fits.

The Isospin coefficient ratio obtained from the decay width is in accordance with expectations.

An alternative method has been used : the β-Recoil

- The ^{8}B suffers a β^{+} decay emiting an e^{+} and ν_e
- Due to momentum conservation the ^{8}Be has a recoil
- This additional momentum is transferred (not always equally) to the emmited α particles



The β-recoil distribution is dependent on the ^{8}Be energy.
(*D. Schardt and K. Riisager, Z. Phys. A 345 (1997)*)

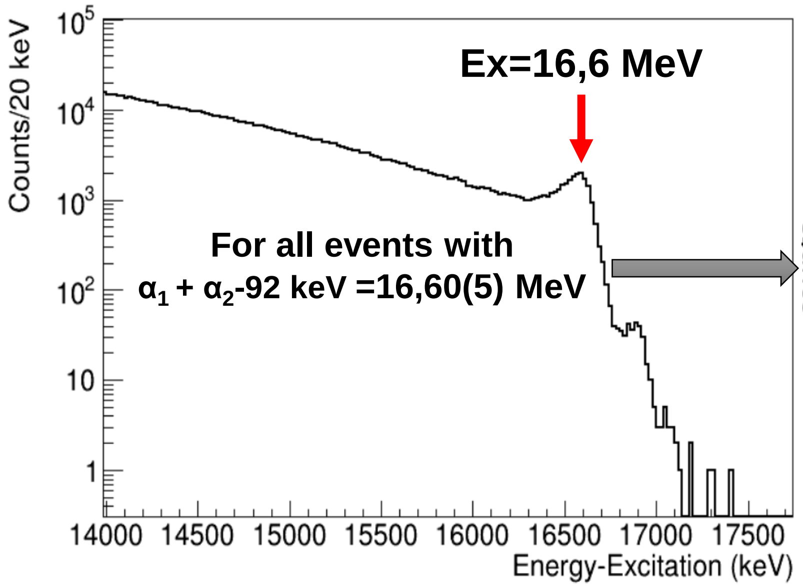
$$\underbrace{w(t)}_{\text{Recoil Distribution}} = \underbrace{N_\beta \int_{W_{min}}^{W_o} \underbrace{F(Z,W)}_{\text{Fermi function}} \frac{p_\beta}{2k}\left[(c_1 - c_2)W(W_o - W) + \underbrace{A}_{\text{Asymmetry parameter}} \frac{c_2^2 - c_1^2}{2} p_\beta \frac{t}{k} - A\frac{c_2^3 - c_1^3}{3} p_\beta^2\right] dW}_{\beta\text{-component}} + \underbrace{N_{EC}\frac{f_{BK} + f_{BL1}}{2T_{max}}}_{\text{Ec-component}}$$

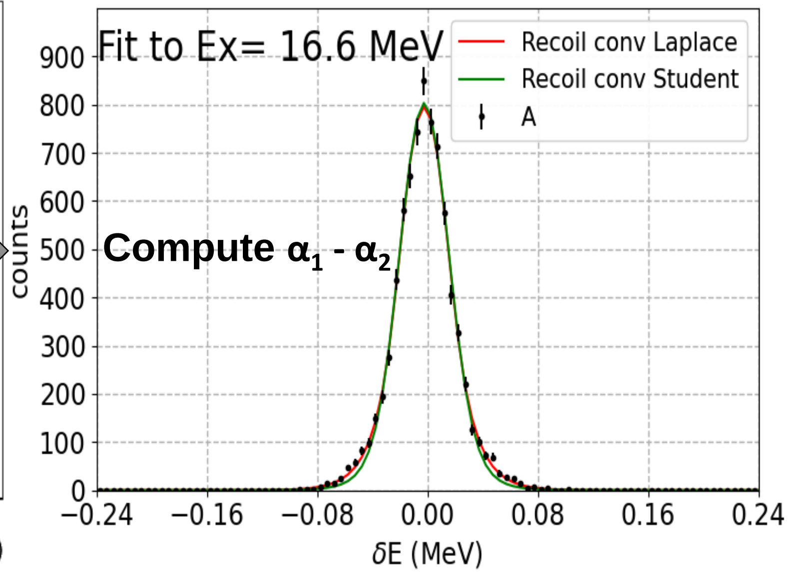
For $^{8}B \rightarrow {}^{8}Be$ the asymmetry parameter is directly related with B_F and B_{GT}

$$\frac{B_F}{B_{GT}}\left(\frac{g_v^2}{g_A^2}\right) = -\frac{(A+1)}{(A-1)} \quad \begin{cases} A=1 \rightarrow B_{GT}=0 \\ A=0 \rightarrow B_F=B_{GT} \\ A=-1 \rightarrow B_F=0 \end{cases}$$

For a fixed value of Ex (i.e $\alpha_1 + \alpha_2$-92 keV) the β-recoil spectrum can be used to obtain B_F and B_{GT}

The β-Recoil spectrum is equivalent to the $\alpha_1 - \alpha_2$ spectrum

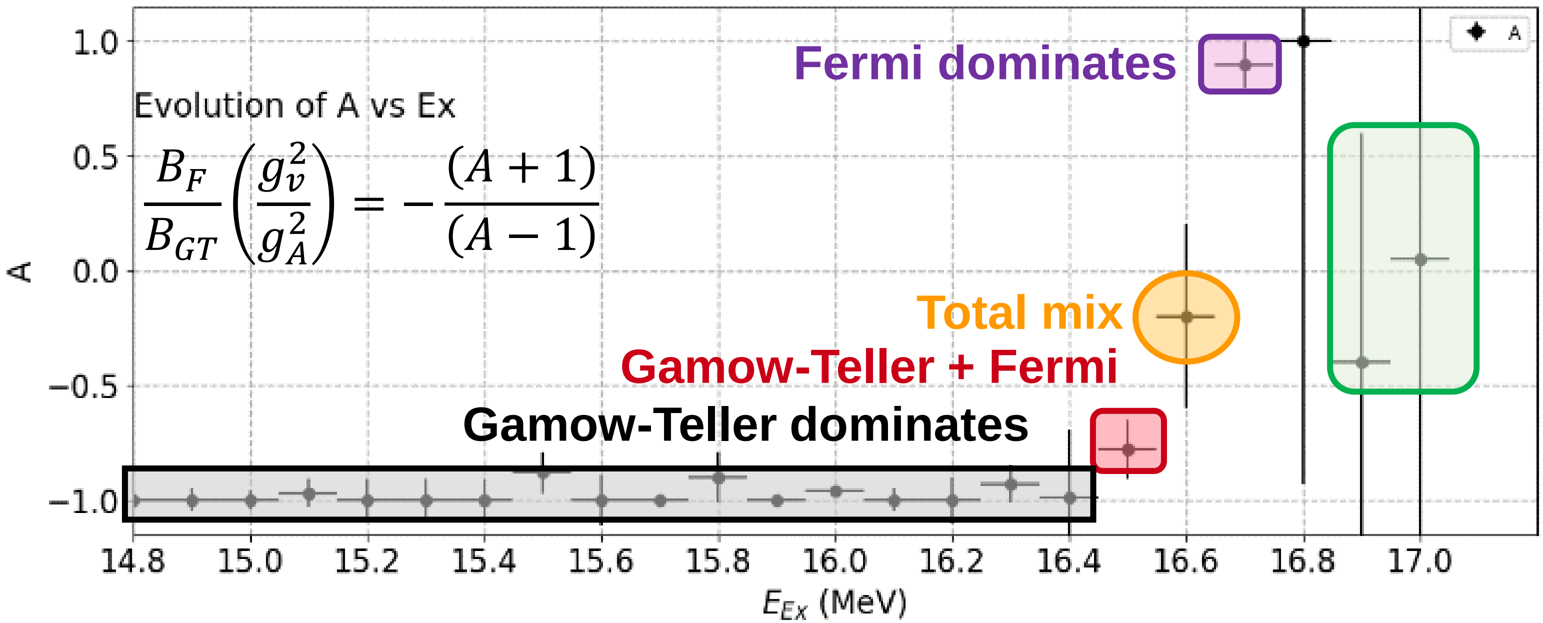




The $\alpha_1 - \alpha_2$ spectrum is fitted using the recoil function folded with a response function (Laplace or T-student) with A as a fit parameter

To get a satisfactory fit; the N_β and N_{EC} parameters must be theoretically computed and fixed.

The Evolution of A can be used to deduce the evolution of B_F and B_{GT}



1) From 3 MeV to 16,2 MeV Gamow-Teller dominates the decay. (A=-1,00(1)-> B_F=0 ; B_{GT} =1).

2) Penetrating the doublet region, the influence of the Fermi contribution becomes noticeable.

3) In the 16,60 (5) MeV region A=0,10(8)-> B_F= B_{GT} =0.5, there is a total Fermi and GT coexistence

4) Between the resonances, the Fermi contribution dominates (A=1,0(4)-> B_F =1 ; B_{GT} =0)

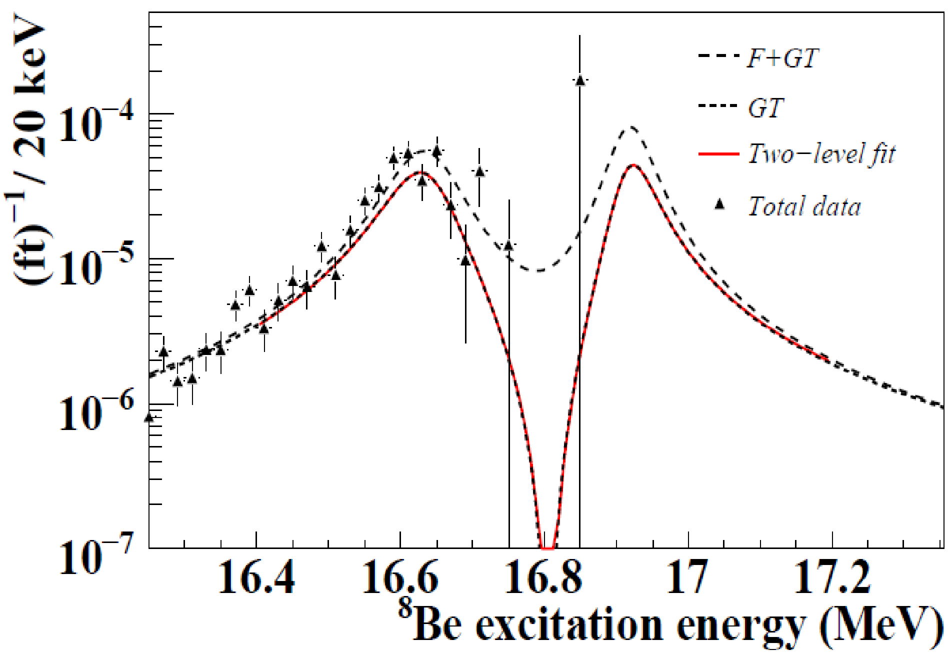
5) In 16,90(5) MeV there is a very high uncertainty!!

The Gamow Teller and Fermi contributions can be distinguish experimentally (for the first time!!) and three observations can be made

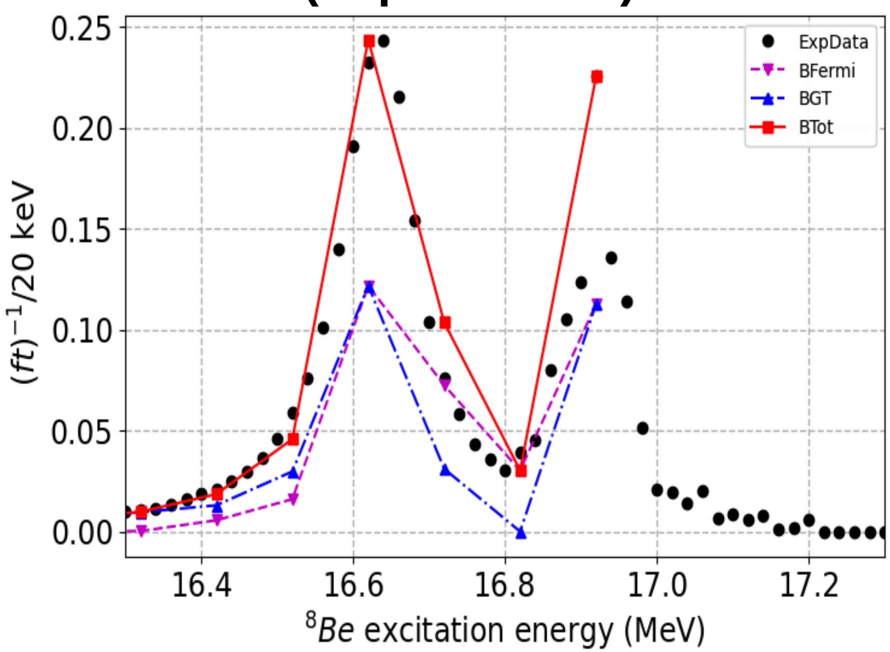
G-T dominates up to 16,3 MeV;
F and GT coexist in the resonances;
Fermi dominates between resonances

This result is consistent with β decay calculations (*S.Hyldegaard, PhD thesis. Aarhus University (2010)*) and hinted in reaction experiments (*W.D. Callender and C.P.Brown, Physical Review 2 (1970)*)

(S.Hyldegaard-JYFL08)



(Experimental)



- IS633 is the first experiment that enables to study the 2^+ doublet of by β/EC where Fermi and Gamow-Teller contributions could be separated.

- R-matrix local fits to the ^{8}Be excitation spectrum to either low or high energy-region produces good results (Comparison with JYFL08 experiment assure that IS633 is consistent with previous results and no extra effect from high statistics were found).

- A R-matrix fit to the full ^{8}Be excitation spectrum produces Γ values for the 3 MeV state that differs from the the literature (This could be due to a very broad intermediate level or caused by coupling to the "non-resonant" continuum).

- The uncertainties obtained for the B_F and B_{GT} were rather large.

- An additional analysis method was used employing the β-Recoil spectrum for each energy bin.

- The β-Recoil analysis confirms that GT transitions dominates up to 16,3 MeV ^{8}Be excitation energy; F and GT contributions coexist in the resonances and the Fermi component dominates between resonances (first experimental confirmation) .

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Special thanks to the members of the MAGISOL/IS633 collaboration

S Viñals[1], M J G Borge[1], O Tengblad[1], E Nácher[2], J Benito[3], P Figuera[4], L M Fraile[3], H O U Fynbo[5], A Gad[5], J Jensen[5], B Jonson[6], R Lica[7], I Marroquín[1], M Munch[5], T Nilsson[6], J D Ovejas[1], A Perea[1], K Riisager[5], S Smain[8] and C Sotty[7]

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And you for your attention !!!
Questions?

The β-recoil distribution is dependent on the ^{8}Be energy. (*D. Schardt and K. Riisager, Z. Phys. A 345 (1997)*)

$$\underbrace{w(t)}_{\text{Recoil Distribution}} = N_\beta \int_{W_{min}}^{W_o} \underbrace{F(Z,W)}_{\text{Fermi function}} \frac{p_\beta}{2k}\left[(c_1-c_2)W(W_o-W) - \underbrace{A}_{\text{Asymmetry parameter}}\frac{c_2^2-c_1^2}{2}p_\beta\frac{t}{k} - A\frac{c_2^3-c_1^3}{3}p_\beta^2\right]dW + N_{EC}\frac{f_{BK}+f_{BL1}}{2T_{max}}$$

β-component

Ec-component

$$W_{min} = \begin{cases} \dfrac{m^2+(W_o+t/k)^2}{2(W_o+t/k)} & \text{for } \dfrac{t}{k} < -(W_o-m) \\ m & \text{for } \left|\dfrac{t}{k}\right| \le (W_o-m) \\ \dfrac{m^2+(W_o-t/k)^2}{2(W_o-t/k)} & \text{for } \dfrac{t}{k} > (W_o-m) \end{cases}$$

$$c_1 = min\left\{\cos\psi_{max}, \max\left[\cos\psi_{min}, \frac{W-W_o-t/k}{p_\beta}\right]\right\}$$

$$c_2 = max\left\{\cos\psi_{min}, \min\left[\cos\psi_{max}, \frac{W-W_o-t/k}{p_\beta}\right]\right\}$$

$$A = \frac{g_v^2 B_F - (1/3 + 2/30\,\underbrace{\tau\theta}_{\text{Angular Momentum}})g_A^2 B_{GT}}{g_v^2 B_F + g_A^2 B_{GT}}$$

$$\theta = \begin{cases} -\dfrac{J'+1}{2J'-1} & J' = J+1 \\ 1 & J' = J \\ -\dfrac{J'}{2J'+3} & J' = J-1 \end{cases}$$

$$\tau = 10\left[\frac{L(L+1)(2L+1)}{(2L-1)(2L+3)}\right]^{1/2}\left[\frac{(2J'-1)(2J'+1)(2J'+3)}{J'(J'+1)}\right]^{1/2} W(2;J'LJ''J'L)$$

For ^{8}B $\xrightarrow{+\beta}$ ^{8}Be ΔJ=0 and ΔL=2 therefore $\tau\theta$ =10 and B_F and B_{GT} can be deduced from A

$$A = \frac{g_v^2 B_F - (1/3 + 2/30\,\tau\theta)g_A^2 B_{GT}}{g_v^2 B_F + g_A^2 B_{GT}} \Rightarrow \frac{B_F}{B_{GT}}\left(\frac{g_v^2}{g_A^2}\right) = -\frac{(A+1)}{(A-1)}$$

- A=1 -> B_{GT}=0
- A=0 -> B_F=B_{GT}
- A=-1 -> B_F=0

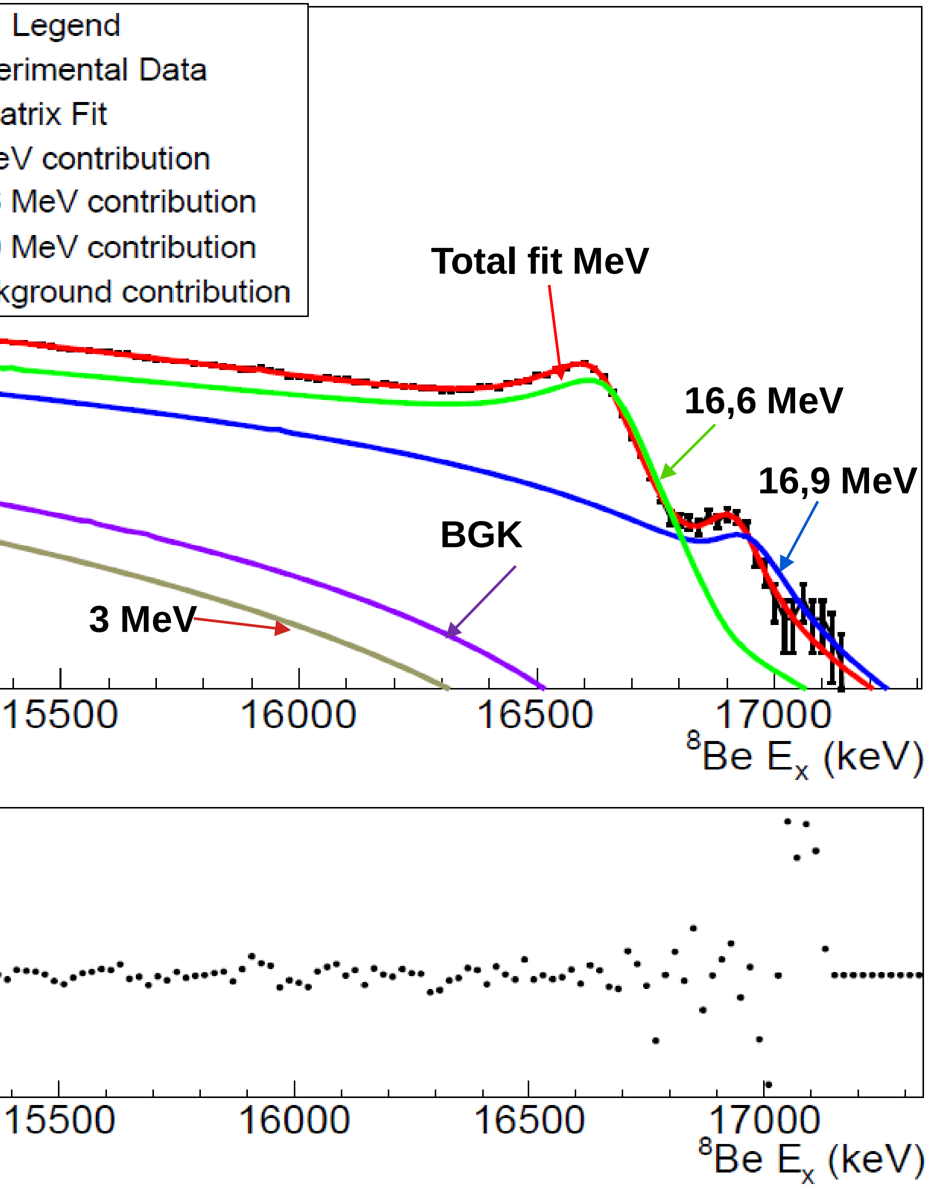
A series of cross-checks were performed to ensure that that results are consistent and do not suffer from systematic errors such as summing or piled-up.

Check I: $\Gamma_{\alpha\alpha}$ = Fixed to the literature values → **The R-Matrix does not generate good results (χ^2= 3991; $\Gamma_{\alpha\alpha}$(3 keV)= 1415.7).**

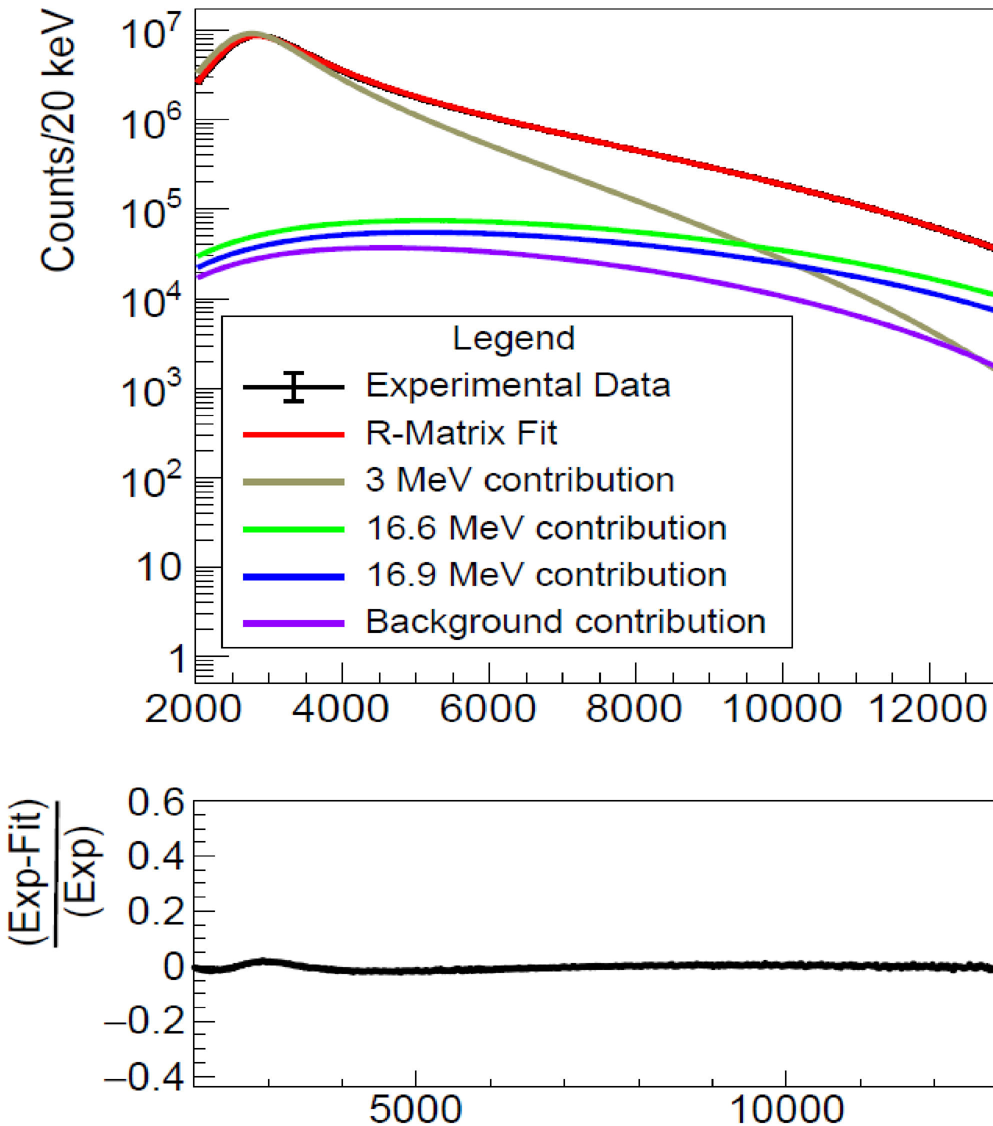
Check II: $\Gamma_{\alpha\alpha}$ = Set to the literature values (but allowed to change) → **The R-Matrix parameters converge to the same values as before. (χ^2= 14; $\Gamma_{\alpha\alpha}$(3 keV)= 1949.8)**

Check III: Set the energy of the BKG level to 37 MeV → **R-Matrix generates the best fit, the results also diverges form the literature (χ^2= 12; $\Gamma_{\alpha\alpha}$(3 keV)= 1883.1)**

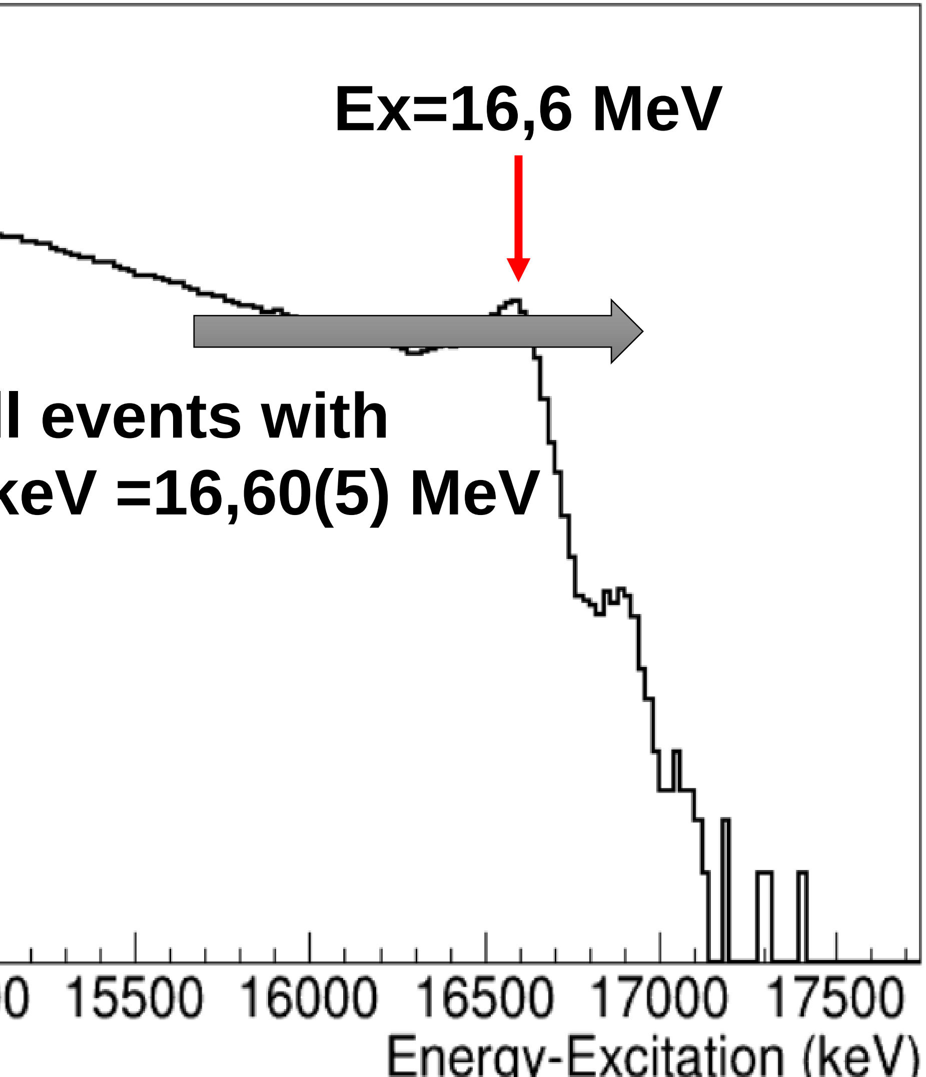
All consistency checks indicate that the R-Matrix converges to $\Gamma_{\alpha\alpha}$(3 keV)$\sim$1890

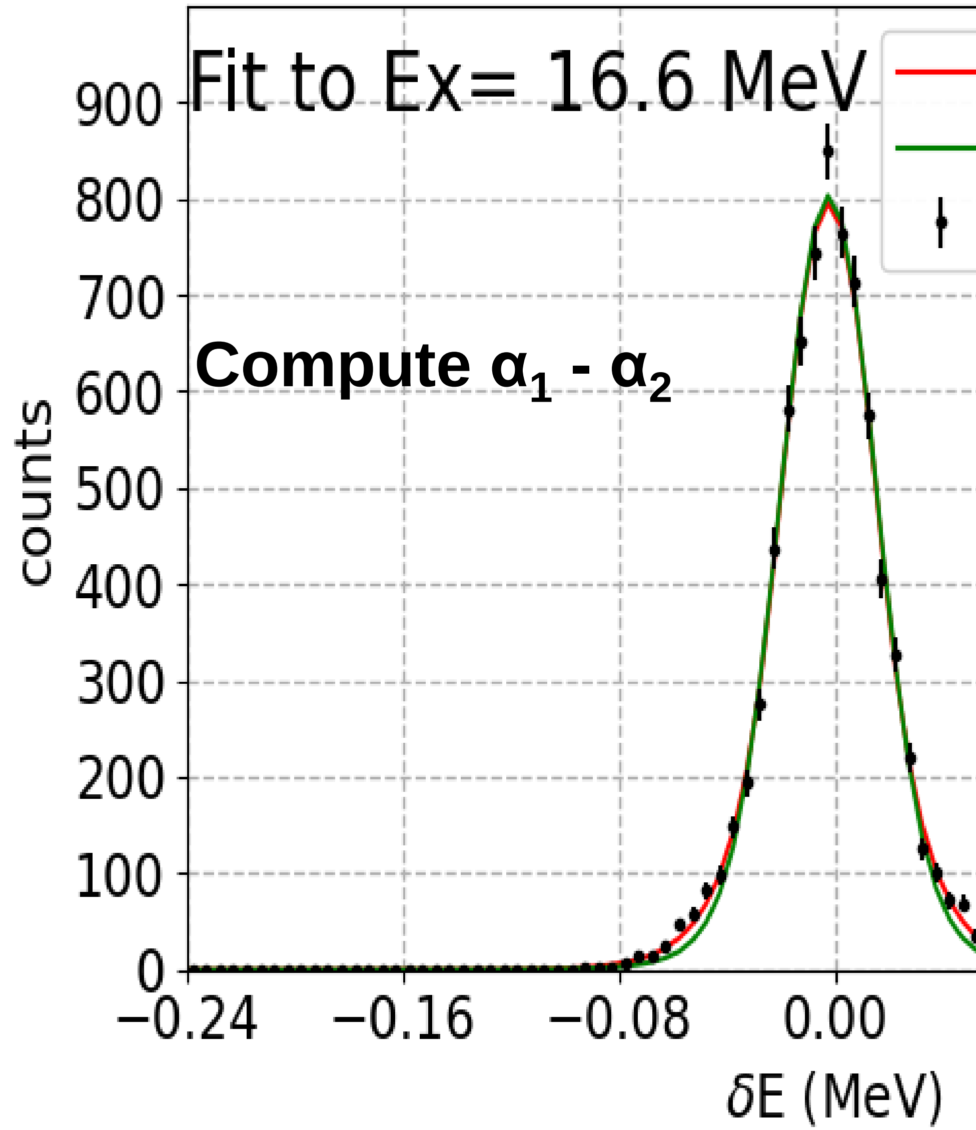


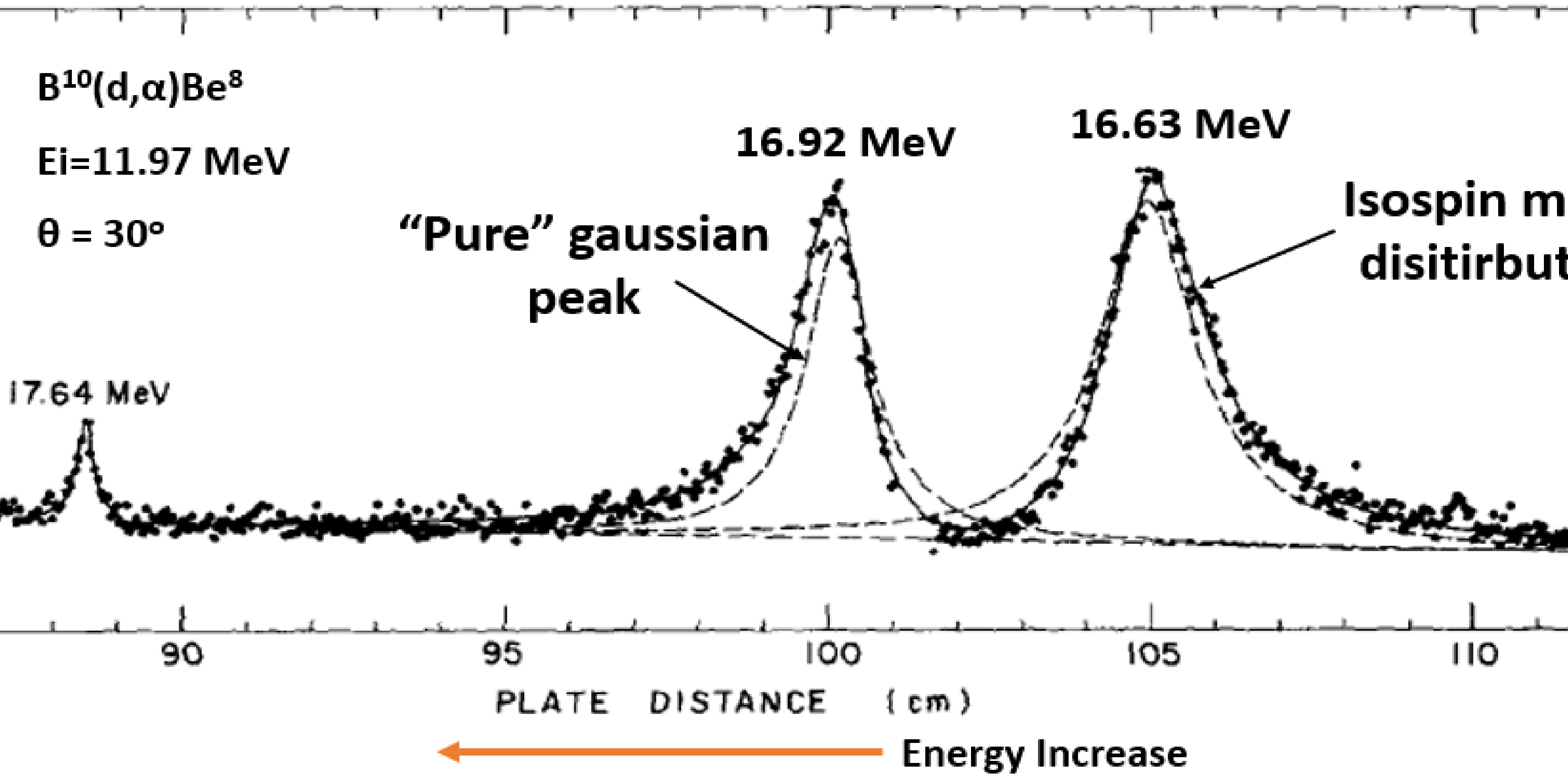
Legend
erimental Data
atrix Fit
eV contribution
MeV contribution
MeV contribution
kground contribution
Total fit MeV
16,6 MeV
16,9 MeV
BGK
3 MeV
15500
16000
16500
17000
^{8}Be E_x (keV)
15500
16000
16500
17000
^{8}Be E_x (keV)



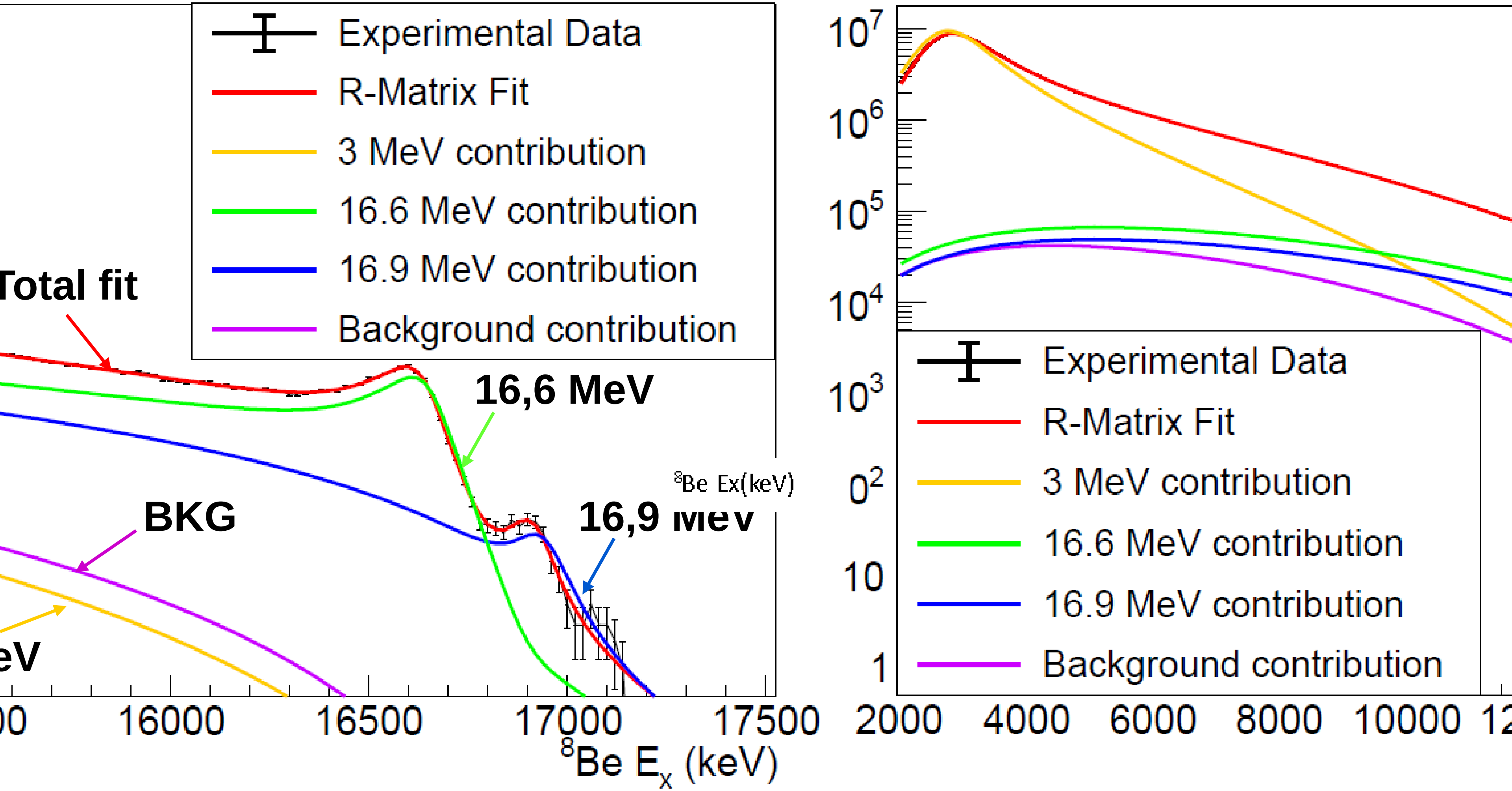
Counts/20 keV
10^7
10^6
10^5
10^4
10^3
10^2
10
1
Legend
Experimental Data
R-Matrix Fit
3 MeV contribution
16.6 MeV contribution
16.9 MeV contribution
Background contribution
2000
4000
6000
8000
10000
12000
$\frac{(\text{Exp-Fit})}{(\text{Exp})}$
0.6
0.4
0.2
0
−0.2
−0.4
5000
10000


Ex=16,6 MeV
ll events with
keV =16,60(5) MeV
0 15500 16000 16500 17000 17500
Energy-Excitation (keV)


Fit to Ex= 16.6 MeV
Compute α_1 - α_2
counts
0 100 200 300 400 500 600 700 800 900
−0.24 −0.16 −0.08 0.00
δE (MeV)



$B^{10}(d,\alpha)Be^8$
Ei=11.97 MeV
θ = 30°
16.92 MeV
16.63 MeV
"Pure" gaussian peak
17.64 MeV
90
95
100
105
110
PLATE DISTANCE (cm)
Energy Increase



Experimental Data
R-Matrix Fit
3 MeV contribution
16.6 MeV contribution
16.9 MeV contribution
Background contribution
Total fit
16,6 MeV
16,9 MeV
BKG
eV
^{8}Be Ex(keV)
16000
16500
17000
17500
^{8}Be E_x (keV)
10^7
10^6
10^5
10^4
10^3
0^2
10
1
2000
4000
6000
8000
10000