R-Matrix study of the β^+ decay of ^{8}B to the highly excited states of ^{8}Be

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Abstract. Experiment IS633 was conducted at the ISOLDE facility with the aim of studying the 2^+ isospin doublet of ^{8}Be, the only expected case of nearly equal isospin configuration mixing. The doublet was previously probed by reaction studies where the feeding does not depend on the isospin. Beta decay studies are sensitive to the isospin composition of the doublet since the Fermi and Gamow-Teller strengths are heavily dependent of isospin. In this experiment the doublet was probed through the EC/β^+ feeding from ^{8}B. A four-particle telescope setup with a C-foil in the centre was employed to stop the ^{8}B beam, the implanted nucleus would decay and populate the doublet that breaks up in two alpha particles that are detected. The statistics achieved in this experiment were two orders of magnitude higher than that of any previous experiment, enabling the first experimental observation of both contributions to the doublet.

1 Introduction

The ^{8}B nucleus is a 1-proton halo nucleus that undergoes β^+ decay and electron capture to ^{8}Be. This EC/ β^+ decay is the main source of high-energy solar neutrinos above 2 MeV and has therefore been the subject of extensive research in astrophysics, particularly regarding the so-called "solar neutrino problem" [1]. At the same time, the decay also offers a unique opportunity to investigate the structure of the 2^+ isospin doublet in ^{8}Be. This doublet, formed by two narrow levels at 16.6 and 16.9 MeV with dominant configurations of ^{7}Li+p and ^{7}Be+n, respectively, is the best-known case of fully mixed isospin states [2]. However, the proposed total isospin mixture has yet to be determined experimentally.

Within the Q-value window, Q_{EC} = 17.9798(1) MeV, the following states in ^{8}Be can be fed through allowed beta transitions as shown in Fig 1.

Primarily, the beta decay feeds a broad state at 3 MeV ($J^\pi = 2^+$, Γ=1513(13) keV) which takes most of the feeding, (>88%) and it is the primary source of high-energy solar neutrinos [1].

Secondly, the ^{8}B decay feeds by allowed EC/β^+ transitions the 2^+ isospin doublet. Decay through this doublet is modelled assuming that the Fermi strength goes to the T=1 component and Gamow-Teller strength only to T=0. As the states are isospin mixed, the wave function of the doublet states can be expressed as:

$$|a\rangle = \alpha\,|T=0\rangle + \beta|T=1\rangle \qquad (1.a)$$
$$|b\rangle = \beta\,|T=0\rangle - \alpha|T=1\rangle \qquad (1.b)$$

Where α and β are the mixture coefficients of the pure states. Therefore, if the states are fully mixed then $\alpha^2/\beta^2=1$.

The α and β mixture coefficients can be related with the resonances through the following expressions:

$$\frac{\alpha^2}{\beta^2} = \frac{B_{GT-16,6}}{B_{GT-16,9}};\ \frac{\alpha^2}{\beta^2} = \frac{B_{F-16,9}}{B_{F-16,6}} \qquad (2)$$
$$\alpha^2 = \frac{\Gamma_{16,6}}{\Gamma_{16,6}+\Gamma_{16,9}};\ \beta^2 = \frac{\Gamma_{16,9}}{\Gamma_{16,6}+\Gamma_{16,9}} \qquad (3)$$

Where B_{GT} and B_F are Gamow-Teller and Fermi strength respectively, and Γ the decay width of each level. To determine the α and β coefficients the relevant information must be extracted from the experimentally obtained alpha spectrum.

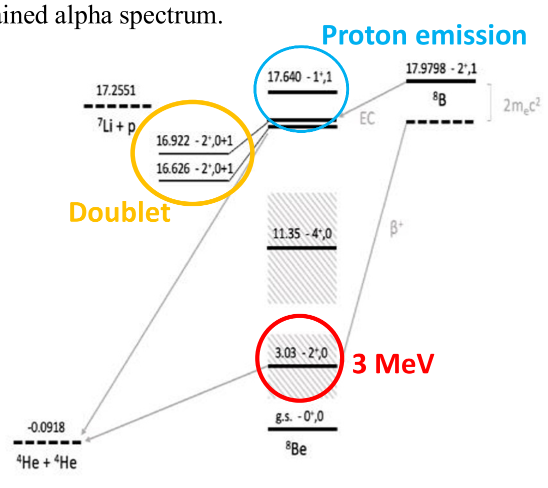

Fig. 1. Decay scheme of ^{8}B to ^{8}Be.

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Considering that the ^{8}Be is unbounded with all its states breaking up into two α particles, and the broad nature of the 3 MeV 2^{+} state, an α-continuum spectrum is measured as observed in previous works [5-10].

Thirdly, in the Q_{EC}-window there is a highly excited 1^{+} level at 17,640 MeV, that decays into ^{7}Li by emitting a low energy (330 keV) proton. This EC-decay can be modelled as occurring in the ^{7}Li core with the halo proton as a spectator [3]. The strength of this branch is estimated from the β-decay of ^{7}Li to be B_{GT} of 1.83 [4].

The first EC/β^{+} decay experiments of 8B were performed by Gilbert in 1954 [5] and improved by Farmer [6] et al, six years later. Its purpose was to test the mirror symmetry with the already studied case of the β^{-}-decay of the ^{8}Li mirror nucleus and to search for a possible new level in the excited ^{8}Be nucleus. The results confirmed the symmetry in the decay schemes of the mirror nuclei (^{8}Li and ^{8}B) and proposed for the first time the existence of two excited states at 3 MeV and 16.7 MeV. In 1964 Matt et al. [7] measured the single α spectrum emphasising the region above 7.5 MeV, the results pointed towards the existence of a 16.6 MeV state with spin and parity 2^{+} and an isospin of T=1 with a small contribution of T=0. Later, Brown et al. [8] fitted the experimental data via a reaction mechanism that assumed a 2^{+} doublet [9] strongly mixed by the Coulomb interaction.

In summary, the 16.626(3) MeV state has been observed by several groups in EC/β^{+}-decay studies. The mainly EC-decay to the 16.922(3) MeV state was first hinted at the previous JYFL08 experiment [10], where 5 events were attributed to the breakup of this state.

2 Experiment IS633

The MAGISOL (Madrid-Aarhus-Goteborg at ISOL)-collaboration has conducted several experiments to study the structure of ^{8}Be. The latest of them, experiment IS633, was performed at the ISOLDE facility at CERN to resolve the doublet in ^{8}Be via a β^{-}-feeding process and from that try to determine the isospin mixing coefficients.

The experimental setup, depicted in Fig. 2, comprised four particle telescopes, each consisting of a Double-Sided Silicon strip Detector (DSSD) with a thickness of 40-60 μm, stacked with a 1500 μm thick Si-PAD detector. A 30 μg/cm^{2} carbon foil catcher was positioned at the centre of the setup. To increase the angular coverage of beta particles, a thick 500 μm DSSD was placed beneath the carbon foil. Overall, the system has an angular coverage of Ω = 38% of 4π. For further details, refer to [11].

A 50 keV $^{8}BF_2$ beam produced online at ISOLDE [12] was implanted in the 138 nm C-foil at a depth of 26 nm [11]. The implanted ^{8}B nucleus decays in the foil, feeding the excited states of ^{8}Be, which breaks up into two alpha particles. The experimental setup surrounding the C-foil detects the emitted alpha particles, yielding information on the excited states of the ^{8}Be nucleus.

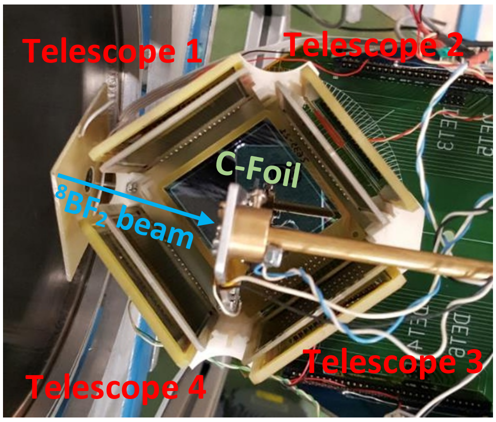

Fig. 2. Top view of the IS633 set up. The four particle telescopes surround the central C-foil catcher, the $^{8}BF_2$ beam impacts from the left side of the set up.

In the analysis procedure, for an event to be considered valid, it must fulfil coincidence conditions: two α particles must be detected in opposite detectors. The line connecting the points where the α-particles are detected in each DSSD should cross the area of the beam spot. This beam spot creates a cone in the DSSD that includes the maximum deviation angle between the two particles, therefore, an event must be detected within this cone. The high statistics obtained in experiment IS633 allowed to resolve the doublet for the first time in an EC/β+ decay study as it can be seen in the lower part of Fig 3

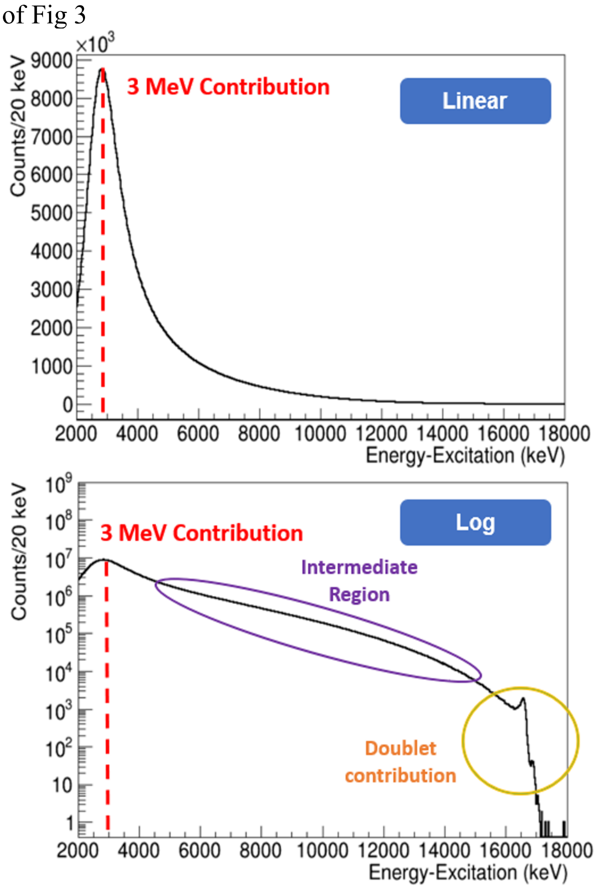

Fig. 3. α-α coincidence spectrum as function of the ^{8}Be excitation energy [$E_{\alpha 1}+E_{\alpha 2}$-92 keV]. Upper figure: linear scale. Lower figure: logarithmic scale with three main regions: the 3 MeV peak, the intermediate region associated with the transition to the continuum, and the 2^{+} doublet (resolved for the first time).

The spectrum shown in Fig. 3 exhibit three distinct regions: the dominant 3 MeV peak, the region of the doublet, and an intermediate region, which is difficult to explain only due to the tail contributions of the 2^+ states, for this region, one should consider whether it corresponds to a direct transition to the continuum.

The α-α coincidence spectrum obtained is corrected for energy losses in the C-foil and for the breakup energy of the alphas. With the corrections applied, a formalism to fit the spectrum is required. Due to all the states being merged into a continuum, a good candidate for fitting the spectrum is the R-Matrix formalism [9].

The R-Matrix formalism was originally developed to study nuclear reactions [13]. This approach divides the configuration space into two radial regions: internal and external, separated by a constant called the channel radius r_o. Each region contains a different part of the reaction process and is dominated by a specific potential. The external region ($r_o < r < \infty$) is dominated by the Coulomb force, while the nuclear interaction dominates the internal region ($0 < r < r_o$). Imposing continuity of the wave function and its derivative at the border between these regions, an expression for a matrix that relates the eigenstates of both regions is obtained, the Reaction Matrix.

$$R_{cc'} = \sum_{\lambda} \frac{\gamma_{\lambda c}\gamma_{\lambda c'}}{E_\lambda - E} \quad (4)$$

R-Matrix is a parametrization of the configuration space in terms of individual resonances, each associated with a reaction channel. These resonances are characterized by specific parameters related to the actual physical reaction, most notably the cross-section. Baker et al. [12] extended this formalism to nuclear β decays.

From an experimental point of view, a spectrum can be decomposed into a series of nuclear resonances, each characterized by specific parameters simplifying a complex fit into a series of individual resonances.

3 R-Matrix analysis

The R-Matrix formalism was employed to analyse the excitation spectrum of ^{8}Be shown in Fig 4. The spectrum is decomposed into four resonances: the 3 MeV, 16.6 MeV, 16.9 MeV levels and a background (BKG) level that models the effects of the combination of the tails of higher energy resonances. Each level is characterized by the energy (E), decay width ($\Gamma_{\alpha\alpha}$), Fermi (B_F) and/or Gamow-Teller (B_{GT}) strengths, the R-Matrix fit must be folded with the response function of the detector [14].

The algorithm to perform an R-Matrix fit has been implemented into the ORM_FIT program developed at Aarhus University [10].

The ORM_FIT code includes a feature that selects the fitting range for the R-Matrix. For this analysis, two main fits were performed: First, a local fit to the doublet, in which only the parameters associated with the 16.6 MeV and 16.9 MeV resonances were allowed to change. Second, was a global fit to the entire spectrum (see Fig. 4), where the initial doublet parameters were set to the ones obtained from the local fit and therefore let them evolve to properly fit the full range. The parameters of the other resonances (3 MeV and BKG) where set free. In all cases the channel radius was fixed to r_0=1.35 fm.

While results of the local fit were consistent with literature [2], in the case of the global fit, the decay width ($\Gamma_{\alpha\alpha}$) of the 3 MeV resonance deviates from the literature value by 400 keV ($\Gamma_{\alpha\alpha}$=1513 (15) keV vs $\Gamma_{\alpha\alpha}$=1957 (18) keV).

Since the global R-Matrix fit gives values that do not align well with those of the literature, a series of internal and external consistency tests were performed. First, the global fits were repeated imposing certain restrictions over the fitting parameters (internal consistency checks), the objective of these checks was to ensure that the algorithm always gives similar results.

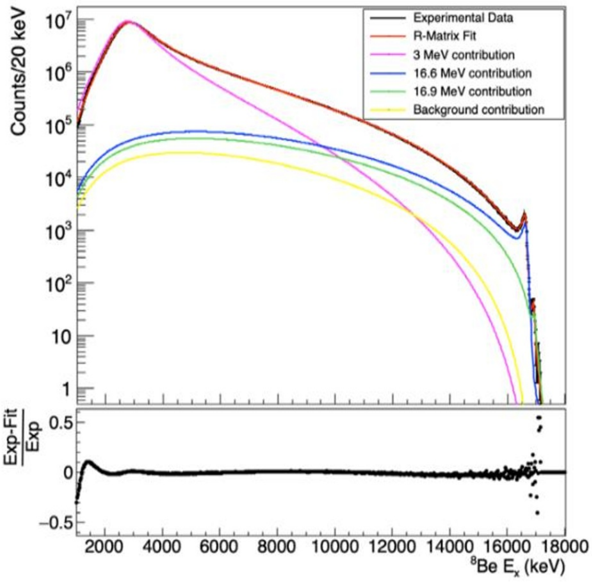

Fig. 4. Upper figure: Global R-Matrix fit (Red) to α-α coincidence spectrum as function of the ^{8}Be excitation energy (black), the individual contributions included in the R-Matrix are those of the 3 MeV (purple), 16.6 MeV (blue), 16.9 MeV (green) and BKG, 21 MeV (yellow) resonances. Lower figure: residue function between the R-Matrix and the data.

A first fit was performed fixing the R-Matrix parameters to those found in the literature, resulting in a fit with a χ^2 of 3991 denoting the low fit quality. Secondly, the literature values were used as a starting point for the fit and allowed to change. The resulting R-Matrix values converged to those of the previous global fit ($\Gamma_{\alpha\alpha}$=1949 (18) keV) with a χ^2 of 14.3. Finally, the fit was repeated with the BKG contribution fixed to 37 MeV. This choice of the background level was motivated by S.Hyldegaar's work [15], who found that a 37 MeV was the optimal energy for the background level. In this case, the fit had a χ^2 of 12.2, better than the initial fit but the width of the 3 MeV level was $\Gamma_{\alpha\alpha}$=1886 (12) keV, still far from the standard literature value.

None of these tests managed to significantly improve the previous results. Fixing the fitting parameters to literature values produced an extremely bad fit, while the other two fits converged to the values obtained in the initial global fit, with only a slight improvement if the BKG level was set to 37 MeV.

Apart from the internal consistency checks of the R-matrix fitting programme, the α-α coincidence spectrum was compared with that of the previous experiment JYFL08 [9] to explore possible contributions from pile-up that should mainly affect the spectrum at around 4.5-6 MeV. To compensate the difference in statistics the IS633 data set was normalized to the 2-4 MeV region of JYFL08 by a scaling factor of 0,0162.

The α-α spectrum of JYFL08 (red solid line) and the IS633 α-α spectrum normalized to the intermediate region (dashed black line) are displayed in Fig. 5. It can be appreciated that both spectra are almost identical.

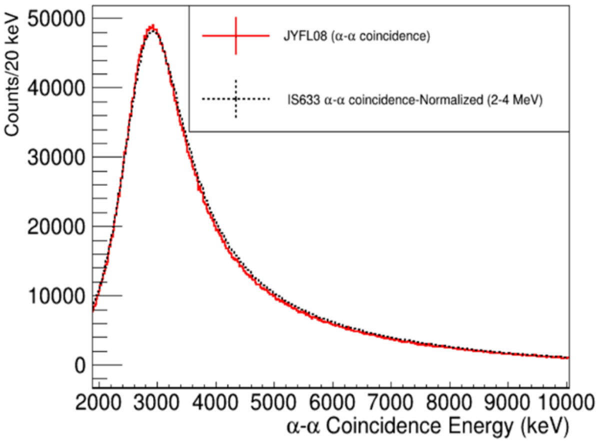

Fig. 5. The α-α coincidence spectrum Red- JYFL08 data; Black- IS633 normalized data.

From this analysis, one can calculate the decay width of the 3 MeV level for both data sets (IS633 and JYFL08) and compare them to see if there is any significant difference. To obtain the width, two methods where proposed: a direct determination of the width at half-maximum (FWHM) and the the R-Matrix fit. The latter was repeated varying the fitting ranges to test the influence of the fitting over the R-Matrix. The results obtained are presented in Table 1.

Table 1: FWHM and R-Matrix (R-Mat) fit for the 3 MeV region for multiple fitting ranges.

R-Mat Fit Range (MeV)	**JYFL08**		**IS633**	
	E (keV)	**$\Gamma_{\alpha\alpha}^{3\,MeV}$ (keV)**	**E (keV)**	**$\Gamma_{\alpha\alpha}^{3\,MeV}$ (keV)**
2-4	3034(34)	1488(12)	2997(36)	1470(15)
2-5	3036(28)	1475(17)	3006(32)	1588(18)
2-6	3047(31)	1516(20)	3020(38)	1655(16)
2-7	3060(26)	1565(13)	3030(37)	1706(18)
FWHM	2980(20)	1510(30)	2980(20)	1525(20)
Lit	**E (keV)**	3030(10)	**$\Gamma_{\alpha\alpha}^{3\,MeV}$(keV)**	1513(15)

The decay width for the 3 MeV level obtained from the R-Matrix fit for both experimental data stets coincides with the literature value of Γ=1513 keV when the fitting range is reduced to the 3 MeV resonance (2-5 MeV).

However, as the fitting range increases and enters into the intermediate region, the value of the decay width increases and starts to diverge from the literature value. This effect is more pronounced when the contributions from borth members of the doublets are included. The explanation for the dependency of the results with the fitting range might lie within the limitations of the R-Matrix method, whose core is the decomposition of the spectrum into well-defined resonances. This approximation is valid for the low and high-energy regions. However, the intermediate region could be caused by a direct non-resonant transition to the continuum. In that case, R-Matrix cannot resolve these non-resonant contributions. One could think that adding another background level could improved the fitting of the intermidiate region, nevertheless the results obtained from this approach are not clear to interpret.

4 Conclusion

Experiment IS633 constitutes an improvement over previous attempts to measure, by beta-decay, the 2^+ doublet of ^{8}Be, resolving the both doublet contributions in the excitation energy spectrum fot the first time.

The R-Matrix formalism is used to study the very complex nature of the spectrum. However, the R-Matrix algorithm could not fit the whole spectrum accurately and the resulting parameters for the well-known level at 3 MeV diverge from the values of the literature. Moreover, the parameters of the 2^+ doublet obtained are dependent of the fitting range. The contribution of a nonresonant direct transition to the continuum could be a possible explanation of this phenomenom.

Acknowledgements

We acknowledge the funding through the grants MCIN/AEI PID2019-104390GB-I00; PRE2020-094522 "ESF Investing in your future", CT31/21-UCM and fundings Next Generation of the European Union, and the MAGISOL collaboration.

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