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Letter

First determination of the isospin mixing in the ^{8}Be 2^{+} doublet via ^{8}B beta decay

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ABSTRACT

We report on the first experimental determination of the Fermi β strength in the β-decay of ^{8}B, enabled by significant improvements in production yields at ISOLDE/CERN. This allows the direct observation of isospin mixing in the 16.6 and 16.9 MeV 2^{+} doublet in ^{8}Be. Specifically, the 16.9 MeV state is resolved in β-decay for the first time with sufficient statistics to test a widely used two-level model. With the high statistics we could perform two independent analyses: one based on the observed β-strength distribution within the R-matrix framework, and a second based on the extracted β-recoil broadening. The latter makes it possible to extract the Fermi and Gamow-Teller strengths up to the electron-capture region. The obtained strengths are fully consistent with the two-state isospin mixing model.

Much of the richness of nuclear structure arises from having two fermionic particles, protons and neutrons, as building blocks, which gives rise to isospin, T, as a fundamental degree of freedom in nuclei. Most nuclear states have almost pure isospin; the best known exception involves the 2^{+} doublet states in ^{8}Be positioned at excitation energies of 16.6 MeV and 16.9 MeV that have pronounced isospin mixing, each state is assumed to contain about equal amounts of isospin zero and one. Earlier determinations of their isospin mixing probed the $T = 0$ component; here we present the first determination based on probing both the $T = 0$ and the $T = 1$ components. Our method relies on the difference in beta recoil for Fermi and Gamow-Teller transitions and may therefore be generalized and used for beta decay determinations of isospin mixing also in heavier proton rich systems as a complement with high potential to the determinations in nuclear reactions (see e.g. Mitchell et al. [1]).

The 2^{+} doublet states have long been recognized [2] as being close to single-particle states (^{7}Li$+$p and ^{7}Be$+$n, respectively), and therefore the $T = 0$ and $T = 1$ isospin components are mixed. Much of the experimental data on both states [3] can be understood in terms of this interpretation, and a simple two-level model proposed by Barker [4,5]. Two good examples of the currently available experimental knowledge are the α-α scattering reaction [6] and the ^{10}B(d,α)^{8}Be reaction [7,8], where the states are populated through their $T = 0$ components and clear interference is observed. These two reactions have provided the most precise information on the states. However, in both cases, the contributions from other levels have been a concern, particularly in the α-α scattering, since the doublet weakly couples to the 2α channel, resulting in widths of the highly excited states in the order of only 100 keV. In this work, we fill the substantial experimental gap by probing also the $T = 1$ component. Thus, we present the first experimental verification of the two-body model of Barker [4,5].

The β-decay of ^{8}B to ^{8}Be, with $Q_{EC} = 17.9799(10)$ MeV [9], was recognized early on [2] as having strong transitions (i.e. large matrix elements) to both doublet states, but until recently [10] only the 16.6 MeV state was observed experimentally. We report here on the first

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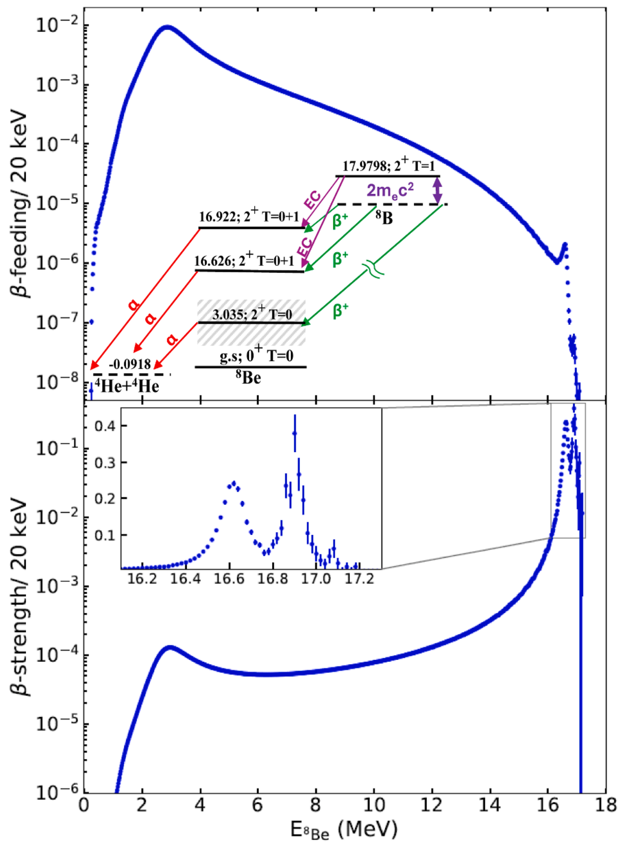

Fig. 1. Top: Experimental β-feeding of the $^{8}B \rightarrow ^{8}Be$ decay as a function of the ^{8}Be excitation energy. The relevant parts of the decay scheme are shown in an inset. **Bottom:** Deduced β-strength distribution B_β; the inset shows the region of the 2^+ doublet on a linear scale.

determination of beta feeding of the 16.9 MeV state with sufficient statistics to allow for its detailed study, note that decays here mainly occur via electron capture. An essential feature of β-decay is that the Fermi component only probes the isospin T = 1 component, so that the Fermi strength distribution directly tracks the isospin mixing. Allowed Gamow-Teller transitions may change isospin by up to 1 unit, in our case T = 0,1.

Both states of the doublet decay mainly via two-α breakup (the partial width for γ deexcitation is only a few eV). In the breakup of ^{8}Be states, both α particles have equal centre-of-mass energies, E^{cm}. However, following the β-decay the excited ^{8}Be nucleus recoils with an energy E^R, so the energies of the emitted α particles E_{α_1,α_2} are shifted according to:

$$E_{\alpha_1,\alpha_2} = E^{cm} + \frac{E^R}{2} \pm \sqrt{2E^{cm}E^R}\cos\theta \tag{1}$$

where θ is the center-of-mass angle between the directions of the recoiling ^{8}Be and the emitted α particle, the $\pm$ signals are for the two α particles. Since ^{8}Be is heavier than the emitted leptons (positron and electron neutrino), E^R is on the order of keV, but in the α particles' energy shifts it can reach several hundred keV. This is well known and has been used repeatedly to probe the weak interaction structure at lower ^{8}Be excitation energies (see e.g. Lauterjung et al. [11], Lauritsen et al. [12], Barnes et al. [13], Gallant et al. [14]). We note that, for our case, the leptons in Fermi decay have more aligned momenta than in Gamow-Teller decay and thus give rise to higher recoil energies and therefore broader recoil distributions. By observing both α particles in coincidence, one obtains two independent pieces of information: (1) the sum energy, $E_S = E_{\alpha_1} + E_{\alpha_2}$, of both particles gives the ^{8}Be excitation energy $E_{^8Be}$ ($E_S = E_{^8Be} + S_\alpha$, where $S_\alpha = 91.84(4)$ keV [9], as ^{8}Be is unbound) and its distribution yields the total β strength, B_β. (2) the energy difference, "$E_{\alpha_1} - E_{\alpha_2}$", gives the β-recoil distribution that, for a given excitation energy, depends on the ratio of the Fermi to Gamow-Teller strengths. We shall extract the isospin-mixing information from these two distributions.

Our experiment was made possible by a dedicated effort at the ISOLDE facility at CERN. Boron isotopes were produced and extracted via fluorination to give molecular beams of $^{8}BF_2^+$ [15]. This enabled the production of up to 10^5 ^{8}B/s with an average experimental count rate of 25 kHz per detector. The extracted low-energy radioactive beam was stopped in a 31 μg/cm^2 carbon collection foil surrounded by double-sided Si strip detectors in a close geometry that recorded the α particles from the decays. The energy resolution of the detectors used was below 35 keV. A detailed description of the set-up and experimental details are given in Viñals et al. [16], which also contains an extensive investigation of the response function of the Si detectors. We shall here outline briefly the relevant parts of the analysis procedure. A more complete account will be given elsewhere and can be found in two PhD theses [17,18].

The ^{8}B beta decay scheme is shown as an inset of the top panel of Fig. 1. The sum energy for two coincident α particles gives the experimental β-feeding spectrum plotted in the upper panel of Fig. 1 versus the ^{8}Be excitation energy. From this and the well-known relation $ft = K/B_\beta$ we can extract the β strength distribution: $B_\beta = B_F + \left(g_A/g_V\right)^2 B_{GT}$, where $K = 6144(4)$ s [19], B_F and B_{GT} are the reduced matrix elements squared for the Fermi and Gamow-Teller components and $g_A/g_V = -1.2753(13)$ [20]. The deduced β strength is displayed in the bottom panel of Fig. 1.

The measured β strength shows a strong enhancement of more than two orders of magnitude around the doublet, which shows that there are no indications for other 2^+ states situated close to, nor giving a large contribution below the doublet. This gives support to the use of Barker's two-level model that assumes that the wavefunctions of the 16.6 MeV and 16.9 MeV states, $|16.6\rangle$ and $|16.9\rangle$, can be written

$$|16.6\rangle = \alpha|T=0\rangle + \beta|T=1\rangle; \quad |16.9\rangle = \beta|T=0\rangle - \alpha|T=1\rangle, \tag{2}$$

where the $T = 1$ component can be assumed to be the isobaric analogue state of the ^{8}B ground state and the $T = 0$ component in the two states is the same, so that a sizable mixing with other states can be excluded. The α and β parameters fulfill the condition $\alpha^2 + \beta^2 = 1$ and the ratio of their squares α^2/β^2 provides the degree of isospin mixing. More complete model calculations of the doublet have been undertaken [21–24], but the simple model gives a convenient parametrization as outline here. In this work we test the two-level model.

β-recoil broadening study– We have extracted the experimental recoil spectra as it has been done before [10] employing $\delta E = (E_{\alpha_1} - E_{\alpha_2})/2$ for 100 keV intervals in the excitation energy, the δE values are binned in 5 keV steps. The $E_{^8Be}$ =16.0 MeV and $E_{^8Be}$ =16.6 MeV distributions are shown in Fig. 2.

For each value of $E_{^8Be}$, the Fermi-to-Gamow-Teller ratio can be extracted from the individual recoil distributions (like the ones shown in Fig. 2). For this purpose we employ the formalism given in Schardt and Riisager [25], that describes the β-recoil distribution in terms of the asymmetry parameter A, related to the Fermi and Gamow-Teller strengths for the $2^+ \rightarrow 2^+ \rightarrow 0^+$ transitions through the relation:

$$A = \frac{B_F - (\frac{g_A}{g_V})^2 B_{GT}}{B_\beta} \tag{3}$$

so for a pure Gamow-Teller transition $A = -1$, for a pure Fermi transition $A = +1$, and in a completely mixed case $A = 0$. As seen in Fig. 2 the fit at $E_{^8Be}$ =16.0 MeV is a pure Gamow-Teller transition while the fit at $E_{^8Be}$ =16.6 MeV gives an asymmetry value corresponding to a strong mixture of Fermi and Gamow-Teller components.

The difference between the recoil spectra for Fermi components and Gamow-Teller components is clearly visible for lower excitation energies where the latter dominates, but the difference becomes less near the end-point where the beta-particles becoming non-relativistic; this is

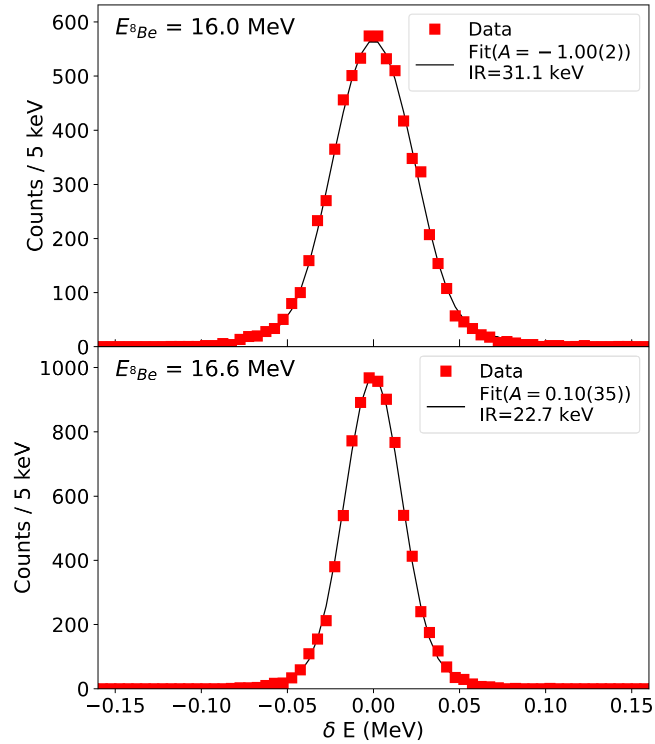

Fig. 2. β-recoil distributions, calculated from the mean energy difference, δE, between the two α particles emitted in the breakup of ^{8}Be, for different values of the ^{8}Be excitation energy ($E_{^8Be}$). Both projections of excitation energy are carried out within 100 keV windows, i.e. ± 50 keV. The theoretical curve includes the Fermi and Gamow-Teller recoil distributions folded with the experimental response, with only the A-parameter as a fit parameter. **Top:** β-recoil distribution at $E_{^8Be}$ = 16.0 MeV, outside the doublet region, fitted with A = -1.00(2) and χ^2/d.o.f = 0.58. **Bottom:** β-recoil distribution at $E_{^8Be}$ = 16.6 MeV, fitted with A =0.10(35) and χ^2/d.o.f = 0.40. Note that the pure Gamow-Teller distribution in the top panel due to the excitation energy dependence is wider than the mixed transition in the bottom panel.

because the angular correlation term contains a factor v_e/c [25]. A good understanding of the detector response is hence essential in order to extract reliable results. The detailed description [16] of the experimental response function of the set up agrees well with the experimentally measured resolution that for δE is approximately a Gaussian with σ = 20 keV with tails of about 3 % intensity due to extra energy loss in the read-out contacts. Together with the response function the energy losses in the collection foil have been taking into account, as shown in Fig. 2 our description of the recoil spectra is good.

The trends of the widths for both the theoretical and experimental recoil distributions as a function of excitation energy are compared in the upper part of Fig. 3. We employ the interquartile range (IR), the extent of the middle half of the data, as a robust measure of spread. Although the width includes several effects, the statistical precision of IR is better than that of the asymmetry parameter, A, whose experimental values are included for completeness in the bottom part of the same figure. The data are presented in 100 keV bins, and the theoretical distributions for the separate β^+ Fermi (F) and Gamow-Teller (GT) distributions, as well as the pure electron capture (EC) distribution, have been evaluated using the experimental intensity distribution within the bin and properly folded with the experimental response function [16].

We find that the Gamow-Teller component dominates the decay up to above 16 MeV, after which the Fermi component gradually increases until 16.5–16.7 MeV, where the EC contribution becomes noticeable. This corroborates the results shown in Fig. 2. Above 16.96 MeV, only EC decays are present, and the sensitivity to the A parameter is lost

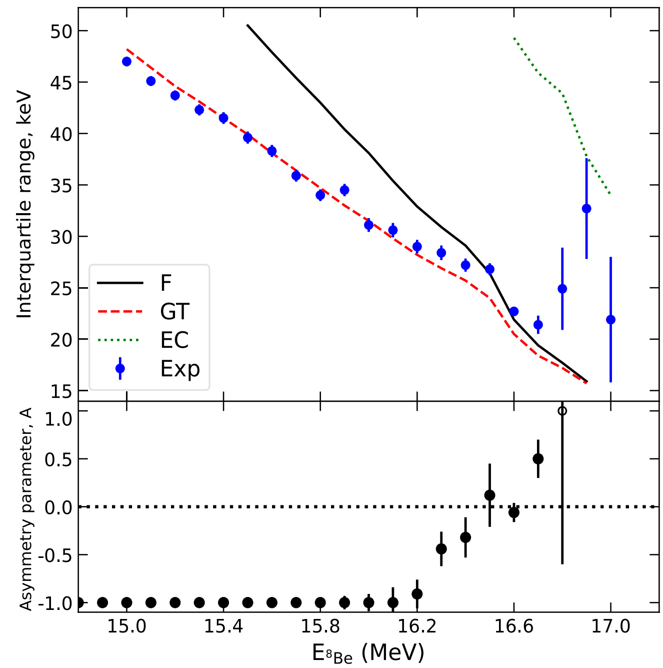

Fig. 3. Top: Interquartile range of recoil distributions versus ^{8}Be excitation energy, $E_{^8Be}$. Experimental values in 100 keV bins are compared to values for pure Fermi (F), pure Gamow-Teller (GT) and pure Electron Capture (EC) recoil distributions, all folded with the experimental response function. **Bottom:** Evolution of the asymmetry parameter A as a function of the ^{8}Be excitation energy, the point at 16.8 MeV, shown as an open circle has a large error bar, for higher energies one can not distinguish different contributions.

at 16.8 MeV. Still, it is clear from Fig. 3 that the Fermi and Gamow-Teller distributions are becoming hard to distinguish already before that. Nevertheless, the data as well as the asymmetry parameter A clearly indicate the presence of a Fermi component in the doublet region. The kink at 16.5 MeV in the distributions is caused by the response function in combination with the rapid decrease in count rate above 16.6 MeV.

R-matrix Analysis– The experimental β feeding as a function of the ^{8}Be excitation energy (top panel of Fig. 1) has been fitted within the R-matrix framework as formulated in particular in Barker [26] and Brune [27].

Here we concentrate on the end-point region, but as it is obvious from Fig. 1, there is much more statistics at lower excitation energy that easily can bias the fitting at the spectral endpoint.

Apart from the broad level at 3 MeV and the doublet at 16.6 MeV and 16.9 MeV it is necessary to introduce one more level in the fit. Sometimes this level is referred to as a background, while others interpret it as an intruder state. From the bottom panel of Fig. 1 one would expect that both this level and the 3 MeV level will have a negligible effect on the fit in the doublet region, but they are nevertheless maintained in the R-matrix fits. What is important here is that a full R-Matrix fit with only Gamow-Teller contributions from all these four levels gives an unsatisfactory fit. Only when both Fermi and Gamow-Teller are allowed, the R-matrix fit is reasonable; this is fully consistent with the results from the β-recoil broadening study discussed above. The chi-square value per degree of freedom increases from 1.1 to 52.8 if the Fermi component is set to zero and the shape of the 16.9 MeV level is not reproduced. Fig. 4 shows the experimental data with error bars, the best R-Matrix fit in the region of interest in red and in dashed blue the fit when the Fermi strength is put to zero and we fix the energy of the 16.9 MeV level. Two important remarks; in the absence of Fermi component the separation between the levels should be sharper and the 16.9 MeV results to be extremely narrow.

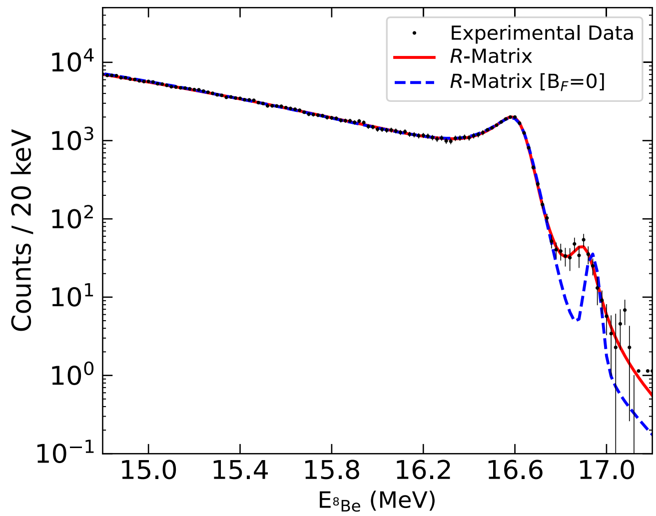

Fig. 4. R-Matrix fits to the ^{8}Be excitation spectrum. The experimental data, shown as black dots, are overlaid with the best R-Matrix fit ($\chi^2/d.o.f$ =1.13) is shown in red. An R-Matrix fit imposing B_F =0 ($\chi^2/d.o.f$ =52.8) is shown in dashed blue. Fitting the spectrum in the B_F =0 case requires fixing the centroid position. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Results, specifically for the 2^+ doublet, of the R-Matrix fit to the full ^{8}Be excitation spectrum. The α^2/β^2 isospin mixing ratios, derived from the different strengths and widths (see text), are given in the rightmost column. In the bottom line, the widths of the levels obtained in α scattering reaction studies.

	16.6 MeV	16.9 MeV	α^2/β^2
B_F	0.83(18)	1.19(30)	1.43(11)
$(g_A/g_V)^2 B_{GT}$	1.20(19)	0.86(8)	1.40(8)
Γ (keV)	107.6(2)	72.8(14)	1.48(3)
Γ^{Ref} (keV) [6]	107.7(5)	74.4(4)	1.45(1)

The reason why the R-Matrix fit is sensitive to two β feeding parameters for both doublet states is due to the destructive and constructive interference effects connected to the two different isospin values, T = 0 and T = 1. The doublet states α decay via their T = 0 components. If those doublet states were fed via their T = 0 component, this will lead to destructive interference between the levels, as shown in reaction experiments, e.g. [8]; conversely, if the states were fed via T = 1, the interference will be constructive, as is also clear from Barker's two-level model. Since (the real part of) the amplitude from each level changes sign at the level energy, the interference pattern will be the opposite at energies below and above the doublet, so that the T = 1 component will be concentrated around the doublet and only the T = 0 component is seen at excitation energies below 16 MeV. Fermi decay is only T = 1, whereas Gamow-Teller decays can have both T = 0 and T = 1 components (although the latter is believed to be significantly smaller than the former). This difference in interference patterns allows the R-matrix fit to distinguish the two isospin components.

Discussion– We shall quote here the results for the best R-Matrix fits with a 20 keV binning as presented in Fig. 4. Table 1 gives the Fermi and Gamow-Teller strength values for the doublet obtained in the R-Matrix fit of the full spectrum. The quoted uncertainties include (anti-) correlations between the T = 1 and T = 0 strength for the 16.6 MeV level, as well as between the two T = 1 strengths; correlations between β strength parameters and the widths of the two levels are also included in the uncertainties.

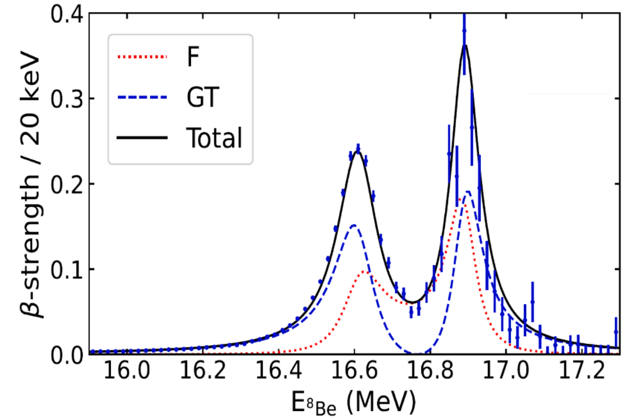

Fig. 5. Experimental β-strength above 16 MeV is compared to calculations within Barker's two-level model, separating the Fermi and Gamow-Teller strengths.

The total T = 1 strength is 2.02(11), which, with a total Fermi strength of 2 (considering the sum rule $\sum B_F = T(T+1) - T_{zi}T_{zf}$) indicates a Gamow-Teller T = 1 component at most of order 0.1. At the same time, the T = 0 β strength is 2.06(6) (all from Gamow-Teller decays), 20 times larger than the T = 1 Gamow-Teller strength component.

Since the T = 1 Gamow-Teller contribution is almost negligible, Barker's two-level model allows several straightforward determinations of the isospin mixing ratio α^2/β^2: (1) as the ratio of Fermi strengths for the 16.9 MeV to the 16.6 MeV level; (2) as the ratio of Gamow-Teller strengths for the 16.6 MeV to the 16.9 MeV level; and (3) as the ratio of the widths of the 16.6 MeV and 16.9 MeV levels. Our resulting α^2/β^2 ratios are remarkably consistent as shown in Table 1. It is important to notice that α^2/β^2 was up to now only obtained from the widths of the levels. This is the first time that the mixing has been obtained from beta decay with access to both components, in particular, the 16.9 MeV level. The current best determination of the isospin mixing parameters was obtained from the widths of the two levels, as determined in reaction experiments [6] (the widths come from the α decay and are therefore proportional to the square of the $T = 0$ amplitudes). The reference widths for the doublet and α^2/β^2 ratio are included in Table 1 for comparison.

Finally, since the T = 1 Gamow-Teller contribution is so small, we can make a qualitative argument on the isospin decomposition of the doublet by considering the experimental β strength, as shown in Fig. 5. Our results corroborated those obtained in reaction studies with a totally different approach. The curves in Fig. 5 illustrate how the data can be understood within Barker's two-level model. The total Fermi strength B_F is set to 2 (i.e. assuming negligible mixing with states outside the doublet), the Gamow-Teller strength $(g_A/g_V)^2 B_{GT}$ is 2.6 to $T = 0$ and 0.01 to $T = 1$, the mixing parameter is $\alpha^2 = 0.58$, within the error bar of the deduced experimental value, and the two levels are positioned at 16.600 MeV and 16.900 MeV with an average width of 110 keV. (So the levels appear broader and situated slightly below the values obtained from the detailed R-matrix fit. The larger apparent beta strength is due to the small energy shift that changes the effective Q-value, in particular for the upper level). The important observation is that a strong Fermi contribution is needed in order to explain the non-vanishing intensity between the two peaks, as predicted by the interference arguments presented above, and that the Fermi parts vanish very quickly at lower and higher energies.

In conclusion– We have in this work extended the use of the β-recoil broadening method as a tool up to the high excitation energies, where EC decays dominate. We have determined the strength distribution for the β decay of ^{8}B into ^{8}Be for the first time up to 17 MeV excitation energy and shown that the strength selectively goes to the 2^+ doublet at

16.6/16.9 MeV. We have further demonstrated that the beta transition is of Gamow-Teller type until at least 16 MeV excitation energy in ^{8}Be. We have given qualitative arguments and demonstrated the need for both Fermi and Gamow-Teller strength based on R-matrix fit and their different interference patterns in the doublet region. We have tracked the relative Fermi and Gamow-Teller strength distribution up to 16.7 MeV, showing that both components are needed for a satisfactory fit of the doublet region. We have shown that all results are consistent with the Barker model of isospin mixing and that the model allows three different estimates of the mixing parameter α^2/β^2 to be made. The estimates are consistent and all our values agree with the literature value. We can summarize saying that reaction and the present β-decay experiments agree that the mixing of the $T=0$ and $T=1$ components in the doublet is not identical.

The techniques used here rest on well-understood physics and may be employed also for heavier proton-rich systems in cases where the IAS is proton unbound. Analysis of the beta-delayed protons from the IAS and levels around it will allow the isospin distribution to be tracked in detail, provided the beam intensity is sufficient. This may allow isospin mixing to be probed also in quite proton rich nuclei where the mixing is believed to be larger than for more stable nuclei.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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