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The ^{8}B Neutrino Spectrum

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Knowledge of the energy spectrum of the neutrinos emitted in the β decay of ^{8}B in the Sun is needed to interpret the neutrino spectrum measured on Earth. Experimentally, the ^{8}B neutrino spectrum may be extracted from the measurement of the β-delayed α spectrum. In this contribution, the results of a recent α-α coincidence measurement are presented and compared to previous measurements. The implications for the neutrino spectrum are clarified.

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1. Introduction

Not only do the solar neutrino detectors Super-Kamiokande (SK) and the Sudbury Neutrino Observatory (SNO) count neutrinos, they also measure their energy spectrum. Due to detection thresholds both detectors are primarily sensitive to the ^{8}B neutrinos. The solar neutrino spectrum measured on Earth is predicted to be distorted compared to the ^{8}B laboratory spectrum due to the transition from matter-enhanced oscillations above 3 MeV to vacuum oscillations below. Above the detection thresholds of SK and SNO (≈ 4 MeV), the distortion is expected to be on the order of 10%. Observation of this distortion would provide independent experimental evidence of the MSW mechanism [1, 2, 3] responsible for the enhanced oscillation probability in matter. The most recent spectra published by SK [4] and SNO [5] remain consistent with an undistorted spectrum. Within a decade, SK should be able to resolve a 10% distortion with 3σ significance [4]. This estimate assumes that the ^{8}B laboratory spectrum is known to an accuracy much better than 10%. However, two recent laboratory measurements [6, 7] of comparable precision are in substantial disagreement, differing by as much as 10% for large neutrino energies. This will complicate the search for spetral distortion, in particular at high energies where it may also obscure a possible *hep* neutrino signal, i.e. neutrinos from the $^3\text{He} + p \to {}^4\text{He} + e^+ + \nu_e$ reaction. This provides the motivation for our new measurement of the ^{8}B neutrino spectrum.

Recently, the Borexino detector has measured the ^{8}B neutrino spectrum down to 3 MeV [8]. Borexino also detects the low-energy ^{7}Be neutrinos. Combined with a prediction of the absolute neutrino fluxes from the standard solar model, their data is consistent with the prediction of the MSW-LMA solution. In particular, they confirm the enhancement of the transition probability above 3 MeV due to the transition from vacuum to matter-enhanced oscillations.

A schematic illustration of the β decay of ^{8}B is given in Fig. 1. Transitions from the 2^+ ground state of ^{8}B to the 0^+ ground state of ^{8}Be or the very broad 4^+ state at 11.4 MeV are second forbidden and hence strongly suppressed. A recent experimental study [10] gives an upper limit of 7.3×10^{-5} for the branching ratio to the ground state. No 1^+ or 3^+ states are energetically accessible. This means that the decay proceeds exclusively by allowed transitions to the 2^+ states. In the following discussion, the distribution of excitation energies populated in ^{8}Be will be referred to as the E_x distribution. The majority of the decays proceed via the broad 3 MeV state, resulting in a broad distribution of α-particle energies peaked around 1.5 MeV.

2. Previous measurements

The ^{8}B neutrino spectrum cannot be derived theoretically because nuclear theory is unable to give a reliable prediction of the E_x distribution. Therefore, measurements are needed. In the first two studies of the β decay of ^{8}B only singles α spectra were measured [11, 12]. The E_x distribution had to be unfolded from the recoil broadening distribution. More recently, the singles β spectrum was measured by [13]. In this case, the E_x distribution had to be unfolded from an even broader β spectrum.

A measurement of the total energy of the two α particles provides a direct (no need for unfolding) and hence more reliable determination of the E_x distribution. Such measurements have only recently become feasible thanks to advances in detector technology. In the first measurement of

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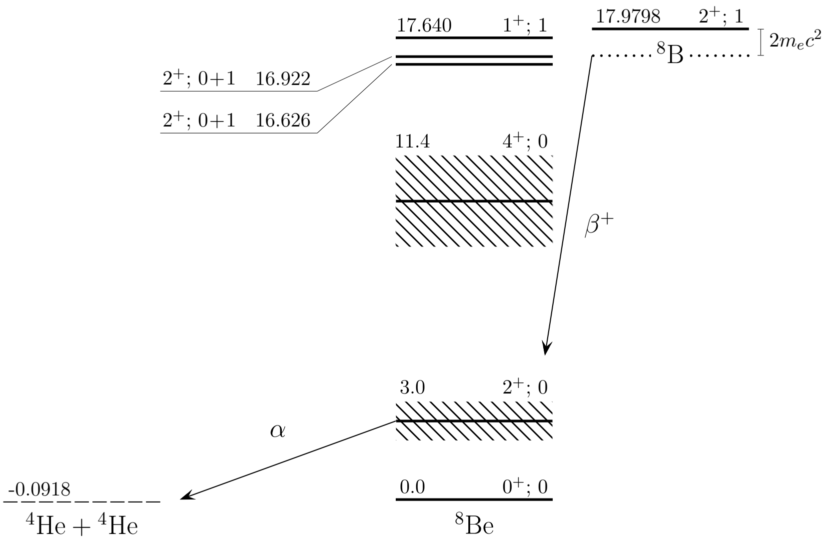

Figure 1: Nuclear levels in ^{8}Be below the ground state of ^{8}B. The levels are labeled by their energy above the ^{8}Be ground state (in MeV), their spin-parity and their isospin. Energies and quantum numbers are taken from [9]. The 2^+ doublet found at an excitation energy of 16 MeV is strongly isospin mixed.

this type [6], the ^{8}B activity was implanted in a thin carbon foil and the α particles were measured in coincidence in two Si detectors placed at opposite sides of the foil. A strong magnetic field was applied to sweep away the positrons. In this way, β summing and unwanted β-α coincidences were effectively eliminated. In the second measurement of this type [7], the ^{8}B activity was implanted into an Si detector and the total energy of the α particles directly measured. One great advantage of this approach is the complete absence of insensitive layers of material in which the α particles lose energy. One drawback is the systematic shift in energy of several tens of keV due to β summing which must be accounted for with simulations. In between the measurements of [6] and [7], another measurement was performed by [14] using a conventional single-α technique. The results of [7] and [14] are in excellent agreement but disagree with the results of [6]. According to [7] and [14] the peak of the E_x distribution is narrower and occurs about 50 keV higher in energy than found by [6]. The uncertainty in the determination of the peak position is quoted as 12 keV by [6], 9 keV by [7] and 6 keV by [14].

Recently, it was reported [15] that [6] have recognized that they underestimated the uncertainties related to the energy loss generated by the carbon buildup in their foil, so that a claim of a disagreement between the measurements of [6] and [7, 14] no longer should be made.

3. Present experimental approach

Our collaboration has performed two independent experiments in which the energy of the two α particles was measured by different techniques. The first experiment was performed in January 2008 at the IGISOL facility in Jyväskylä, Finland, using a setup similar to that of [6]. The α particles were measured in coincidence in separate detectors facing a thin carbon foil in which the ^{8}B activity was implanted at 20 keV. Our setup differs from that of [6] in that we use segmented Si detectors [16] to reduce β summing and unwanted background from β-α coincidences. Consequently, a strong magnetic field to sweep away the positrons is not needed. This was a significant source of systematic uncertainty in their measurement. Like [7], we use the β-delayed α emitter ^{20}Na for energy calibration. By implanting the ^{20}Na activity in the same foil as used for the ^{8}B activity, we reduce the systematic uncertainties from energy loss corrections compared to [6] who relied on standard α sources for the energy calibration. Unlike [7], we measure the energies of the α particle and the recoiling ^{16}O ion separately, meaning that we do not have to correct for the different response of Si detectors to α particles and ^{16}O ions. The second experiment was performed at the turn of the year 2008/2009 at the KVI facility in Groningen, The Netherlands, using an implantation technique similar to that of [7]. The setup was improved by using a finely segmented Si detector with strips only 300 μm wide, whereby the effects of β summing were much reduced [17]. Here, only results from the IGISOL experiment will be presented. The analysis of the KVI experiment is underway and will provide an important check of the IGISOL experiment.

4. Results

The E_x distribution obtained in the present study is shifted 20 keV up in energy relative to the distribution of [6] and 20–25 keV down in energy relative to the internally consistent distributions of [7] and [14]. The uncertainty in the determination of the peak position in the present study is estimated to 6 keV.

The neutrino spectrum calculated from our E_x distribution is shown in Fig. 2 (a). The relative deviation with respect to the neutrino spectrum calculated from the E_x distribution of [7] is shown in Fig. 2 (b). A significant deviation of several percent is seen at high neutrino energies with our spectrum at these energies being the most intense. This is a direct consequence of our E_x distribution being shifted 20-25 keV down in energy relative to the distribution of [7]. The odd-looking wiggle around 0.5 MeV is due to the 16 MeV doublet.

The calculation of the neutrino spectrum is complicated by the presence of recoil order terms, affecting the neutrino spectrum at the level of 5–10% [7]. In addition, radiative corrections affect the neutrino spectrum at the level of 1%. A detailed and comprehensive account of the steps involved in the calculation is given by [7]. Recoil order terms and radiative corrections are not taken into account in the present calculation, the purpose of which merely is to estimate how the neutrino spectrum is modified by our—what we believe to be—improved determination of the E_x distribution.

5. Conclusion

Using a coincidence-detection technique, we have measured the ^{8}Be excitation energy distribution (E_x distribution) in the decay of ^{8}B. The main feature of this distribution is a broad peak centered at $E_x \approx 3$ MeV. The distribution obtained in the present study is shifted 20–25 keV down in energy relative to the internally consistent distributions of [7] and [14] which are held as the current standard [15]. Our measurement gives a more intense neutrino spectrum at high neutrino energies. The deviation reaches 8% at $E_\nu = 15$ MeV. Below 11 MeV, our spectrum deviates by less than 1% from the neutrino spectrum of [7]. We believe that our experimental approach gives an improved

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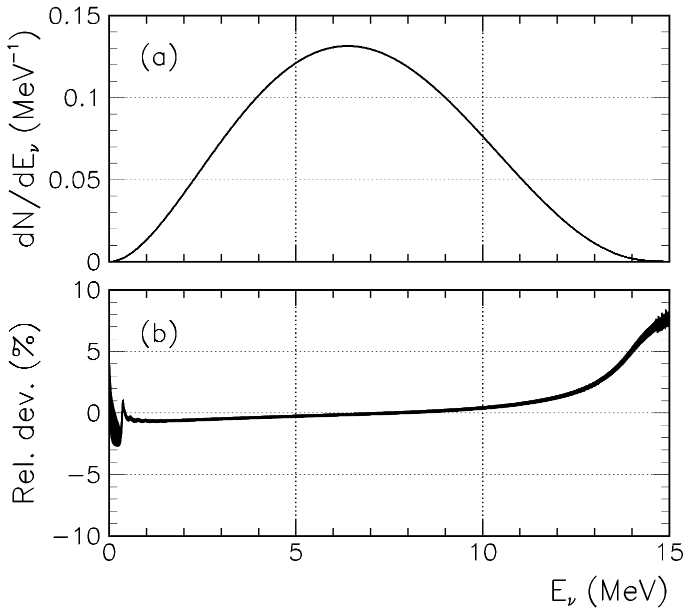

Figure 2: (a) Neutrino spectrum calculated from the E_x distribution obtained in the present study neglecting recoil order terms and radiative corrections. **(b)** Relative deviation with respect to the neutrino spectrum calculated from the E_x distribution of [7]. The width of the band indicates 1σ uncertainties calculated by adding the uncertainties on the two neutrino spectra in quadrature. Only statistical uncertainties were considered in the calculation of the uncertainties on our neutrino spectrum.

handle on systematical effects compared to the approaches of [7] and [14]. The complete calculation of the neutrino spectrum, following the prescription of [7] remains to be done. However, the conclusions already made regarding the implications of our new measurement for the neutrino spectrum, will not change substantially. The deviation between us and [7] is well below the precision of the existing solar neutrino data except at the very highest neutrino energies ($E_\nu > 13$ MeV) where the deviation may have some implication, in particular for the upper limit, up to now set on the *hep* neutrino signal [18]. The deviation is comparable in magnitude to the distortion expected due to the transition from matter-enhanced oscillations above 3 MeV to vacuum oscillations below.

A paper describing the details of the experiment and the data analysis is in preparation.

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