Measurement of the $\alpha$ Energy Spectrum from 8B and Determination of the Shape of the $\nu$ Spectrum

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SuperK, SNO, ICARUS... will look at distortions of the $8B\nu$ spectrum
\[ 16004.5(5) \quad 2^+ \] 
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\[ \beta^- \]

\[ \gamma \quad M1, E2 \]

\[ 3040(30) \quad 2^+ \quad \Gamma = 1500(20) \]

\[ 16922(3) \quad 2^+ \quad \Gamma = 174.0(4) \]

\[ 16626(3) \quad 2^+ \quad \Gamma = 108.1(5) \]

\[ 17979(1) \quad 2^+ \quad 8_B \]

\[ 8_{Li} \]

\[ 4_{He} + 4_{He} \]

\[ -91.84(4) \quad 0^+ \quad 0.00(4) \quad 0^+ \]

\[ 8_{Be} \]
High-energy $\nu$'s come from $^8\text{B}$

- $^8\text{Be}$
- $\nu$ and $e^+$
- To get the energies of $\nu$'s

Can measure the energies of $\alpha$'s
FIG. 2. Measured $\beta$ momentum spectra. The error bars, where not shown, are smaller than the size of the points. (a) The $\beta^-$ spectrum of $^{12}$B used to calibrate the spectrometer. A fit is performed to obtain the calibration parameter $R_0$ (see Ref. 15). (b) The $\beta^+$ spectrum of $^8$B. The solid line is the predicted spectrum which gives the best agreement (see Table I). The dashed line shows a normal allowed spectrum for a hypothetical sharp final state at $E_x \approx 3$ MeV in $^8$Be.

when both recoil order terms and radiative corrections are
Fig. 1. Combined $^8\text{B}$ plus $\nu_{e\bar{e}}$ energy spectrum. The total flux of $\nu_{e\bar{e}}$ neutrinos was varied to obtain the best-fit for each scenario. The figure shows the Ratio of the measured [1] to the calculated number of events with electron recoil energy $E$. The measured points were reported by the SuperKamiokande collaboration at Neutrino 98[1]. The calculated curves are global fits to all of the data, the chlorine [20], GALLEX [21], SAGE [22], and SuperKamiokande [1] total event rates, the SuperKamiokande [1] energy spectrum, and the SuperKamiokande [1] Day-Night asymmetry. The calculations follow the precepts of BKS98 [23] for the best-fit global solutions for a standard 'no-oscillation' energy spectrum, as well as MSW and vacuum neutrino oscillation solutions. The horizontal line at Ratio = 0.37 represents the ratio of the total event rate measured by SuperKamiokande to the predicted event rate[9] with no oscillations and only $^8\text{B}$ neutrinos.

For vacuum oscillations, the value of $\alpha$ corresponding to the global $\chi^2_{min}$ does not depend strongly on $\Delta m^2$ and $\sin^2 2\theta$ within the acceptable region. The improvement in the C.L. for acceptance increases from 6% to 15% when an arbitrary $\nu_{e\bar{e}}$ flux is considered.

The best-fit global MSW solution with an arbitrary $\nu_{e\bar{e}}$ flux has neutrino parameters given by $\Delta m^2 = 5.4 \times 10^{-6}\text{eV}^2$ and $\sin^2 2\theta = 5.0 \times 10^{-3}$, which
Figure 1: Normalized energy spectra of $^8 \text{B}$, hep and eB neutrinos.
Figure 3: Observed electron energy spectrum normalized to SSM expectations (dots). The solid line is the prediction for $\Phi_{\nu_e} = 1.1 \times 10^4 \text{ cm}^{-2}\text{s}^{-1}$. 
FIG. 2. Compilation of $^8$Be($2\alpha$) decay data. The bin widths are different for different experiments. The data WA1 and WA2 are shifted on the vertical axis.

FIG. 3. Values of the normalized chi square in a fit to the experimental positron spectrum, using the input alpha decay data of Fig. 2, with an allowance for a possible bias, $\beta$, in the detected alpha particle energy. The curves are remarkably similar, modulo a constant bias.

FIG. 4. Experimental data on the positron spectrum, together with the best fit and the $\pm 3\sigma$ fit, corresponding to WA1 alpha decay data within the bias range $\beta = 0.025 \pm 0.050$ MeV.

FIG. 5. The best estimate (standard) $^8$B neutrino spectrum $\lambda$, together with the spectra $\lambda^\pm$ allowed by the maximum ($\pm 3\sigma$) theoretical and experimental uncertainties.
Advantages of our Setup:

1) Detectors completely blind to $\beta$'s
   a) allowed us to count $\alpha$-$\alpha$ coincidences without $\beta$'s.
   b) cleared low-energy $\beta$ backgrounds.
   c) avoided $\beta$ summing.

2) Continuous $\alpha$-energy calibration.

3) Continuous foil-thickness monitoring.
Energy calibrations are taken within each cycle in both detectors with mixed (148Gd+241Am) sources.
We measured detectors dead layers and calculated energy loss in the dead layers plus foils

![Graph showing energy loss and dead layer/foil distinction.]

We corrected the 8B spectrum event-by-event for energy loss.
$E_{\alpha 1} + E_{\alpha 2} = \text{constant}$
Efficiency for $^8$B

Energy $^8$Be (MeV)
The problem: \[ -\frac{\hbar^2}{2m} \frac{d^2\phi}{dr^2} + V(r) \phi = E \phi \] (1)

Instead, we solve: \[ -\frac{\hbar^2}{2m} \frac{d^2X_\lambda}{dr^2} + V X_\lambda = E_\lambda X_\lambda \] (2)

\[
\left( \frac{dX_\lambda}{dr} + b X_\lambda \right)_{r=a} = 0
\]

The solutions to the real problem can be expanded in terms of the \( X_\lambda \)'s:

\[
\phi = \sum_\lambda A_\lambda X_\lambda
\]

\[
A_\lambda = \int_0^a X_\lambda \phi \, dr
\]

From (1) and (2):

\[
\frac{\hbar^2}{2m} \left( \phi \frac{dX_\lambda}{dr} - X_\lambda \frac{d\phi}{dr} \right) = (E - E_\lambda) A_\lambda
\]

\[
\phi(r) = G(r,a) \left\{ \phi(a) + b \phi(a) \right\}
\]

\[
\uparrow
\]

\[
\frac{\hbar^2}{2m} \sum_\lambda X_\lambda(r) X_\lambda(a)
\]

\[
\frac{E_\lambda - E}{E_\lambda - E}
\]

define 'reduced width': \( x_\lambda^2 = \frac{\hbar^2}{2m} \left[ X_\lambda(a) \right]^2 \)

\[ R^* : R = \sum_\lambda \frac{x_\lambda^2}{E_\lambda - E} \]
To calculate cross section:

\[ \phi_{\text{outside}} = I - U \theta \]

\[ S = \frac{\pi}{k^2} \left| 1 - U \right|^2 \]

\[ I = \frac{e^{-ikr}}{\sqrt{4\pi r}} \]
\[ \theta = \frac{e^{+ikr}}{4\pi r} \]

To get \( U \) we take the logarithmic derivative and equate it to the value inside:

\[ U = e^{-2ika} \frac{1 - bR + ikR}{1 - bR - ikR} \]

\[ S = \frac{\pi}{k^2} \left| 2 \sin ka \ e^{ika} - \frac{2k \gamma^2}{(E_0 - E) - (b + ik) \gamma^2} \right|^2 \]
8B energy spectrum
R-matrix fit to the data

\[ N(E) = \left( \frac{N_t}{6166\pi} \right) f_p P_2 \left( \frac{\left| \sum_{j=1}^{n} \frac{M_{0j} \gamma_j}{E_j - E} \right|^2 + \left| \sum_{j=1}^{n} \frac{M_{1j} \gamma_j}{E_j - E} \right|^2}{\left( 1 - (S_2 - B_2 + iP_2) \sum_{j=1}^{n} \frac{\gamma_j^2}{E_j - E} \right)^2} \right) \]  

(1)

The 16 MeV doublet was assumed to be a near equal mixture of \( T = 0 \), and \( T = 1 \). Let \( \psi_a \) and \( \psi_b \) be two wavefunctions with isospin 0 and 1, respectively:

\[ \psi_2 = \alpha\psi_a + \beta\psi_b, \quad \psi_3 = \beta\psi_a - \alpha\psi_b \]

The values of \( \alpha \) and \( \beta \) were extracted from the widths:

\[ \alpha^2 = \frac{\Gamma_2}{\Gamma_0}, \quad \beta^2 = \frac{\Gamma_3}{\Gamma_0}, \quad \Gamma_0 = \Gamma_2 + \Gamma_3. \]  

(2)

The relation between the reduced width \( \gamma_i \) and the width \( \Gamma_i \) for a given level were approximated by the following formulas

\[ \gamma_1^2 = \frac{\Gamma_1}{2P_2(E_1) - \Gamma_1 \frac{d\ln(E)}{dk}}, \quad \gamma_2^2 = \frac{\alpha^2 T_0}{2P_2(E_2)}, \quad \gamma_3^2 = \frac{\beta^2 T_0}{2P_2(E_3)}. \]  

(3)

The matrix elements for the 16 MeV doublet can then be expressed in terms of the matrix elements of the functions \( \psi_a \) and \( \psi_b \).

\[ M_{2\bar{2}} = \beta M_{0\bar{0}} \]

\[ M_{2\bar{3}} = -\alpha M_{0\bar{0}} \]

\[ M_{2GT} = \alpha M_{GJT} + \beta M_{GJT} \]

\[ M_{3GT} = \beta M_{GJT} - \alpha M_{GJT} \]

\[ M_{GJT} = \sqrt{2} \]

\[ M_{GJT} = 0 \]

\[ M_{GJT} = 0 \]

\[ M_{GJT} = 2.64 \]

The value of \( M_{GJT} \) was left as a free variable in the \( \chi^2 \) fit. It was also assumed that the contribution from \( M_{GJT} \) would not be significant and was held fixed at zero.
8Be endpoint distribution
present results vs. previous results

![Graph showing comparison between present and previous results for 8Be endpoint distribution.](image)
Neutrino energy spectrum