A direct search was made for a threshold kink in $^{63}\text{Ni}$ $\beta$-ray spectrum due possibly to a sizeable admixture of 17keV neutrino. A fine energy scan was performed using a magnetic spectrometer over the specific energy region with very high statistics and a very high signal-to-background ratio. The resultant mixing strength is $|U|^2 = (-0.011\pm0.033\text{(stat.)}\pm0.030\text{(sys.)})\%$ and its upper limit $|U|^2 < 0.073\%$ (95% C.L.). The result clearly excludes neutrinos with $|U|^2 \geq 0.1\%$ for the mass range from 11 to 24keV.

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0.073% (95% C.L.) UPPER LIMIT ON 17keV NEUTRINO ADMIXTURE

Takayoshi Ohshima*
National Laboratory for High Energy Physics, KEK
Oho 1-1, Tsukuba, Ibaraki 305, Japan

Abstract
A direct search was made for a threshold kink in $^{63}$Ni $\beta$-ray spectrum due possibly to a sizeable admixture of 17keV neutrino. A fine energy scan was performed using a magnetic spectrometer over the specific energy region with very high statistics and a very high signal-to-background ratio. The resultant mixing strength is $|U| = -0.011 \pm 0.033$ (stat.) $\pm 0.030$ (sys.) % and its upper limit $|U|^2 < 0.073$% (95% C.L.). The result clearly excludes neutrinos with $|U|^2 > 0.1$% for the mass range from 11 to 24keV.

INTRODUCTION
It was already found 58 years ago in 1934, that is a few years after the birth of the Fermi's $\beta$-decay theory, that the Kurie plots of measured $\beta$-ray spectra were not as straight as theoretically expected. A noticeable excess was seen in a low energy part of the spectrum. This discrepancy was at the time interpreted as an indication of necessity in revising the Fermi's theory, but not as a sign of heavy neutrino production. For instance, Konopinski and Uhlenbeck even proposed a revised theory in 1935 to explain the experiment. Various investigations carried out over about 20 years finally revealed that the low energy excess was the result of energy-losses in a source substance and of backscatterings at a source backing plate.

It is interesting to see that we have been again faced with a controversy on the $\beta$-ray spectral shape. This time, however, it is frequently interpreted as arising from a 1% admixture of 17keV neutrino, thus causing excitement among particle physicists.

CONSIDERATIONS
Even though the low-energy excess mentioned above can be reduced by experimental efforts, it never disappears. The first key to successful experiment is therefore how reliably one can control this effect, generally represented by a low-energy tail in the so-called Response Function $R(E)$. The backscattering usually dominates 20-30% of $R(E)$ in an experiment with a $\beta$-ray source separated from a detector, and exhibits approximately a flat distribution with the amplitude $\delta \ (keV)^{-1}$ down to zero energy. $\beta$-rays of energy $E'$ flow in to lower energies. This contribution can be estimated by approximating the spectrum $N(E)$ to be proportional to the square of the
energy measured from the endpoint $E_0$,

$$ N(E) \propto (\Delta E)^2, \quad \Delta E = E_0 - E. $$

Then

$$ \frac{\text{(Tail effect)}}{N(E)} \sim \int_{E_0}^{E} \frac{\delta \cdot N(E')dE'}{N(E)} \sim \frac{\delta}{3} \Delta E. \quad (1) $$

This is a cumulative effect over $E$ to $E_0$, so that, even though the amplitude is only $\delta \cdot O(10^{-3}$/keV), the net effect will be amplified by a factor $\Delta E$ of typically a few tens keV, easily resulting in a few % excess. Experiment's knowledge might be limited to $O(10^{-4}$/keV) precision, and then one ends up with $O(10^{-3})$ uncertainty in the measured spectrum.

Such effect can not be ignored in a search for a heavy neutrino with a mixing strength $|U|_1^2$ of 1% level. It has to be taken into account, for instance, as the so called shape correction term in a spectral formula. This term also includes other ambiguities, depending on experimental method. It should never be neglected unless experimentally justified.

Previous experiments measured a spectrum over a wide energy region and made a $\chi^2$ fit to the spectrum looking for a difference in curvature above and below the heavy neutrino production threshold $E_{th}$. In such data, the lower the $\beta$-ray energy $E$ is, the higher the statistical accuracy becomes because of $N(E) \propto (E_0 - E)^2$, but the larger the ambiguity is due to the tail effect. The situation is reversed at higher energies. As a result, the analysis will be strongly biased by the low energy portion of the data where the uncertainty is large.

In a high energy region, especially above $E_{th}$, an accuracy in background estimate significantly affects the curvature determination unless the signal-to-background ratio is large.

For instance, when a solid state detector is used, that ratio is only 6 - 60 even at the 17keV neutrino threshold due to signal pile-up and residual radioactive nuclei. Under such condition, inaccurate knowledge of the background might artificially create or blow out a heavy neutrino effect.

**EXPERIMENT**

We adopted the strategy to search directly for a kink due to the 17keV neutrino emission by means of a fine scan over narrow energy region in question with equally high statistics both above and below $E_{th}$. It is to avoid confusion between the kink and the usual shape correction term based on their distinct energy dependences. For the same purpose, $R(E)$ was experimentally determined with high precision using a monochromatic $\beta$-source. To be decisive on the mixing strength of 1% level, we aimed to achieve 0.1% sensitivity in $|U|_1^2$.

The $\beta$-ray source was $^{63}$Ni (580$\mu$Ci, $4 \times 20$mm$^2$, $E_0=66.7$keV, life-time=100years). It provides a high count rate, about 12 times the usual $^{35}$S at $E_{th}$. The monochromatic $\beta$-source for calibration was $^{109}$Cd (150$\mu$Ci, 62.5keV K conversion line, life-time=453days). To have the same thickness and the same backing plate as the active Ni source, this calibration source was made by mixing $^{109}$Cd with natural Ni atoms. Measured spectrum of the K conversion line accurately represents our response function that combines all the effects such as the spectrometer optics, the energy-loss and the backscattering. Fig.1(a) shows the $R(E)$ thus obtained after subtracting contributions from higher energy conversion lines.

The $\beta$-ray was analyzed by the $\pi \sqrt{2}$ type iron-free magnetic spectrometer at INS (Institute for Nuclear Study). The avail-
achieving two orders of magnitude improvement in statistics over the previous measurements. Signal-to-background ratio was as high as 1000 at the $E_0$, since problems with pile up or residual radioactive nuclei were a negligible contribution in the present setup.

A measurement was also made near $E_0$ where the heavy-neutrino effect should not exist and the shape correction term can be ignored. It provided us with one of the important ways to perform consistency checks.

**ANALYSIS**

The measured spectra $N_{\text{exp}}(E)$ were analyzed in terms of a $\chi^2$-fit to the formula,

$$N_{\text{exp}}(E) = A_0 \int \tilde{N}(E') [1 + \alpha(\Delta E')] \times R(E', E) dE' + B(G(E)$$

where $A_0$ represents a normalization constant, $\alpha$ a shape correction factor, $|U|^2$ a mixing strength, and $m^2_H$ the heavy neutrino mass squared. $E_T$ and $p$ are total energy and the momentum of the $\beta$-ray, respectively. $F(Z, E)$ is the radiatively corrected, relativistic Fermi-function. $B(G(E)$ represents the background spectrum as a combination of a constant and a small linear term.

First, the spectrum around $E_0$ was analyzed by setting both $|U|^2$ and $\alpha$ to zero. The best fit curve is shown in Fig.1(b), where the resultant $\chi^2$/degrees-of-freedom(d.o.f.) was 116.6/104 and the endpoint energy was

$$E_0 = (66945.9 \pm 2.7) \text{ eV}. \quad (4)$$

$B(G(E)$ determined here was used in following analyses.

Next, thirty individual spectra measured near $E_{1k}$ in individual chamber cells were an-

![Figure 1. (a): $^{109}$Cd K-line spectrum served as the response function $R(E)$. (b): Measured $^{63}$Ni $\beta$-spectrum near $E_0$ with the best fit curve.](image)
alyzed with the following five or six free parameters; $|U|^2$ for $m_{H} = 17\text{keV}$, $\alpha$, $A_o$, and two additional normalization factors between two sub-regions, with $E_o$ either fixed to the value (4) or left free. $R(E)$ was slightly different among 30 spectra because of the spectrometer optics. The resulting reduced $\chi^2$ values and $|U|^2$ values are shown in Fig.2 for the spectra recorded at individual chamber cells. Fig.3 compares the deviations from the best fits with either $|U|^2$ left free or fixed to 1%. They are the results of the 6-parameter fits, but there is no significant difference from those obtained with 5 parameters. It is clear from Fig.2(a) that $|U|^2$ fixed to 1% results in much larger $\chi^2$ values. 30 values of $|U|^2$ shown in Fig.2(b) average to $(-0.029 \pm 0.038\%)$ and give $\chi^2$/d.o.f. of 1.13.

$\chi^2$ vs. $|U|^2$ relation is shown in Fig.4 for individual spectra, while Fig.5 shows other parameters resulting from the same fits. The averaged endpoint energy comes out to be $<E_o> = (66942.8 \pm 5.5)\text{eV}$, (5) in good agreement with the separately measured result (4), and the shape correction factors ($\alpha$'s) are the order of $10^{-4}(\text{keV})^{-1}$. On the other hand, when $|U|^2$ is set to 1%, the average endpoint becomes $<E_o> = (66881.3 \pm 4.6)\text{eV}$, in clear contradiction with (4). The relative normalization factors obtained out of the fits are plotted in Fig.5(c) and 5(d). These factors can be independently evaluated as the ratio $\eta$ of the total counts summed over the 3 overlapped data points between successive sub-regions.
As seen in the figure, these two methods give completely consistent results only when $|U|^2$ is left free.

Finally global fits were made for all of the thirty spectra by treating $E_0$ and $|U|^2$ as common parameters. Fig. 6 shows the results, where 1800 data points are displayed in 50eV bins for the sake of illustration. Here we find $\chi^2$/d.o.f. = 1701/1678 = 1.01 and the best fit parameters turn out to be

$$E_0 = (66943.3 \pm 4.1) \text{ eV}, \quad (6)$$

$$|U|^2 = (-0.011 \pm 0.033) \% \quad (7)$$

The expected size of 1% heavy-neutrino mixing effect is indicated by the curve in Fig. 6(a). Fig. 6(b) is the result obtained with $|U|^2$ = 1% fixed, and in this case we find $\chi^2$/d.o.f. = 2467/1679 = 1.47 and $E_0 = (66882.4 \pm 4.6)$ eV. This $E_0$ value is again in clear contradiction with the separate measurement (4).

Table 1 summarizes the results of various fits. It is clear that the heavy-neutrino mixing $|U|^2$ is equivalent to zero in both individual and global fits. $\chi^2$ values are always larger by about 1000 units if 1% mixing is assumed, as seen in Table 1. Systematic errors arise from uncertainties in the $\beta$-ray transmission through the detector window and the tail component in $R(E)$. Compared to these, the error from the background estimation is an order of magnitude smaller because of our excellent signal-to-background ratio. The final result with the statistical and systematic

![Figure 4](image)

Figure 4. Relation of $\chi^2$ vs. $|U|^2$ for individual 30 spectra with 54 d.o.f. each. Closed circles are the $|U|^2$s obtained by the best fit.

![Figure 5](image)

Figure 5. $E_0$ (a), $\alpha$ (b), and two relative normalization factors (c) and (d) from the individual fits made with $|U|^2$ left free (closed circles) and fixed to 1% (open). The horizontal line in (a) indicates the averaged $E_0$, Eq. (5), obtained by the fit with $|U|^2$ free. The relative normalization factors are normalized by the $\eta$ (see text). The dotted curves indicate a range of the statistical uncertainty of the $\eta$. 

5
Figure 6. Deviations from the best global fit with $|U|^2$ free (a) and fixed to 1% (b). The curve in (a) indicates the size of 1% mixing effect of the 17keV neutrino. Resultant parameters of these fits are indicated in Table 1.

Table 1. Results of various fits with $m_H=17$keV. The number in < > is the average of the 30 resultant values obtained by the individual fit. Details are described in text.

| Fit near $E_0$ | $\chi^2$ | d.o.f. | $|U|^2$ (%) | $E_{\nu} - 66900$ (eV) |
|---------------|---------|--------|-------------|---------------------|
| Individual Fits | 116.6 104 | fixed to 0.0 | fixed to 45.9 | 45.9±2.7(stat.)±3.2(sys.) |
| $|U|^2=\langle-0.022±0.033\rangle$ | $<0.022±0.033>$ | fixed to 45.9 | $<18.7±4.6>$ |
| $|U|^2=\langle-0.029±0.038\rangle$ | $<-0.029±0.038>$ | $<42.8±5.5>$ |

$|U|^2=(0.029±0.038±0.028)$%, $|U|^2 < 0.077%$ at 95% C.L.

systematic errors; ±0.014% (window trans.), ±0.024% (R-tail)

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<th>Global Fits</th>
<th>2744.3 1680</th>
<th>fixed to 1.0</th>
<th>fixed to 45.9</th>
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<td>$</td>
<td>U</td>
<td>^2=\langle-0.029±0.038±0.028\rangle$</td>
<td>$&lt;-0.011±0.033&gt;$</td>
</tr>
<tr>
<td>$</td>
<td>U</td>
<td>^2=\langle-0.011±0.033±0.030\rangle$</td>
<td>$&lt;-0.011±0.033±0.030&gt;$</td>
</tr>
</tbody>
</table>

$|U|^2=(0.011±0.033±0.030)$%, $|U|^2 < 0.073%$ at 95% C.L.

systematic errors; ±0.013% (window trans.), ±0.027% (R-tail)

Study of smoothness
(see text) $<-0.008>$ fixed to 45.9
systematic errors is consistent with zero,
\[ |U|^2 = (-0.011 \pm 0.033 \pm 0.030) \% , \] (8)
and thus one can set its upper limit for the 17keV neutrino to
\[ |U|^2 < 0.073\% . \] (95\% C.L.)

The endpoint \( E_0 \) was obtained from two independent data sets, one measured near \( E_0 \) and the other around \( E_{th} \). The two results, Eq.(4) and Eq.(6), agree very well with each other and also with the value of \( E_0=(66946\pm20)\text{eV} \) measured by Hetherington et al.\(^5\).

In order to demonstrate that the shape correction term does not harm our experimental sensitivity on \( |U|^2 \), an additional analysis was performed in the following way. Each of the 30 spectra was prepared with the relative normalization among three energy regions done based on the number of counts in overlapped data points, the \( \eta \) normalization not by a fit. It was then divided into two parts: One below 50keV (A) that is sensitive to the 17keV neutrino effect, and the other above 50keV (B) that is not. First, a fit was made to the data in B with two free parameters \( \alpha \) and \( A_\alpha \) fixing \( E_0 \) to (4) and \( |U|^2 \) to zero. Then the resulting fit was extrapolated to the A region, and there we found \( \chi^2/d.o.f.=1.52 \) as an average over 30 spectra. When the 1\% mixing effect was added to the extrapolation, it considerably increased to 21.72. A next fit was made to the data in A with a single parameter \( |U|^2 \) fixing \( \alpha \) and \( A_\alpha \) to those obtained in the B region. This resulted in \( |U|^2 = -0.008\% \) with \( < \chi^2/d.o.f.>=0.97 \). As a whole, the study concludes that the spectra measured above and below \( E_{th} \) exhibit smooth continuation, that the shape correction factors determined above \( E_{th} \) well reproduce the data below \( E_{th} \) with a null mixing, and consequently that there is no structure at all hinting at the existence of the heavy neutrino.

**CONCLUSIONS**

New measurement, directly sensitive to a possible kink in the \( \beta \)-ray spectrum of \( ^{63}\text{Ni} \) due to the 17keV neutrino, was carried out by a fine energy scan with very high statistics and a very high signal-to-background ratio. The resulting mixing strength is
\[ |U|^2 = (-0.011 \pm 0.033 \pm 0.030) \% , \] (10)
which is 22 \( \sigma \) away from 1\%, its upper limit being
\[ |U|^2 < 0.073\% . \] (95\% C.L.) (11)

The study was extended to different masses of a heavy neutrino and its result is plotted in Fig.7. The curve corresponds to the upper limit at 95\% C.L. No neutrino exists with \( |U|^2 \geq 0.1\% \) in the mass range from 11 to 24keV.

![Figure 7.](image-url)
ACKNOWLEDGEMENT

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7. In our previous analysis reported in H. Kawakami et al., Phys. Lett. B287, pp. 48–50, (1992), the spectra of three sub-regions were uniquely normalized to have the same total counts over the three overlapped data-points between the sub-regions. The normalization errors were then statistically added to each data-point. The analysis described in the text should be taken as the revised one, although the difference between present and previous ones does not substantially affect the results.