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THE SOURCE SPECTRUM OF REACTOR ANTINEUTRINOS

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Abstract - The cumulative beta spectrum of $^{235}$U and $^{239}$Pu thermal neutron induced fission fragments was measured with a magnetic beta spectrometer in the range $E_B = 1.5$ to $8$ MeV. The beta spectra were converted in the correlated $\bar{\nu}_e$ spectrum of a nuclear reactor. Thus a basis is given for reactor neutrino experiments such as the search for neutrino oscillations.

The interpretation of experiments with reactor $\bar{\nu}_e$, such as the search for $\nu$ oscillations, depend on the knowledge of the $\bar{\nu}_e$ source spectrum of the reactor. This source spectrum is composed of a superposition of $\bar{\nu}_e$ spectra of beta decaying fission products in the reactor core. Most of these $\bar{\nu}_e$ are found below $\sim 10$ MeV.

A composition of this spectrum using experimental and calculated data for the individual fission products is found to be very difficult. Beta branches comprising several hundreds of fission products have to be taken into account and the various calculations differ considerably from each other (see comparison in refs. /1, 2/).

An experimental approach to this problem is possible by measuring the cumulated beta spectrum of the fission products. The difficulties inherent with measurements of this beta spectrum arise from the high $\gamma$ background, the strong decrease in intensity with energy and from a proper absolute calibration (per fission) of this spectrum. Finally the conversion into the correlated $\bar{\nu}_e$ spectrum needs much care, in particular when a precision of a few percent is demanded.

In the following we would like to discuss the experiments on these beta-spectra for $^{235}$U and $^{239}$Pu fission as performed at the magnetic spectrometer BILL /3/ of the High Flux Reactor, Grenoble. Since a part of this work has already been published elsewhere /1, 2/ we like to concentrate more on some possible systematic errors in this method.

The measurement of the cumulated beta-spectrum

The target arrangement is shown in fig. 1. Fig. 2 illustrates a beta spectrum measured on-line after 6 hours exposure time to neutrons. The reactor power was reduced to limit self-heating of the target. An accuracy of $\leq 5\%$ was achieved for the main part of spectrum /1, 2/. The electron beam emerging from the target is well separated from the $\gamma$-background by the sequence of the two double-focusing iron-core magnets of the BILL spectrometer. Electrons arising from the absorption of
fission correlated γ-rays in the cover foil are of an intensity of less than 0.3% compared with those from the beta decays. Another contamination of the beta spectrum may come from internal conversion electrons (ICE) competing with these γ-decays. The main component stems from the (n, γ) reaction on the fissile nucleus. Above ~ 1.5 MeV these ICE’s contribute by less than 1% to the cumulated beta spectrum, as can be estimated: for instance, for 235U and E = 1.5 MeV, the number of γ-rays from the (n, γ) reaction is roughly 0.6 γ’s per MeV, per absorbed neutron, given by γ-ray intensity distributions (ref. /4/) and the cross section ratio σ(n, γ) to σ(n, f). The internal conversion coefficients for common multipolarities is less than ~10^{-2} for Z = 92 and 1.5 MeV.

The resulting electron intensity gives < 6 x 10^{-3} per MeV to compare with the intensity of the beta spectrum of 1.31 per MeV /1/. Clearly individual lines may contribute more at such low energies, in particular if they are of multipolarity E0. Above ~ 2.5 MeV strong individual lines become unlikely due to the strongly increasing level density with nuclear excitation energy.

Conversion to the correlated \( \nu_e \) spectrum

The cumulated beta spectrum of the fission products is a very complex superposition of many branches with different \( E_\beta \) values, intensities and Z values (proton number). Our conversion method starts by approximating the experimental beta spectrum by about 25 hypothetical, allowed beta-branches \( \beta_i(E, E_\beta, Z) \) with amplitude \( a_i \). The mean value \( \bar{Z} \) used in the Fermi function is a function of \( E_\beta \), known from the average characteristic of fission products /2/. The final \( \nu_e \) spectrum is then the sum of the individually converted spectra

\[
N_\nu(E_\nu) = \sum_i a_i \beta_i(E, E_\nu, E_\beta, \bar{Z})
\]

The strongly decreasing intensity of the beta spectrum well defines the strength of the \( \beta_i \) branches, since a high energy branch will not significantly influence the intensity of a low energy branch.
A further test of this conversion method can be made using the approximate relation for relativistic beta decays:

\[ P_v (E_v) \sim P_\beta (E_{\text{tot}} - \Delta E) \]

\[ E_{\text{tot}} = E_\beta + m_e \]

\[ \Delta E \text{ Coulomb term} \]

With this approximation, calculated spectra \( N_{\text{cal}} \), \( N_{\nu} \) can be used for the conversion, if \( N_{\text{cal}} \) agrees reasonably well with our experimental beta spectrum \( N_{\text{exp}} \):

\[ N_{\nu} (E_v) = N_{\text{cal}} (E_v) \times \frac{N_{\text{exp}} (E_{\text{tot}} - \Delta E)}{N_{\text{cal}} (E_{\text{tot}} - \Delta E)} \]

Fig. 3 compares \( N_{\nu} (E) \) and \( N_\beta (E_{\text{tot}} - \Delta E) \) spectra. For simplicity \( \Delta E = 0 \) is chosen. The correlated deviation for \( N_{\nu} \) and \( N_\beta \) gives confidence to our conversion method, for which an uncertainty of 3 to 4% was estimated /2/.

Fig. 3 - Relative differences of the \( N_\beta \) and \( N_\nu \) spectra of the present work to various calculations: DVSM /5/, VSMS /6/ and KM /7/. \( E_{\text{tot}} \) denotes the energy including the rest mass. The deviations \( (N_{\text{exp}} - N_{\text{cal}})/N_{\text{exp}} \) between \( N_\beta \) and \( N_\nu \) are the same within a few percent.

The conversion method is based on the assumption of only beta decays with the statistical shape. For a further refinement the contribution of first-forbidden beta-decays and from radiative corrections in the beta-decay (bremstrahlung) must be discussed. A first estimate of the effect of radiative corrections modified the deduced \( N_\nu \) spectrum only slightly (< 1% at \( E_\nu = 4 \text{ MeV}, 3 \% \) at 7 MeV), using the theory of Sirlin /8/.

It should be noted that the comparison of the present result with the reaction rates of the \( \nu_e \) detector at the Gsigen power reactor /9/ gives information on the neutron life-time \( \tau_n \), since the cross section \( \sigma (p + \bar{\nu}_e + n + e^+) \) is proportional to \( 1/\tau_n \).
For the case of no-oscillations of neutrinos a value of $\tau_n = 882 \pm 41 \ (68\% \ c.l.)$ can be deduced. Allowing oscillations an upper limit $\tau_n < 923 \ s$ is given. Inversely this discussion shows the importance of a precise knowledge of $\tau_n$ for the interpretation of neutrino oscillation experiments with reactor neutrinos.

In conclusion the $\bar{\nu}_e$ source spectrum of reactors can be deduced from the correlated beta spectra of fission products. A precision better than 6\% can be achieved, including the uncertainty in the conversion of $N_\beta$ to $N_\nu$.

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