Possible implications of a reactor-status effect on the β+ decay rate of ^{22}Na

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Recently, a reproducible reactor-status effect was measured for the decay of ^{22}Na. However, the effect was not observable for the β- decay of ^{60}Co. Since no systematic cause for this effect was found, the possibility exists that it is caused by an interaction of reactor antineutrinos with the source nucleus. The observed effect is 18 orders of magnitude larger than for the antineutrino capture of a free proton. A possible explanation is a final-state interaction between the incoming antineutrino and a neutrino in the source nucleus. The effect has still to be confirmed by an independent measurement. In this paper, the consequences for applications in monitoring nuclear facilities are discussed, as well as the consequences for fundamental physics and the opportunities for resolving some outstanding questions about neutrino properties.

Keywords: Reactor antineutrinos; decay rate ^{22}Na and ^{60}Co; reactor monitoring; neutrino–antineutrino boson; Dirac/Majorana; neutrino mass; THz detection.

1. Introduction

In the search for an electron antineutrino detection method with sensitivity below the 1.8 MeV threshold for the inverse β decay reaction on a free proton, β decay counting experiments with ≈3 kBq ^{22}Na and ^{60}Co sources were conducted at Unit #1 (2.775 GW$_{th}$) of the Koeberg Nuclear Power Station in South Africa. The goal was to determine if the rate of decay is measurably influenced by a change in the ON–OFF status of such a reactor.[1]

This paper assesses the possible implications of the analysis of this set of measurements. In this paper, we summarize the set-up and data; for details the reader is referred to Ref. 1. The experimental setup consisted of a single 10.4 cm long, 10.4 cm diameter cylindrical NaI well counter with a 51 mm long, 12 mm wide axial well to

measure de-excitation and annihilation photons associated with β decay. Its volume and well shape were purposely chosen to use coincidence summing in the interval 170–2452 keV to differentiate between electron capture and β^+ emission in ^{22}Na. The Pb-shielded setup was placed in the seismic vault underneath the containment building, thereby shielding the measurement arrangement from the reactor core by 8 m of solid, uncompromised concrete. Background radiation, responsible for approximately 1% of the total count rate with either source placed in the NaI well, increased by merely 3% when the reactor status changed from OFF to ON. This small increase is semiquantitatively explained by fast neutrons exciting ^{208}Pb nuclei throughout the Pb castle.

In the offline analysis of the ^{22}Na data, three regions of interest (RoI) were set. Their labels and ranges are: TOT: 170–2452 keV, MED: 1151–1351 keV, and HI: 1353–2452 keV. HI exclusively contains pulses from β^+ decay, whereas MED captures both EC and β^+ decay. While TOT has maximum overlap with MED and HI, it also covers the two annihilation peaks and their continua. Considering also the branching ratios of ^{22}Na decay, TOT is thus dominated by β^+ decay. The rationale for coincidence summing is now clear: without it, distinguishing between the two decay modes with a γ-ray detector is more difficult as it requires accurate knowledge of the 511 and 1275 keV peak shape and efficiencies.

For ^{22}Na, two series of measurements were made, each comprising a ON-OFF-ON period of the reactor.[1] The ON and OFF periods are listed in Table 1.

Table 1. Reactor-status periods for two measurement series with the ^{22}Na source.

Series	Reactor status	Period (DOY 2013)	From	Until
1	ON1	3–43	3-Jan-2013	12-Feb-2013
1	OFF1	58–110	27-Feb-2013	20-Apr-2013
1	ON2	117–140	27-Apr-2013	20-May-2013
2	ON3	283–314	10-Oct-2013	10-Nov-2013
2	OFF2	320–361	16-Nov-2013	27-Dec-2013
2	ON4	367–405	2-Jan-2014	9-Feb-2014

The outcome of the analysis (see Ref. 1) may be summarized as the fractional activity change from OFF to ON and yields:

(a) $(ΔA/A)_{TOT}$ = [-3.02±0.14(*stat*)±0.07(*syst*)] x 10^{-4},
(b) $ΔA/A)_{MED}$ = [+1.44±0.42(*stat*)±0.22(*syst*)] x 10^{-4}, and
(c) $(ΔA/A)_{HI}$ = [-2.70±0.26(stat)±0.04(*syst*)] x 10^{-4}.

To minimize systematic effects, the count rate in a gate covering the sumpeak in the ^{60}Co spectrum was assessed. No significant difference between ON and OFF was obtained.

The negative signs for the RoI, TOT, and HI in the ^{22}Na data indicate that no additional process, such as neutron capture for example, is contributing to the count rate. This result points to an interference effect between the antineutrinos produced in the

fission and the β^+ emission in ^{22}Na. According to Eq. (12) in Ref. 1, $\sigma = \frac{\lambda}{\phi_v} \frac{|\Delta A|}{A}$ with $\phi_v{}^v$ being the antineutrino flux. The corresponding cross-section for the effect $((1.59 \pm 0.08)x10^{-25}$ cm^2) is 18 orders of magnitude larger than for the inverse beta decay process on a free proton; the ^{60}Co measurement was carried out, and an extensive search for systematic effects was undertaken without result. Hence, the present results may have considerable impact on nuclear safeguards implementation by applying the method to the detection and monitoring of nuclear facilities, such as reactors and subsurface facilities. Moreover, the result may also have an impact on fundamental physics, but for both, this will require independent confirmation.

In this paper, we focus on the potential applications, assuming that the effect of reactor status on the β^+ decay rate of ^{22}Na has been confirmed. To assess these applications, several additional assumptions have been devised regarding the properties of the reaction mechanism involved.

2. Applications to Monitoring Nuclear Facilities

In the search for devices to monitor nuclear facilities, the most common method is based on the detection of antineutrinos by the inverse beta decay (IBD) processes. In a recent paper by Kim,[2] an overview is given of various reactor monitoring projects. The disadvantage of the IBD based detectors is the small cross section of the IBD process, which results in large volume detectors that have to operate at short distances to the reactor. The advantage of the IBD measurements is that the energy spectrum of the antineutrinos can be measured precisely, breaking the degeneracy between reactor thermal power and fissile content that is inherent in detectors that rely on antineutrino rate measurement alone. Moreover, deconvolution models have been developed[3,4] that extract information about the core fissile content from spectral data, with predicted accuracies of detecting changes at the 8 kg level for weapons-grade or reactor grade plutonium, for reactor thermal powers less than 1000 MWt for a 5 tonne organic liquid detector at 15 m stand-off and 90 day measuring time.[3] This is to be compared to the measurements with a 3 kBq ^{22}Na source that used a 3 kg NaI detector at 16 m stand-off and an ON-OFF-ON period of about 100 days for a $\Delta\lambda/\lambda = -10^{-4}$ change in decay rate. The mechanism leading to the reactor-status effect and its antineutrino energy dependence are yet unknown, and so is the spectral sensitivity.[1]

Another recent development is the detection by means of coherent scattering.[5] Using a 14.6 kg CsI(Na) detector near the Oak Ridge Spallation neutron source, an effect was measured in about 300 days live time.

The Koeberg type of measurement would benefit from the 18 orders of magnitude larger cross section compared to IBD but would likely have little possibility to provide information on the fuel composition. The measurements indicate that the effect on the decay of the source could be measured at about 16 m from the core of the reactor, using a $\approx$3 kBq ^{22}Na source. A multiple detector system, containing 9 detectors with sources of 50 kBq for example, would allow detection of a similarly sized effect at a distance of

about 200 m, since the radiation flux decreases by the square root of the increase of the distance. This implies that a detector could be set up in a van located outside the reactor building, allowing remote monitoring of the reactor's core. We estimate that such a set-up, including Pb-shielding, would occupy about 1 m^3. A first attempt to measure the effect using a 50 kBq source failed due to the contributions of accidental coincidences to the spectrum.[6] To solve this problem requires investigations with faster scintillators and faster analogue to digital converters.

Another option to monitor nuclear facilities may be provided by optimizing the choice of the source. The limit of the count rate will be in the source strength. Assuming that the interaction of the (electron) antineutrinos takes place with one of the bound protons in the nucleus, one may look for a nucleus with a larger number of protons per becquerel. Unfortunately, most radionuclides capable of emitting positrons either have a shorter half-life than ^{22}Na or their decay is dominated by electron capture. The most promising radionucleus is ^{26}Al with a half-life of $7.17x10^5$ years. This is more than $2.7x10^5$ longer than the half-life of ^{22}Na and predominantly decaying by positrons (~80%). This implies that the number of protons per becquerel for ^{26}Al would be about $3x10^5$ times larger than for ^{22}Na. This factor is an order of magnitude larger than the size of the reactor status effect and implies that the β^+ decay would be fully suppressed during the reactor ON status.

This result indicates that the assumption of interaction with any bound proton is too simplistic. Interactions with closed-shell protons are unlikely since there is no equivalent neutron vacancy available (Pauli blocking). Moreover, like β decay, the J transfer determines if the transition is allowed or forbidden. In the β^+ decay of both ^{22}Na and ^{26}Al, the transitions are based on the angular momentum transfer and allowed and unique second forbidden Gamow–Teller transitions, respectively.[7] This implies that the reactor status effect on ^{26}Al will be reduced by several orders of magnitude compared to the effect on ^{22}Na.

From the above discussion, it is clear that the actual size of the effect will tell us more about the reaction mechanism and the role of the nuclear structure. It will also provide guidance in determining the corresponding distance to the facility with a single- or multiple-detector system. In our experimental work to date, we have tried unsuccessfully to acquire an ^{26}Al source. Despite the isotope's scarcity, we continue to pursue potential suppliers.

3. Fundamental Physics Aspects

Confirmation of the reactor status effect has consequences also for fundamental physics, potentially opening new avenues of investigation into questions about elementary particles. The basis for the reasoning is Fermi's Golden Rule, which expresses the transition rate between an initial and final state in terms of a quantum mechanical product of the wave functions involved and the interaction of the Hamiltonian and the density of

states. According to Fermi's Golden Rule, the decay constant λ is given by the following:

$$\lambda = \frac{2\pi}{\hbar}|M_{if}|^2 * \rho_{PS}, \tag{1}$$

where ρ_{PS} stands for the density of states (phase space). The matrix element M_{if} is defined as:

$$|M_{if}|^2 = < \Psi_i|H_{if}|\Psi_f >. $$

In our case, the operator H_{if} stands for the Gamov–Teller operator.

For the β$^+$ decay of ^{22}Na and for the reactor OFF, the initial and final wave functions are given by:

$$\Psi_i = \Psi_{^{22}Na(0)} \text{ and } \Psi_f = \Psi_{^{22}Ne(1)}\varphi_{e^+}\Psi_{\nu_e}, \tag{2}$$

and

$$|M_{if}|^2 = < \Psi_{^{22}Na(0)}|H_{if}|\Psi_{^{22}Ne(1)}\varphi_{e^+}\Psi_{\nu_e} >, \tag{3}$$

which leads to λ$_{\text{OFF}}$.

For reactor ON, the source decays in a flux of antineutrinos with the following conditions:

$$\Psi_i = \Psi_{^{22}Na(0)}\Psi_{\overline{\nu_e}} \text{ and } \Psi_f = \Psi_{^{22}Ne(1)}\varphi_{e^+}\Psi_{\nu_e}\Psi_{\overline{\nu_e}}. \tag{4}$$

Note that in the outgoing channel, the wave functions of neutrino and antineutrino are evident. If these two antiparticles have a final-state interaction and subsequently annihilate, the matrix element becomes:

$$|M_{if}|^2 = < \Psi_{^{22}Na(0)}\Psi_{\overline{\nu_e}}|H_{if}|\Psi_{^{22}Ne(1)}\varphi_{e^+} > * < \Psi_{\nu_e}|H_{fs}|\Psi_{\overline{\nu_e}} >, \tag{5}$$

where H_{fs} is the operator for the final-state interaction. This equation leads to λ$_{\text{ON}}$.

In the last set of equations, we note the combination of an antineutrino and a neutrino. If they combine, they may form a neutral boson with J$^\pi$ = 0$^+$ or 1$^+$. If this boson decays by emitting annihilation radiation, two photons will be emitted in opposite directions with an energy equal to the mass of the (anti)neutrino. This process is similar to the formation and decay of positronium, which also has a "para" and an "ortho" state, decaying by annihilation radiation. The quasibound antineutrino-neutrino state is a relative s-state resonance with a "resonance" energy less than 1.8 MeV, which is the threshold of the antineutrino capture by a free proton. Similar quasibound resonance states are known to exist in nuclear physics for particle transfer reactions. For example, we refer to reactions within the outgoing channel for ^{8}Be or ^{2}He, decaying to two α-particles or two protons, respectively.[8] In both cases, the cross-section of the reaction shows a strong increase at low energies.

One of the open questions about neutrinos is whether or not they are their own antiparticles. To phrase the question differently, are neutrinos Majorana or Dirac particles? In Fig. 1, the reactions of reactor antineutrinos with decaying ^{22}Na and ^{60}Co nuclei are depicted schematically. From this schematic, one notices the antineutrino–neutrino and antineutrino–antineutrino pairs for ^{22}Na and ^{60}Co, respectively. If neutrinos

are their own antiparticle (Majorana), then both sources would show the same effect. However, if the reactor status effect is confirmed to be present in ^{22}Na but absent in ^{60}Co, and the particles form a quasibound state, the neutrinos are Dirac particles.

A way to check on the formation of the quasibound state is to measure its decay. If the resonance energy is below 1.022 MeV, the only way to decay for the quasibound state is by electromagnetic (EM) radiation with an annihilation energy equal to the neutrino mass. The mass of the neutrino is not precisely known and ranges from 0.05 to 2 eV.[9] The frequency of the corresponding EM radiation is 12 to 240 THz.

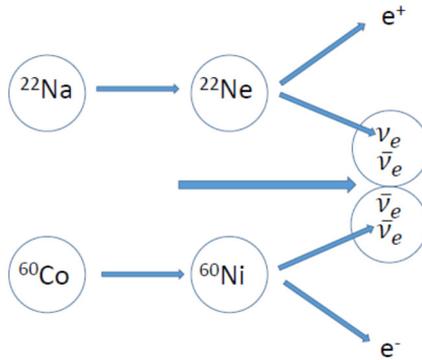
Fig. 1. Schematic representation of the interaction of reactor antineutrinos with neutrinos and antineutrinos released in the decay of ^{22}Na and ^{60}Co, respectively.

4. A Proposal for a Measurement Setup

Measuring very low intensity THz radiation in this frequency range requires detectors to be cooled to milliKelvin temperatures. The lowest noise detectors currently available are transition edge sensors (TES). A TES is a thermal sensor that makes use of the change in resistance when a superconductor transitions from superconducting to normal state. Equipped with a suitable absorber and weakly coupled to the thermal bath by thin SiN strips, detection of radiation from far-infrared to X rays is possible.[10]

The TES can be used as a calorimeter, which enables direct determination of the photon energy. Current state-of-the-art detectors used in astrophysics research exhibit an energy resolution of 0.15 eV for near-infrared photons.[11] Integration of a mere 10 photons is required to obtain the wanted accuracy of 0.05 eV, which takes just a few seconds' integration time, depending on the coupling efficiency. Potentially, this level of detector sensitivity would provide a tool to exploit the correlated emission of the two THz photons, thus distinguishing these neutrino events from the background.

The above assumptions hold if the measurement setup is thermally stable and without interference from outside events. Even when optimized for far-infrared radiation, a Planck cosmic-microwave-background mission has shown that the calorimeter is sensitive to gamma and X rays.[12] In the experiment proposed in this paper, the gamma- and X-ray powers are more than 10 orders of magnitude larger than that of the THz

signal. The main challenge will be preventing this interference from being detected by the calorimeter. To this end, we foresee a combination of a gamma-ray and an X-ray absorber and mirrors that are transparent for ionizing radiation, but reflect the THz radiation (see Fig. 2). To assess the effectiveness of these measures, including synchronized detection for the two photons, we will require a more detailed, preferably experimental, study.
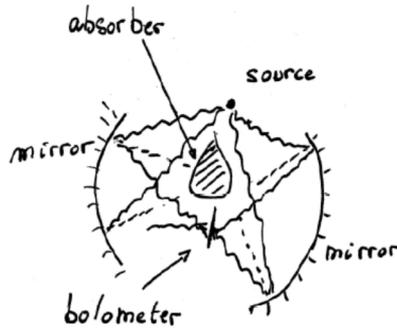

Fig. 2. A sketch of a set-up to measure THz radiation emitted by a quasibound antineutrino-neutrino boson.

5. Discussion and Conclusions

This paper elaborates upon the set of measurement results in which the count rate of a ^{22}Na and a ^{60}Co source were measured at close distance to a nuclear reactor during ON and OFF status. In these measurements, a *ΔA/A* effect of about -3x10^{-4} was observed for ^{22}Na. The results were reproduced in a separate measurement but were not observed with the ^{60}Co source.[1]

If this effect is the result of reactor antineutrinos interacting with the source nuclei, then the cross-section for this reaction is 18 orders of magnitude larger than the antineutrino capture by a free proton. Such a result has far-ranging implications for applications and fundamental physics. Although before such a result will be accepted as real, it should be reproduced in an independent measurement. Nevertheless, it is worthwhile to explore the possibilities such a new phenomenon opens and to lay out how these possibilities can be explored.

In this paper, we have suggested the possibilities for monitoring nuclear facilities at further distance with rather compact detectors. A potential increase in sensitivity may come from the use of ^{26}Al as a source, even though the unknown reaction mechanism strongly determines the extent of improved sensitivity and thereby the reduction in size and weight of such systems. In one of the most optimistic scenarios, drone-based systems may become feasible.

In the field of fundamental physics, we have indicated that if the effect is real and the mechanism for the enhancement in cross section is connected to the formation of a quasibound boson, the present ^{22}Na results that do show an effect compared to the ^{60}Co result that do not show an effect can be understood, assuming (anti)neutrinos are Dirac

particles. In that case, the decay of the quasibound antineutrino–neutrino boson should lead to EM radiation in the THz range, allowing for a direct measurement of the (anti)neutrino mass. In that case, we propose a methodology based on the experience of space research in which THz radiation is measured with bolometers.

In conclusion, with this quite speculative exploration of the potential given by the recently measured reactor-status effect on the decay of ^{22}Na, two outstanding questions regarding the properties of neutrinos may be resolved. In addition, the use of antineutrinos in safeguarding nuclear reactors and possibly tracing illicit storage of nuclear materials with compact antineutrino detectors are two of the potential applications. We eagerly await an independent assessment of the reactor status effect on ^{22}Na.

Acknowledgements

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