CONF-9504276--1
DOE/ER/40537--91

Development of a Compact 20 MeV Gamma-Ray Source for Energy Calibration at the Sudbury Neutrino Observatory

A. W. P. Poon[1] , M. C. Browne[2] and R. G. H. Robertson
Nuclear Physics Laboratory, University of Washington, Seattle, WA 98195, U.S.A.

C. E. Waltham
Department of Physics, University of British Columbia, Vancouver, B.C., Canada V6T 1Z1

N. P. Kherani
Ontario Hydro Technologies, 800 Kipling Avenue, Toronto, Ontario, Canada M8Z 5S4

Abstract

The Sudbury Neutrino Observatory (SNO) is a real-time neutrino detector under construction near Sudbury, Ontario, Canada. The SNO collaboration is developing various calibration sources in order to determine the detector response completely. In this paper, a brief description of the calibration sources being developed by the collaboration will be presented. One of these, a compact ^{3}H(p,γ)^{4}He source, which produces 20 MeV γ-rays, will be described.

1 Introduction

The Sudbury Neutrino Observatory (SNO) is a Čerenkov detector employing 1000 tonnes of heavy water (D_2O), housed in an acrylic vessel, as target. The Čerenkov light is detected by 9600 20-cm photomultiplier tubes mounted spherically around the acrylic vessel in the 7000-tonne light water shield. SNO is a laboratory devoted to study the properties of neutrinos and to resolve the "solar neutrino problem"— a deficit of ν_e coming from the Sun [1, 2, 3, 4]. SNO is now in its final phase of construction in an excavated cavern 2070m below ground in the INCO nickel mine near Sudbury, Ontario, Canada.

Neutrinos interact with the deuterons and the electrons through the following reaction channels:

$$\begin{aligned}
\nu_e + d &\rightarrow p + p + e^- - 1.44\ \text{MeV} &(1)\\
\nu_x + d &\rightarrow p + n + \nu_x - 2.22\ \text{MeV} &(2)\\
\bar{\nu}_e + d &\rightarrow n + n + e^+ - 4.03\ \text{MeV} &(3)\\
\nu_x + e^- &\rightarrow \nu_x + e^- &(4)
\end{aligned}$$

The first reaction is a charged-current (CC) interaction solely of electron neutrinos. The second reaction is a neutral-current (NC) reaction which can be initiated with equal probability by all flavours of neutrinos and their antiparticles. The third reaction is a charged-current interaction of the electron anti-neutrinos (CA), whilst the last reaction is the elastic scattering of neutrinos by electrons (ES). With the capability to detect all flavours of neutrinos and their antiparticles, SNO will be able to determine the origin of the "solar neutrino problem," whether it is unknown solar physics or physics beyond the standard electroweak model. In particular, SNO will be able to detect neutrino oscillations, a mechanism in which a massive neutrino "oscillates" from one flavour to another.

The SNO detector is a very complicated detector. It is necessary to understand the detector response completely in order to extract physics reliably from the data. An arsenal of calibration sources is being developed for the purpose of calibrating the detector. In this paper, we shall first briefly discuss the various calibration sources being developed for the SNO detector. Then we shall focus our attention on one particular calibration source under development — a 20 MeV γ-ray source, in which the γ-rays are produced through the radiative-capture reaction ^{3}H(p,γ)^{4}He.

---

[1] Permanent address: Department of Physics, University of British Columbia, Vancouver, B.C., Canada V6T 1Z1

[2] Permanent address: Department of Physics, North Carolina State University, Raleigh, NC 27695, U.S.A.

2 Calibration of the SNO Detector

The calibration of the SNO detector will be achieved by the insertion of optical light, neutron, β and γ sources into the heavy water and the outer light water regions. The calibration sources cover a wide range of output and will be placed at a sufficient variety of positions in the detector so that the necessary understanding of the detector response is acquired. In the following, we shall describe the calibration sources being developed by the SNO collaboration.

2.1 Optical light sources

Optical light sources to determine the optical light attenuation and scattering in the heavy water, the light water and the acrylic vessel. They will also be used to determine the timing and the quantum efficiencies of the photomultiplier tubes.

The optical properties of the detector and the characteristics of the photomultiplier tubes will be established by means of a "laser ball." A N_2 laser is used to pump separate dye lasers to provide four separate wavelengths in the range of 337 nm and 386 nm. The laser light is transported to a diffuser ball through an optic fibre.

The short wavelengths are where the D_2O and the acrylic attenuations largest. The frequency response of the photomultiplier tubes must also be determined *in situ*. The SNO collaboration plans to use a fast N_2 pulser lamp and light filters to produce light with wavelengths less than 337 nm.

To achieve accurate photomultiplier tube timing calibration, the SNO collaboration has developed a sonoluminesence source. The laser ball and the laser lamp are not ideal for this purpose because of the wavelength dependence of light dispersion in the optic fibre and the filters. Optical light pulses of width <100 ps are emitted when sound waves compress the air bubbles in water — sonoluminescence. The frequency spectrum of such a source is similar to that of a blackbody ranging from several thousand to tens of thousands of Kelvin.

2.2 Neutron sources

Because an excessive neutral current to charged current signal ratio in SNO would indicate physics beyond the standard electroweak model, a thorough understanding of the neutron efficiencies is therefore of utmost importance. The default neutron source to be used for neutron calibration at SNO is a ^{252}Cf fission source. A ^{17}N β-n source is also under development at the moment.

The ^{252}Cf triggerable fission source will be housed in an acrylic capsule where a small plastic scintillator disc is also located. The fission source produces on average 4 neutrons and 20 γ-rays per fission. The trigger will be provided by the scintillator light emitted from the scintillator disc.

The ^{17}N source β-n decay branches have a total branching ratio of about 95%. Whilst the average neutron energy is about 2 MeV for the ^{252}Cf source, the ^{17}N source has somewhat lower neutron energies, dominated by the 0.38 MeV and the 1.17 MeV branches. One feature of this source is that it would be able to use the same transport system as another proposed $\beta - \gamma$ source ^{16}N.

2.3 β and γ sources

Relativistic electrons and γ-rays will be used for energy calibration, for understanding Čerenkov light production in D_2O and H_2O, and for understanding deuteron photodisintegration background in D_2O. An accurate determination of the energy calibration constants is important because the SNO CC energy spectrum is susceptible to distortion if the neutrinos are indeed massive, according to some theoretical models, the Mikheyev-Smirnov-Wolfenstein (MSW) mechanism[5] for instance. Therefore, a thorough understanding the background in SNO is crucial to the determination of the CC to NC ratio. The SNO collaboration is developing several β and γ sources with energies ranging from less than 2 MeV to 20 MeV.

In the ^{228}Th plated wire proportional counter source, the trigger signal will be provided by the β emitted by ^{208}Tl, which is a daughter in the natural Th chain. Subsequent to the β decay is a prompt γ of energy up to 2.6 MeV. This source is particularly useful in understanding the deuteron photodisintegration background, as most of the background in SNO will come from the $\beta - \gamma$ decays in the natural ^{232}Th and ^{238}U chains.

Another calibration source, namely the ^{24}Na source, is being developed to help the SNO collaboration to understand the $\beta-\gamma$ signal from the natural chains. ^{24}Na simultaneously emits two γ rays with energies of 1.37 and 2.74 MeV. Therefore, it can serve both as an energy calibration and as a fair simulation of the $\beta-\gamma$ background with the Compton electron from the 1.37 MeV γ mimicking the β.

There are two principal ^{16}N decay modes. It produces a β with an endpoint of 4.27 MeV and a γ of 6.13 MeV 60% of the time, whilst it produces a 10.4 MeV endpoint β with a 29% branching ratio. The convoluted $\beta-\gamma$ spectrum and the 10.4 MeV endpoint β spectrum provide a spectrum for energy calibration.

The two nuclei ^{8}Li and ^{8}B are mirror nuclei and have similar beta endpoint energies: ^{8}Li has a β^- endpoint of 13 MeV, whilst ^{8}B has a β^+ endpoint of 14 MeV. This makes ^{8}Li an ideal electron source to mimic the ^{8}B solar neutrino spectrum, which is what SNO is sensitive for. The ^{8}Li will be produced via the reaction ^{11}B(n,α)^{8}Li and the ^{8}Li nuclei will be transported by an aerosol to a decay chamber. The decay chamber will be a wire chamber so that the ^{8}Li decays are tagged by the 2α decay of its daughter, ^{8}Be.

Finally, the SNO collaboration is also developing two"accelerator"-type γ-ray calibration sources involving the radiative-capture reactions ^{7}Li(p,γ)^{8}Be and ^{3}H(p,γ)^{4}He. Both of these sources accelerate protons toward a target in a compact ion source. The p^{7}Li source accelerates protons up to about 80 keV to generate γ-rays at 14.2 MeV and 17.3 MeV. The p^{3}H source accelerates protons to a lower energy up to 20 keV because of a lower Coulomb barrier in ^{3}H compared to ^{7}Li. In the following section, we shall devote our discussion to this p^{3}H source.

3 ^{3}H(p,γ)^{4}He 20 MeV γ-ray Source

With the ^{8}B neutrino spectrum endpoint at 15 MeV and the *hep* neutrino energy endpoint at 18.77 MeV, this calibration source will serve to provide an energy calibration point above the solar neutrino energy. This energy calibration point is also a convenient point for calibrating the possible supernova neutrino events when there is a supernova explosion in a nearby galaxy.

There are several constraints in designing this source. It has to be compact and portable, as it will be lowered to the centre of the SNO detector

through the 145-cm diameter neck of the acrylic vessel. The neutron production rate has to be low to ensure SNO's neutral current sensitivity to supernova neutrinos during the scheduled high energy γ calibration. Even though the Q-value of ^{3}H(p,n)^{3}He is -0.763 MeV, which gives a reaction threshold of 1.02 MeV, impurities in the beam and the target will give rise to undesired neutrons through the ^{2}H(t,n)^{4}He, ^{3}H(d,n)^{4}He, and ^{3}H(t,nn)^{4}He reactions. So the discharge hydrogen gas and the target tritium must be of very high isotopic purity. The solid tritium target must also have a high thermal stability to minimise tritium gas mixing into the discharge gas.

Fig. 1 shows the design of the source. It can be divided into two sections: the gas discharge line and the target chamber.

The gas discharge line is principally a cold cathode Penning source. The anode E2 is biased at +2 kV, whilst the cathodes E1, and E3 are grounded. In the design, efforts were made to minimise ion loss to the inner wall; hence, a higher on-target beam current can be attained for a given discharge current. Permanent ceramic magnet rings M provide a 1 kG axial magnetic field keeping the electrons from hitting the anode; hence, generating more discharge. A Zr-V-Fe alloy-type getter pump is attached to E1. The getter pump serves as the dispenser of hydrogen gas. Once a discharge is established in the hydrogen gas, ions (H$^+$, H_2^+ and H_3^+) are accelerated towards the target mounted at the end of the beam line. The ion acceleration is achieved through a -15 to -20 kV bias on the target chamber. In this scheme, the construction of complicated accelerating and focusing electrodes is avoided, hence, keeping the length of the source to a minimum. In fact, the length of the source is only 40 cm.

The target we selected for this source is a solid Sc^{3}H$_2$, primarily because of its good thermal stability. It will be prepared at the Tritium Laboratory of Ontario Hydro Technologies in Toronto, Ontario, Canada. The tritium gas to be used for the target has a high hydrogen isotopic purity: 0.79% ^{1}H, 0.12% ^{2}H, 99.09% ^{3}H. It is clear from Fig. 1 that the source is a sealed one, minimising the hazard of tritium contamination.

The electro-optics of the ion source was first computer simulated and subsequently tested experimentally. The beam current has been measured using two independent methods: by calorimetry and by beam profile integration. In the calorimetry measurement, the temperature of a copper target was monitored. The beam power was later calibrated by an electric heater embedded in the target. We designed and constructed a special Faraday cup for measuring the beam profile. The cup was biased such that secondary electron effects were minimised. The beam current measured by the two methods agree with each other within experimental error. Fig. 2 shows the results of the beam current measurement. It is clear from the figure that we can get a total ion current of more than 100 μA at an accelerating voltage of 20 kV when the ambient H_2 pressure is less than 0.8 mTorr.

We also designed and constructed a mass spectrometer to measure the mass composition of the ion beam. Ions of different masses are separated by a magnetic field perpendicular to the ion beam propagation. Our experiment showed that protons compose (63±15)% of the beam, the rest being H_2^+ and H_3^+ molecular ions, at an ambient H_2 partial pressure of 0.3 mTorr. With such a high beam current and an expected minimum triton to scandium stoichiometric ratio of 1 to 1, the source will be capable of producing 1 γ a second, which is one of the design criteria of the source.

We are now in the process of making a deuterated scandium target Sc^2H_2 on molybdenum substrate to fully test out the tritiated target fabrication procedure before using the tritium facility at Ontario Hydro Technologies.

4 Conclusions

The calibration sources being developed for calibrating the SNO detector cover a broad range of energies. Calibration constants can be extracted reliably using this extensive set of sources. A thorough understanding of the SNO detector will enable the SNO collaboration to identify the source of the "solar neutrino problem."

References

[1] Homestake Collaboration, *Nucl. Phys.* **B38** (Proc. Suppl.), 47 (1995).

[2] Kamiokande Collaboration, *Nucl. Phys.* **B38** (Proc. Suppl.), 55 (1995).

[3] GALLEX Collaboration, *Phys. Lett.* **B327**, 377 (1994).

[4] SAGE Collaboration, *Phys. Lett.* **B328**, 234 (1994).

[5] S.P. Mikheyev and A. Yu. Smirnov, *Yad. Fiz.* **42**, 1441 (1985); L. Wolfenstein, *Phys. Rev.* **D17**, 2369 (1985).

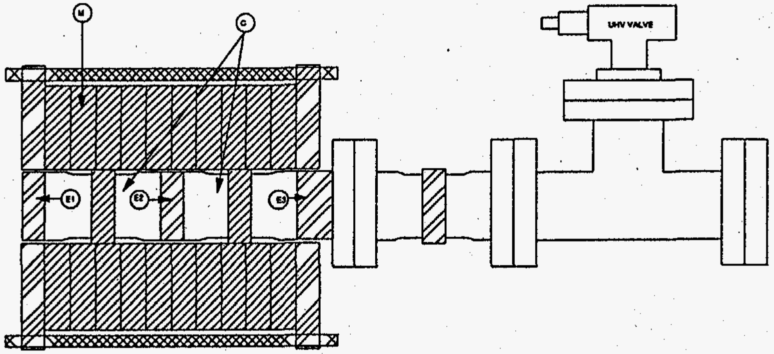

Figure 1.

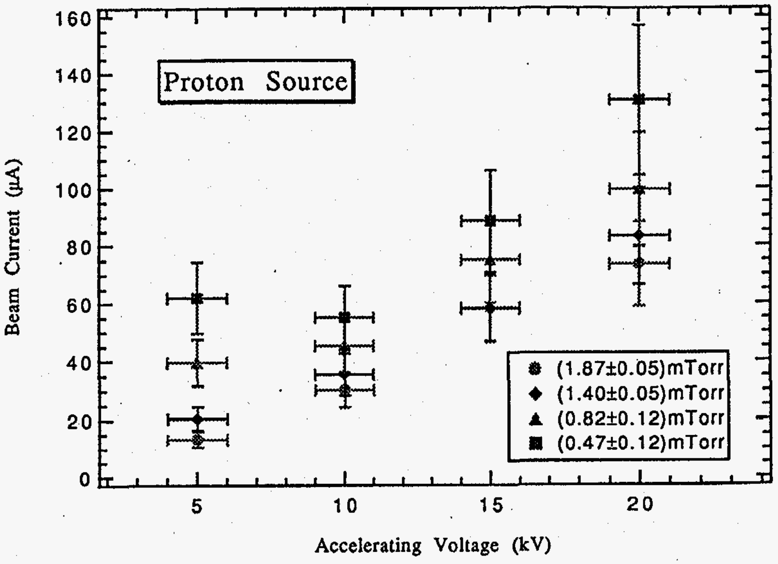

Figure 2.

Development of a Compact 20 MeV Gamma-Ray Source for Energy Calibration at the Sudbury Neutrino Observatory

A. W. P. Poon[1] , M. C. Browne[2] and R. G. H. Robertson
Nuclear Physics Laboratory, University of Washington, Seattle, WA 98195, U.S.A.

C. E. Waltham
Department of Physics, University of British Columbia, Vancouver, B.C., Canada V6T 1Z1

N. P. Kherani
Ontario Hydro Technologies, 800 Kipling Avenue, Toronto, Ontario, Canada M8Z 5S4

Abstract

The Sudbury Neutrino Observatory (SNO) is a real-time neutrino detector under construction near Sudbury, Ontario, Canada. The SNO collaboration is developing various calibration sources in order to determine the detector response completely. In this paper, a brief description of the calibration sources being developed by the collaboration will be presented. One of these, a compact $^3H(p,\gamma)^4He$ source, which produces 20 MeV γ-rays, will be described.

1 Introduction

The Sudbury Neutrino Observatory (SNO) is a Čerenkov detector employing 1000 tonnes of heavy water (D_2O), housed in an acrylic vessel, as target. The Čerenkov light is detected by 9600 20-cm photomultiplier tubes mounted spherically around the acrylic vessel in the 7000-tonne light water shield. SNO is a laboratory devoted to study the properties of neutrinos and to resolve the "solar neutrino problem"— a deficit of ν_e coming from the Sun [1, 2, 3, 4]. SNO is now in its final phase of construction in an excavated cavern 2070m below ground in the INCO nickel mine near Sudbury, Ontario, Canada.

Neutrinos interact with the deuterons and the electrons through the following reaction channels:

$$\begin{aligned}
\nu_e + d &\rightarrow p + p + e^- - 1.44\ \text{MeV} \qquad (1)\\
\nu_x + d &\rightarrow p + n + \nu_x - 2.22\ \text{MeV} \qquad (2)\\
\bar{\nu}_e + d &\rightarrow n + n + e^+ - 4.03\ \text{MeV} \qquad (3)\\
\nu_x + e^- &\rightarrow \nu_x + e^- \qquad (4)
\end{aligned}$$

The first reaction is a charged-current (CC) interaction solely of electron neutrinos. The second reaction is a neutral-current (NC) reaction which can be initiated with equal probability by all flavours of neutrinos and their antiparticles. The third reaction is a charged-current interaction of the electron anti-neutrinos (CA), whilst the last reaction is the elastic scattering of neutrinos by electrons (ES). With the capability to detect all flavours of neutrinos and their antiparticles, SNO will be able to determine the origin of the "solar neutrino problem," whether it is unknown solar physics or physics beyond the standard electroweak model. In particular, SNO will be able to detect neutrino oscillations, a mechanism in which a massive neutrino "oscillates" from one flavour to another.

The SNO detector is a very complicated detector. It is necessary to understand the detector response completely in order to extract physics reliably from the data. An arsenal of calibration sources is being developed for the purpose of calibrating the detector. In this paper, we shall first briefly discuss the various calibration sources being developed for the SNO detector. Then we shall focus our attention on one particular calibration source under development — a 20 MeV γ-ray source, in which the γ-rays are produced through the radiative-capture reaction $^3H(p,\gamma)^4He$.

---

[1] Permanent address: Department of Physics, University of British Columbia, Vancouver, B.C., Canada V6T 1Z1

[2] Permanent address: Department of Physics, North Carolina State University, Raleigh, NC 27695, U.S.A.

2 Calibration of the SNO Detector

The calibration of the SNO detector will be achieved by the insertion of optical light, neutron, β and γ sources into the heavy water and the outer light water regions. The calibration sources cover a wide range of output and will be placed at a sufficient variety of positions in the detector so that the necessary understanding of the detector response is acquired. In the following, we shall describe the calibration sources being developed by the SNO collaboration.

2.1 Optical light sources

Optical light sources to determine the optical light attenuation and scattering in the heavy water, the light water and the acrylic vessel. They will also be used to determine the timing and the quantum efficiencies of the photomultiplier tubes.

The optical properties of the detector and the characteristics of the photomultiplier tubes will be established by means of a "laser ball." A N_2 laser is used to pump separate dye lasers to provide four separate wavelengths in the range of 337 nm and 386 nm. The laser light is transported to a diffuser ball through an optic fibre.

The short wavelengths are where the D_2O and the acrylic attenuations largest. The frequency response of the photomultiplier tubes must also be determined *in situ*. The SNO collaboration plans to use a fast N_2 pulser lamp and light filters to produce light with wavelengths less than 337 nm.

To achieve accurate photomultiplier tube timing calibration, the SNO collaboration has developed a sonoluminesence source. The laser ball and the laser lamp are not ideal for this purpose because of the wavelength dependence of light dispersion in the optic fibre and the filters. Optical light pulses of width <100 ps are emitted when sound waves compress the air bubbles in water — sonoluminescence. The frequency spectrum of such a source is similar to that of a blackbody ranging from several thousand to tens of thousands of Kelvin.

2.2 Neutron sources

Because an excessive neutral current to charged current signal ratio in SNO would indicate physics beyond the standard electroweak model, a thorough understanding of the neutron efficiencies is therefore of utmost importance. The default neutron source to be used for neutron calibration at SNO is a ^{252}Cf fission source. A ^{17}N β-n source is also under development at the moment.

The ^{252}Cf triggerable fission source will be housed in an acrylic capsule where a small plastic scintillator disc is also located. The fission source produces on average 4 neutrons and 20 γ-rays per fission. The trigger will be provided by the scintillator light emitted from the scintillator disc.

The ^{17}N source β-n decay branches have a total branching ratio of about 95%. Whilst the average neutron energy is about 2 MeV for the ^{252}Cf source, the ^{17}N source has somewhat lower neutron energies, dominated by the 0.38 MeV and the 1.17 MeV branches. One feature of this source is that it would be able to use the same transport system as another proposed $\beta - \gamma$ source ^{16}N.

2.3 β and γ sources

Relativistic electrons and γ-rays will be used for energy calibration, for understanding Čerenkov light production in D_2O and H_2O, and for understanding deuteron photodisintegration background in D_2O. An accurate determination of the energy calibration constants is important because the SNO CC energy spectrum is susceptible to distortion if the neutrinos are indeed massive, according to some theoretical models, the Mikheyev-Smirnov-Wolfenstein (MSW) mechanism[5] for instance. Therefore, a thorough understanding the background in SNO is crucial to the determination of the CC to NC ratio. The SNO collaboration is developing several β and γ sources with energies ranging from less than 2 MeV to 20 MeV.

In the ^{228}Th plated wire proportional counter source, the trigger signal will be provided by the β emitted by ^{208}Tl, which is a daughter in the natural Th chain. Subsequent to the β decay is a prompt γ of energy up to 2.6 MeV. This source is particularly useful in understanding the deuteron photodisintegration background, as most of the background in SNO will come from the $\beta - \gamma$ decays in the natural ^{232}Th and ^{238}U chains.