Quick Introduction to Neutrino Detectors

In a nuclear reactor, fission emits large numbers of subatomic particles called *neutrinos*. These particles leave the reactor building in all directions and cannot be shielded. Detection technology now exists to measure these emissions and potentially use them to monitor reactors and associated facilities. Reactor neutrino detection has been demonstrated at distances of 10 m to 100 km, aboveground and belowground, and with corresponding detector sizes of 1–1,000 metric tons.

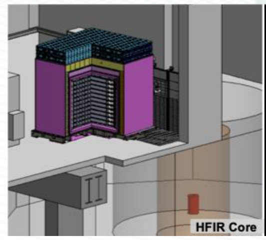
Currently, neutrino detectors can provide three important pieces of information about reactors:

1. **Reactor state (on/off):** Neutrino emissions are much higher when a reactor is operating. A neutrino detector can detect a reactor turning on or off from a distance.
2. **Reactor power:** Measuring the rate of neutrino emissions from a reactor reveals the reactor's power level in real time.
3. **Fissile content of core:** Observing the rate and energy spectrum of neutrino emissions from a reactor over time can provide information about the core contents, such as removal of plutonium from the core.

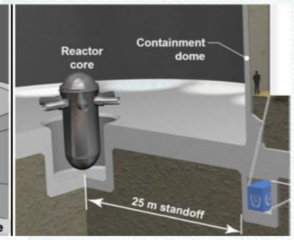
With further research and development, neutrino detectors could provide the following information:

- **Isotope production in reactors:** Neutrino detectors could look for the distinctive signals of isotope production technology, including plutonium breeding blankets and tritium production via lithium bars.
- **Irradiated fuel:** After removal from a reactor, fuel continues to produce low-level neutrino emissions, which could be monitored in fuel storage facilities.
- **Post incident state of a reactor facility:** After an accident, a neutrino detector could provide information about the state of the reactor core and facility.

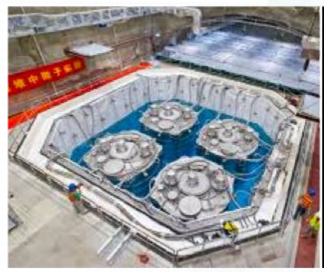
Demonstrated neutrino detection systems



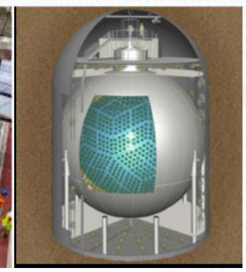
PROSPECT
Size: 4 tons
Location: Above ground
Distance: ~8 m
Reactor: Research reactor
(Credit PROSPECT collaboration)



SONGS
Size: 0.7 tons
Location: Below ground
Distance: ~25 m
Reactor: Single power reactor
(Credit SONGS Collaboration)



Daya Bay
Size: 20 tons
Location: Below ground
Distance: ~1.7 km
Reactor: Multiple power reactors
(Credit Daya Bay Collaboration)



KamLAND
Size: 1,000 tons
Location: Below ground
Distance: ~175 km
Reactor: Multiple power reactors
(Credit KamLAND Collaboration)

Note: The PROSPECT system works on the earth's surface, and similar systems could be deployed on a mobile platform. The other three detector technologies require an underground site.

Compared to other reactor monitoring tools, neutrino detectors have these advantages:

- Reactor power and fissile content can be monitored *without* operator declarations of reactor power, operating history, or refueling schedule.
- Detectors are always located outside of the reactor building, so no connection to plant facilities is required. Consequently, they are minimally invasive.
- There are no known ways to shield, suppress, or fake a neutrino signal.
- Unattended and remote operation is normal for this technology.

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Limitations of neutrino detection technology

- Very long-range monitoring (hundreds of kilometers) would require very large detectors, so shorter distances are more practical. Shorter distances will require permission from the reactor operator or host country for deployment.
- Neutrino detectors can be rendered inoperable in many ways, most of which are similar to any other active monitoring device (e.g. cameras, deployed on-site at a nuclear facility).
- The cost is relatively high compared to existing methods.

Cost estimates

- $1–2M per ton for surface detectors
- $5-10M per 10 ton below ground liquid scintillator
- $50-100M per 1000 ton below ground water detector
- Plus deployment specific costs

Neutrinos

Neutrinos are practically massless, electrically neutral, stable particles. Nuclear reactors and associated materials, like spent nuclear fuel or reprocessing waste, emit electron antineutrinos in beta decays. For brevity the term "neutrino" is used throughout with the understanding that these are electron antineutrinos. The three interaction channels, ordered by their relevance for applications, are: inverse beta decay (IBD), electron scattering (ES) and coherent elastic neutrino nucleus scattering (CEvNS).

Reactor Neutrino Emissions

Neutrinos originate from the beta decays of neutron-rich fission fragments and on average 6 neutrinos per fission are produced with 2 of them being able to induce IBD. A reactor of 1 GW thermal power produces approximately 10^{20} neutrinos per second; a 1 kg detector at a distance L=10m from reactor with thermal power P=1 GW results in 4,000 IBD reactions per year 4000/10 $m^2 L^2$PGW.

The fission fragment distribution depends on which isotope is undergoing fission, therefore the aggregate neutrino emissions also vary in total number and energy spectrum. For example, fission of plutonium-239 results in a softer (lower average energy) neutrino spectrum than fission of uranium-235. This isotopic effect is preserved in all neutrino interaction modes but requires collection of sufficient event statistics to be utilized.

Types of Neutrino Interactions

There are three primary neutrino interactions. The first has been extensively demonstrated by experiments at nuclear reactors while the other two have limited or no demonstrations at reactors.

1. Inverse Beta Decay (IBD)

In IBD a neutrino interacts with a free proton (hydrogen nucleus) and produces a positron and a neutron, where the positron carries almost all of the kinetic energy of the neutrino and the neutron carries almost all of the momentum. Neutrons are heavier than protons and thus there is a minimum reaction (threshold) energy of 1.8MeV required. The positron results in a prompt energy deposition, whereas the neutron will be captured, once it thermalizes after 10-200 microseconds, allowing for a delayed coincidence detection. IBD detectors are based on organic scintillators, but water has also been proposed. To date only IBD has yielded signals with characteristics suitable for applications. The IBD cross section weighted over the reactor neutrino spectrum is approximately 6×10^{-19} barn; for reference, 1 barn is a typical neutron scattering cross section on hydrogen.

2. Elastic Electron Scattering (ES)

In ES a neutrino (of any type) scatters off and imparts recoil energy to an atomic electron. This reaction can happen at any neutrino energy, i.e. it is threshold-less, but the recoil energy decreases with neutrino energy. For a water detection medium, the effective cross section for ES averaged over the reactor neutrino spectrum is 1.7×10^{-19} barn. For neutrinos of energies significantly larger than the electron mass of 511 keV the recoil electron approximately preserves the neutrino direction. This reaction has no other signatures that can suppress background, but lends itself well to the use in large-scale water Cerenkov detectors. ES with directional information has been observed for neutrinos from the Sun down to 3.5 MeV but not yet with reactor neutrinos.

3. Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

In CEvNS a neutrino (of any type) scatters off a nucleus and transfers recoil energy to it. This reaction can happen at any neutrino energy, i.e. it is threshold-less, but the recoil energy decreases with neutrino energy and is typically very low compared to common background sources. The signature of a recoiling nucleus is a very high specific energy loss, but like ES there is only one detectable particle produced making background suppression difficult. The reaction cross section is proportional to the square of the number of neutrons, which for heavy nuclei leads to a significant enhancement and cross sections as large as 10^{-15} barn per target nucleus. However, per unit detector mass the gain relative to IBD is at most a factor of 100. This reaction has been observed for the first time in 2017 with neutrinos of 50MeV energy, and it has not yet been observed for the more challenging case of reactor neutrinos which characteristically have less than 10MeV energy.

Monitoring Reactor Power with Neutrino Detectors

Monitoring a reactor's power output is essential for operational control and can provide information about material fission history during a crucial stage of the nuclear fuel cycle. Information about a material's fission history is useful for *nuclear materials accounting*, a nuclear safeguards inventory process that ensures all special nuclear material at a site is controlled and accounted for.

Existing nuclear safeguards programs for nearly all reactors do not exploit reactor power information; instead, fissile material production is monitored using procedural controls, containment and surveillance, and indirect measurements of spent fuel. Although commercial and research reactor operators collect thermal power information through thermohydraulic measurements, these methods may not be applicable for emerging reactor designs. Monitoring a reactor's power through its neutrino emissions is a noninvasive approach that can benefit both reactor operations and nonproliferation efforts.

Safeguards applications

Detection rates in a neutrino-based reactor power monitor are roughly proportional to the reactor's thermal power divided by the detector's standoff distance squared. Neutrino detection technology supports the following safeguards activities:

a. Determining the presence or absence of a reactor

b. Detecting a change in the reactor state (on/off)

c. Recording reactor power with some accuracy over time

All three activities support nuclear safeguards, but only the third application, recording the power over time, provides operational context. The number of detected events needed increases from simply determining a reactor is present (a) to recording its activities over time (c). Measurements at a distance greater than 100 km are only useful for determining if the reactor is present (a). Inferring a reactor's operational status, (b) and (c), must be done at significantly smaller distances, so these require cooperation with the reactor operator. The typical detector size for learning about the reactor's operational status, (b) and (c), is 1–100 tons.

All three safeguards applications for neutrino detectors have been experimentally demonstrated by basic and applied science experiments. Percent-level accuracy for daily reactor power can be

and has been recorded over years-long time scales, with a sensitivity independent of reactor type and improving with increasing reactor power. With a 4 ton detector[1] at 20 m, the on/off transition of a 100 MW reactor can be observed within 1 day.[2] Detection time increases to 2 weeks for a 20 MW reactor. Such a detector could be deployed over a days-long time scale inside a standard shipping container with minimal infrastructure or at an indoor storage location well-removed from primary reactor operations. For a 30 ton detector at a 1 km distance deployed 100 m underground, the change of on/off state in a 20 MW thermal reactor can be detected within 250 days. This time decreases rapidly with increasing reactor power. For a 100 MW reactor power, the time shrinks to 15 days. The second scenario requires site excavation and detector assembly on-site.

[1] Realistic background measurements based on existing experiments and appropriate for the specific detector and overburden (for shielding purpose) is used in all cases. All detector masses given are based on demonstrated detection efficiencies.

[2] Quoted sensitivities here based on a false positive rate of 1%–5% depending on the specific case and a fixed true positive rate of 95%.

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Fissile Content of Nuclear Reactors

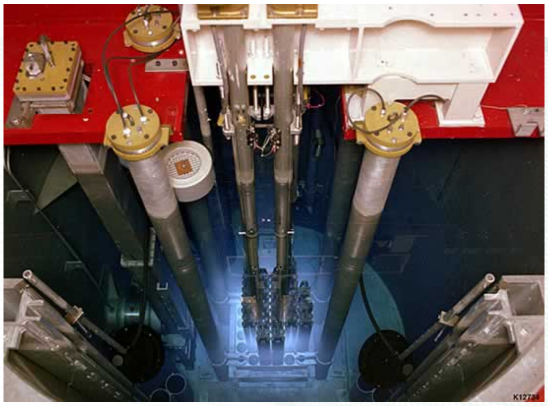
Detecting the diversion or undeclared production of nuclear materials is a primary goal of nuclear safeguards, so knowing the fissile content of a reactor core is important information for safeguards efforts.

Current reactor safeguards implementations use a combination of nuclear material accountancy, nondestructive and destructive measurements of fuel, and containment and surveillance. The combination of pre- and post-irradiation measurement of reactor fuel and predictions of fuel activation and depletion from modelling, using the declared operating history, can be used to validate that history after the fact and produce an indirect estimate of fuel fissile content.

Future reactor types that use fuel dissolved in the coolant, such as liquid metal and molten salt reactors, pose a considerable safeguards challenge. Conventional accountancy and containment and surveillance techniques, based on tagging discrete fuel elements, will not be possible. Fissile materials accounting, based on chemical analysis of molten salts or liquid metals, introduces a new proliferation pathway through sample collection.

Neutrino measurements can provide a continuous measurement of reactor fissile content. The energy spectrum of neutrinos is sensitive to the specific mix of fissionable isotopes in the reactor. These characteristic energy changes have been theoretically predicted[1] but only recently experimentally observed.[2] Inference of reactor fissile content using antineutrino measurements requires a relatively high counting rate to achieve the necessary statistical uncertainty. Therefore, a neutrino detector would have to be close to the reactor, likely less than 1 km, which would require cooperation of the reactor operator. Any configuration that can measure the core fissile content will also provide an accurate measurement of reactor power.

In terms of absolute plutonium mass, the sensitivity is best for reactor types with a high fission density, such as traditional pressurized light water moderated designs, and decreases for decreasing fission density, such as natural uranium–fueled graphite-moderated designs. To determine absolute plutonium mass, this measurement becomes more difficult as the reactor thermal power increases because the plutonium content increases with power.



Diversion of 8 kg of plutonium in a 100 MW light water reactor can be detected by a 20 ton detector at a distance of 20 m within 200 days without information about the reactor's operating or refueling history.[3] In this example, the detector system would fit inside a standard shipping container and could be deployed with minimal infrastructure aboveground within a very short period of time (days), assuming that the detector system has been assembled off-site.

[1] P. Huber. "Reactor Antineutrino Fluxes: Status and Challenges." *Nucl. Phys. B*. 908. July 2016.
[2] D. Adey et al (Daya Bay Collaboration). "Extraction of the 235U and 239Pu Antineutrino Spectra at Daya Bay." *Phys. Rev. Lett.* 193. September 2019.
[3] E. Christensen et al. "Antineutrino Reactor Safeguards: A Case Study of the DPRK 1994 Nuclear Crisis." *Science and Global Security*. 23. 2015.

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Non-Fission Material Transmutation

Neutrino detection

For each beta decay, a corresponding *neutrino* is also emitted. This panel will explore the detection of neutrinos from reactor materials other than fuel, such as the production of weapons, medical, or industrial isotopes.

Detecting neutrinos from a nuclear reactor largely involves measuring the decay of fission products. Neutrinos can also be generated from nuclear reactions besides fission, which may happen both intentionally or inadvertently. These reactions include, but are not limited to, reactor production of plutonium via breeding blankets, tritium via lithium bars, or various industrial or medical isotopes. These production mechanisms create lower energy neutrinos at significantly reduced numbers compared to the fission of a power reactor. Consequently, detecting these production activities requires detection technologies that have not yet been implemented at nuclear reactors.

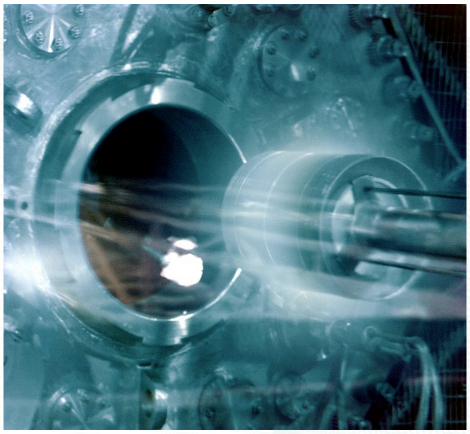
Non-Fission Transmutation

Non-fission material transmutation broadly refers to the elemental or isotopic change of material in a reactor, either intentionally or as byproducts, through nuclear processes other than fission. Significant material transmutation can occur within a variety of design components in a reactor. Generally, the reactor monitoring applications commonly discussed rely on the proportionality of detected neutrino rate to fissions (i.e., power level).

Although fission reactions ultimately yield the bulk of the neutrinos, other neutron-induced interactions associated with transmutation can, under certain situations, produce a significant, and potentially detectable, number of non-fission-derived neutrinos. The contribution of these reactions to heat production is small compared to fission (i.e., contribution to power level), but they can become important as the required precision of neutrino production predictions and subsequent reactor monitoring is increased.

Safeguards considerations

The most prominent transmutation is the production of plutonium using a breeding blanket,[1,2] which requires additional safeguards considerations. Transmutations produce fissile plutonium isotopes without contributing significantly to the power level. Reactors



configured in this way are called *breeders* because they produce more fissile content than they consume. The extent to which these transmutations can be detected via their associated neutrinos needs to be explored further, though studies suggest that recently demonstrated coherent scattering neutrino detection technologies may provide a viable pathway to realizing this capability.[3,4] A similar situation includes the detection of nuclear reactor production of tritium via lithium transmutation.[5,6]

Monitoring reactors for production of other isotopes of interest, such as medical or industrial isotopes, has yet to be explored. In addition to the technical challenges of lower signal rate and energy threshold compared to fission products, variations in reactor designs have the potential to complicate predictions of non-fission material transmutations and thus detection confidence. Nonetheless, the detection of non-fission-related neutrinos for applications other than power monitoring has yet to be deeply explored, and defining the potential advantages of the capability for traditional safeguards measures in this area is necessary.

[1] B. Cogswell. "Detection of Breeding Blankets Using Antineutrinos." *Science and Global Security*, 24, 2016.
[2] C. Stewart. "Employing Antineutrino Detectors to Safeguard Future Nuclear Reactors from Diversions." *Nature Communications*. 10, 2019.
[3] J. Ashenfelter et al. (PROSPECT Collaboration). "Non-Fuel Antineutrino Contributions in the High Flux Isotope Reactor." Manuscript in preparation for submission to Physical Review C. 2020.
[4] G. Angloher et al., *European Physical Journal C*. 79, 1018 (2019).
[5] V. I. Lyashuk, "High Flux Lithium Antineutrino Source with Variable Hard Spectrum. How to Decrease the Errors of the Total Spectrum?" 2016. December 23, 2016. 7 pp. e-Print: arXiv:1612.08096.
[6] A. Conant. "Antineutrino Spectrum Characterization at the High Flux Isotope Reactor Using Neutronic Simulations." PhD Dissertation. Chapter 8: Absolute Flux Correlations and Measurement. July 2019.

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Regional Reactor Discovery, Exclusion, and Monitoring

This panel will explore the prospects for neutrino detection to benefit two remote proliferation detection use cases: discovery of undeclared, research-scale nuclear reactors and verification of the operation and monitoring of known nuclear reactors. These capabilities are sought for reactor–detector distances that exceed 2 km.

Small (tens of megawatts) undeclared nuclear reactors can produce plutonium at a high enough rate to support clandestine nuclear weapons programs. Consequently, their discovery and exclusion in a regional context is a high priority for nuclear nonproliferation. Unverified operation of declared nuclear reactors presents similar nonproliferation concerns. Neutrino-based methods may expand the existing technical tool set for reactor discovery, exclusion, and monitoring by exploiting a characteristic signature of fission that is immune to shielding and spoofing.

Compared to existing methods for remote reactor observation, neutrino detectors offer unique features that may be of use in current or future monitoring activities. The existing tools and technologies exhibit limitations such as intermittent operation, unpredictability in the efficacy of data collection and source term magnitude, limited geographical coverage, or inability to provide tight constraints on the reactor location. By contrast, unique features of neutrino detectors include: persistence; the ability to detect or exclude reactor activity in a wide geographical region without external cueing information; insensitivity to weather, shielding and other environmental factors; the potential to place constraints on, or directly measure, the operational status and total thermal power of the reactor and thereby estimate the maximum possible rate of plutonium production in the discovered reactor.

The technology has already been demonstrated over the 2–20 km range in existing underground scientific experiments and could be adapted for monitoring and exclusion applications with little or no design modifications required. Challenges for long-range reactor discovery, exclusion, and monitoring using neutrino detectors include the intrinsically low signal rate and the need to suppress both the neutrino and non-neutrino backgrounds. Because of the low neutrino interaction rate, discovering a 50 MW reactor within a year from 1,000 km distance would require a 335 kt detector,[1] provided that such a detector can reject the neutrino backgrounds from

existing reactors. The largest existing neutrino detector, Super Kamiokande, has an active volume of about 25 kt and cost about $100M to build.

[1] Bernstein *et al.*, "Neutrino Detectors as Tools for Nuclear Security," Rev. Mod. Phys. 92 (2020) 011003.

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Post-Accident Reactor Monitoring

This panel will explore the application of neutrino detectors, which have been demonstrated as reactor monitors at full power, to scenarios involving fuel signatures that could signal a reactor accident or a transient event.

Neutrino detectors have demonstrated the capability to monitor reactor operation, including status, power level, and fissile inventory. All demonstrations have focused on reactors operating in steady state at full power. The technology has improved so that accident scenarios, in which there may or may not be sustained fission source of neutrinos, could now be considered. Challenges and considerations for this application include signal rates, background rejection, potential physical translation of fuel, and resilience to adverse or severe conditions.

Nuclear reactors are designed to operate under normal conditions as well as under certain accident conditions, which occur with an anticipated frequency and can include fuel damage, containment integrity, or radiation release off-site. Real-time information about a nuclear reactor after an accident can be crucial to maintaining the integrity of the reactor and radiological safety of the area. If an accident is known to have occurred, more information about the extent of the contamination is needed. Because neutrino detectors detect the by-products from fission, a sustained signal could be indicative of a continuing chain reaction that has yet to be brought under control.

The International Atomic Energy Agency would like to monitor reactivity for an extended period of time after an accident, and current neutron monitors may experience harsher than normal operating conditions or calibration challenges.[1] Having a real-time method of assessing whether fuel changed state is desirable if an accident remains in a critical configuration.

In the case of the Fukushima accident, the fuel melted, and traditional instrumentation was not available or useful.[2] A major challenge of neutrino detection in this application is the small magnitude of the signal compared to full power operation. The detection has flexibility in operating modalities (e.g., permanently emplaced or mobile), although the latter will have background rejection challenges depending on the distance. The extent to which neutrino detectors are applicable under a wide range of accident scenarios needs to be investigated (e.g., the levels of radioactivity may be so high that operation of neutrino detectors is difficult).

[1] "Accident Monitoring Systems for Nuclear Power Plants." International Atomic Energy Agency. 2015.
[2] M. Fackler. "Six Years After Fukushima, Robots Finally Find Reactors' Melted Uranium Fuel." *New York Times*. November 19, 2017.

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Spent Fuel Monitoring

This panel will explore the prospects of neutrino detection for monitoring spent fuel, which has applications in verification of isotopic composition, reprocessing efforts, and nuclear archaeology.

Fewer neutrinos are emitted from spent fuel than from operating reactors. The time scale and various applications have been studied from days after irradiation to long-term storage in a geological repository, but only the former has been measured to date. The low signal-to-background ratio poses a significant challenge in the development of this technology, and future research and development is necessary to further this application.

Neutrino emissions from fuel post-irradiation declines very quickly, within minutes, to a small fraction of the rate during irradiation with the highest energy neutrinos vanishing the fastest. Twenty-four hours after irradiation, only a handful of fission fragment isotopes emit neutrinos above inverse beta decay threshold, which constitutes the limit of our ability to detect neutrinos at reactors. On longer time-scales, only strontium-90, which has a half-life of 29 years, remains with neutrino emissions above the inverse beta decay threshold. Strontium-90's decay chain can produce neutrinos up to 2.2 MeV energy. The fission yield of strontium-90 is around 5%, so it is copiously produced and notably retained in the aqueous phase of the PUREX process. Therefore, also reprocessing waste will exhibit significant neutrino emission because about 1 mol (90 g) of strontium-90 ends up in the waste stream for about 4 kg of separated plutonium. This amount of strontium-90 would result in about 25 events per year in an ideal 5 ton inverse beta decay detector at a of 10 m. The half-life of strontium-90 is long enough that even the oldest spent fuel, dating to 1943, still contains 16% of its original strontium content.

Scenarios

1. Long-term monitoring of geological spent nuclear fuel repositories, such as at the Yucca Mountain Nuclear Waste Repository.[1]
2. Verification of dry-storage casks.[2]
3. Locating reprocessing wastes in cleanup efforts at known plutonium production sites, like the Hanford Site.[3]
4. Nuclear archeology—After denuclearization, a complete understanding of all past plutonium production is desirable and neutrino emission from buried reprocessing waste can, in principle, provide an estimate of total plutonium production at a given site. [4]

The challenge in all cases is that event rates are relatively low compared to a running reactor, and the neutrino energy is quite low, accentuating the issue of random backgrounds from natural radioactivity. To date the only actual detection of post-irradiation neutrinos has taken place on a time-scale of days after irradiation. Scenario 1 can be addressed with current detector technology, using single-volume large scale (thousands of tons) liquid scintillator detectors buried deep underground. For scenario 4 scaling, from demonstrated detector performance at the surface without overburden, indicates that reprocessing waste corresponding to 80 kg of separated plutonium could be detected in less than 2 years with a detector which fits inside a standard shipping container. Scenarios 2 and 3 seem to be more challenging and may require further detector research and development. In particular, directional neutrino detection in ton-scale detectors would greatly enhance capabilities for those two cases.

1 V. Brdar, P. Huber, J. Kopp, Phys. Rev. Appl. 8, (2017) 054050.
2 Ibid.
3 Ibid.
4 E. Christen, P. Huber, P. Jaffke, Science & Global Security 23 (2015) 40.

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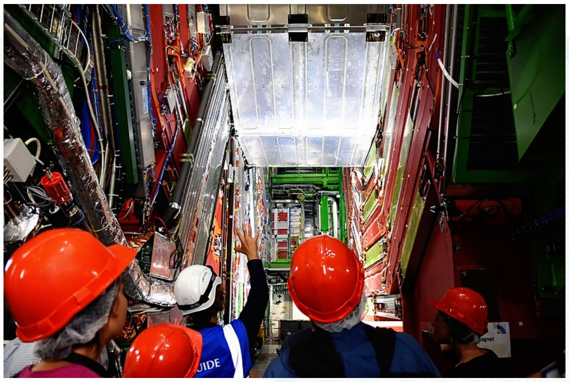
Neutrino Detection Scientific Engagement

Beyond a technical role as reactor monitors, neutrino detectors offer opportunities to build trust with adversaries, reemploy former weapons scientists, and connect the intellectual resources of the basic science community with nuclear security challenges.

These opportunities arise from an application in which neutrino detectors have already proven useful during the past 60 years: as collaborative tools for science. From a small experiment run by US weapons lab scientists, neutrino physics has grown to a multibillion-dollar venture linking thousands of physicists in the United States, Europe, Russia, China, South Korea, and elsewhere.



Opportunities for engagement

Connections to cutting-edge science and to a global community of physicists are special assets that neutrino detectors bring to the Department of Energy's Office of Defense Nuclear Nonproliferation mission. These assets offer utility to the Office of Defense Nuclear Nonproliferation and other nonproliferation agencies in multiple ways:

- Cooperatively fielding a neutrino detector, especially at a former military reactor, could be a low-stakes way to help build trust between the United States and another nation. US agencies have relied on technical projects to help build trust with former adversaries since the Cooperative Threat Reduction program in the former Soviet Union. More recently, neutrino projects have been suggested as one part of "a broader opening of scientific engagements" with Iran.[1] Other cooperative opportunities for neutrino detectors could also arise in the future.[2] In general, neutrino detectors are well-suited to cooperative exercises because they are a novel, militarily-insensitive, and somewhat remotely deployable tool. Because the neutrino physics community spans many nations such a project could be supported multilaterally.
- Cooperative neutrino projects could help connect an adversary's former weapons scientists to nonmilitary work. Directing former weapons scientists to peaceful occupations, rather than work in another weapons program, was one aim of the original Cooperative Threat Reduction program. Officials have also emphasized this objective for North Korea and Iran.
- A cooperative, neutrino-based reactor monitoring project would be a gateway for technical personnel to enter the international particle physics community.
- Applied neutrino projects could help connect scientists and students from the particle physics community with challenges in the US nuclear security enterprise. In particular, these projects can help attract graduate students to security careers.

[1] Joint Comprehensive Plan of Action Annex 3 - Civil Nuclear Cooperation,
[2] R. Carr et al., Science & Global Security 27 (2019).

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