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Cerium Ruthenium Low-Energy Antineutrino Measurements for Safeguarding Military Naval Reactors

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The recent agreement to transfer nuclear submarine reactors and technology from two nuclear-weapon states to a non-nuclear-weapon state (AUKUS deal) highlights an unsolved problem in international safeguards: how to safeguard naval reactor fuel while it is on board an operational nuclear submarine. Proposals to extend existing safeguards technologies and practices are complicated by the need for civilian international inspectors to gain access to the interior of the submarine and the reactor compartment, which raises national security concerns. In this Letter we show that implementing safeguards on submarine propulsion reactors using a low-energy antineutrino reactor-off method, between submarine patrols, can by-pass the need for onboard access all together. We find that, using inverse beta decay, detectors can achieve a timely and high level of assurance that a submarine's nuclear core has not been diverted (detector mass of around 100 kg) nor its enrichment level changed (detector mass of around 10 tons).

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Introduction.—Highly enriched uranium (HEU) for military naval reactors poses challenges for nonproliferation [1,2]. The Treaty on the Non-Proliferation of Nuclear Weapons (NPT) allows the withdrawal of HEU from the civilian realm, and thus safeguards, to move it to military nonexplosive uses, like naval reactors. This is of concern because it could create a pathway to nuclear weapons for nonweapon state parties without the risk of detection via international safeguards. To date, only states with nuclear weapons have deployed nuclear powered submarines, which rendered proliferation concerns theoretical. Brazil's plans to build a nuclear powered submarine make this concern concrete, but progress towards deployment has been slow [3]. With the recently announced Australia-U.K.-U.S. (AUKUS) agreement [4] to transfer nuclear submarines from two NPT weapon states (the U.S. and U.K.) to a NPT nonweapon state (Australia) the question of how to implement naval reactor safeguards has become urgent.

One approach is to phase-out reliance on HEU in naval propulsion [1,2,5]. Both the U.S. and U.K. navies exclusively employ HEU above 90% enrichment [6] in submarine propulsion and, in particular, the U.S. Navy has not pursued switching to low-enriched uranium (LEU) [7,8]. However, regardless of if HEU or LEU is used in naval reactors, safeguards are valuable throughout the entire naval fuel cycle, from enrichment and fuel fabrication to final fuel disposal after use. Usually the need for keeping military secrets is cited to counter this possibility, however, some studies [1,9,10] argue that the need for secrecy does not preclude meaningful comprehensive naval fuel cycle safeguards, if managed access to the reactor is available. Here we address the specific subproblem of safeguarding the fuel after it has been loaded into the reactor and during its use in an actively deployed submarine. In particular, we consider the case of no access to the reactor or on board the submarine, which goes beyond what has been considered in the literature. We propose using off-line, i.e., during reactor shutdown, neutrino [11] measurements in port to ascertain the presence of a nuclear reactor. Neutrino emissions after reactor shutdown have been considered in the context of spent nuclear fuel, see, e.g., Ref. [12], and have been observed by the Double Chooz experiment [13]. The new technique we propose here is based on the observation of CErium RUthenium Low Energy ANtineutrino (CeRuLEAN) emissions.

For naval reactors one safeguards objective is verification that the vessel is nuclear powered, i.e., that the reactor is present and has not been replaced with a non-nuclear energy source [14]. For a would-be proliferator without domestic nuclear reactor expertise this presents a possible diversion pathway. In the literature a technical proposal for implementation of this objective has emerged: flux tabs [1]. Flux tabs are made of a material which gets activated, i.e., becomes radioactive, under neutron irradiation. The idea is to place flux tabs close to (but outside of) the reactor, in areas that receive a significant flux of fast neutrons from the fissions going on in the reactor. The level of radioactivity in flux tabs is proportional to the energy the reactor has produced. The problem is that these flux tabs must be installed close to the reactor and, hence, an inspector needs access to the vessel and to get close to the reactor. In order to protect classified information this requires "managed access" to the naval base and submarine, which is logistically complex. In this Letter we demonstrate that a small neutrino detector using the CeRuLEAN technique can serve as a direct equivalent of flux tabs *without* the need for onboard managed access to the submarine.

Submarine and reactor considerations.—Power consumption for a submarine is dominated by the power used for propulsion. Propulsion power is proportional to the drag, which is proportional to the third power of the speed, v^3. Assuming full design reactor power P_d at top speed we obtain the fractional power usage as a function of speed,

$$P(v) = P_d \left(\frac{v}{v_{\max}}\right)^3, \quad (1)$$

and we take $v_{\max} = 35$ kn and $P_d = 150\ \mathrm{MW_{th}}$. This reactor power corresponds to the S6G reactor in U.S. *Los Angeles* class submarines, and is similar to the output of the S9G reactor in *Virginia* class vessels [15]. Furthermore, following Ref. [16] we assume that the vessel spends two-thirds of the year at sea, conducting two patrols of 4 months each per year, and one-third of the year in port, representing a maximum possible in-port detector dwell time of 4 months per calendar year. Taking an average cruise speed of 22 kn, power consumption while at sea is 1/4 P_d. It follows that attempts at monitoring a naval reactor while at cruising power requires "drive-by" style monitoring, resulting in a small product of dwell time and reactor power. This makes online monitoring (when the reactor is operating) of the reactor core via the usual neutrino-based techniques [17–19] impractical. Limited dwell time while the reactor is on also precludes the use of exotic techniques like the observation of breeding neutrinos [20] or nonlinear effects related to power density [21].

Details of naval reactor design and operation are shrouded in secrecy, but gross characteristics are available in the open literature. We follow Ref. [16], which to our knowledge is the only detailed reactor engineering study of submarine reactors which is openly accessible. The goal of Ref. [16] was to understand how different fuel enrichment levels affect submarine reactor size and lifetime. Five different reactor cores were studied and for the analysis presented here we find that our results do not change appreciably between one of these five options. For the results presented in the main text we assume HEU cores, see the Supplemental Material [22] for details.

Off-line reactor monitoring.—A nuclear reactor emits neutrinos even after shutdown, stemming from fission fragments with longer half-lives. To use inverse beta decay as the detection reaction we seek isotopes with beta endpoint energies in excess of 1.8 MeV. There are four decay chains that fulfill this criterion [12] and have lifetimes exceeding minutes, listed in Table I.

TABLE I. Isotopes suitable for off-line monitoring. Beta decay information from ENSDF [23] and cumulative fission yield (CFY) information from JENDL-4.0 [24].

Parent	^{90}Sr	^{144}Ce	^{106}Ru	^{88}Kr
Lifetime τ (d)	15 218	411	536	0.2
Daughter	^{90}Y	^{144}Pr	^{106}Rh	^{88}Rb
Q_β (MeV)	2.28	3.00	3.54	5.31
σ_{IBD} $[10^{-43}\ \mathrm{cm}^2]$	0.08	0.45	0.75	2.84
CFY ^{235}U	0.057	0.055	0.004	0.035
CFY ^{239}Pu	0.02	0.037	0.042	0.012

The decay energy Q_β of the ^{90}Sr/^{90}Y chain is low and, thus, its inverse beta decay cross section σ_{IBD} is also low. The resulting suppression in the signal makes this chain not ideal for measurement. The ^{88}Kr/^{88}Rb chain has a lifetime too short to effectively contribute to the detected rate. This leaves ^{144}Ce/^{144}Pr and ^{106}Ru/^{106}Rh as the best candidates. The cumulative fission yields (CFYs) for ^{235}U and ^{239}Pu fission are quite similar for ^{144}Ce, but distinct by an order of magnitude for ^{106}Ru. Hence, measuring the ratio of ^{144}Ce to ^{106}Ru is a direct measurement of the plutonium fission fraction, explored in detail in the Supplemental Material. Note, the detection of neutrinos from a purpose-made ^{144}Ce source has been proposed for sterile neutrino searches with the Borexino detector [25].

The lifetimes for ^{144}Ce and ^{106}Ru are comparable to the patrol and off-duty periods postulated for a submarine, thus, we need to calculate their abundance n_i with i being one of the four isotopes:

$$n_i'(t) = -\frac{1}{\tau_i} n_i(t) + \mathrm{CFY}_i^{\mathrm{U235}} f_{\mathrm{U235}} F(t) + \mathrm{CFY}_i^{\mathrm{Pu239}} f_{\mathrm{Pu239}} F(t), \quad (2)$$

where f represents the fission fraction for ^{235}U or ^{239}Pu, as applicable, $f_{\mathrm{U235}} = 1 - f_{\mathrm{Pu239}}$, and $F(t)$ is the overall fission rate corresponding to 31.5 MW divided by the energy per fission (200 MeV) for the four months the vessel is at sea with $F(t) = 0$ for the two months in port.

For the detector monitoring setup, we assume a 1 ton detector at 5 m from the center of the reactor and a cumulative dwell time of 2 months [26]. For total event numbers, we expect for a fresh core between 108 and 164 events for an f_{Pu239} of 0 or 1, respectively. After about 5 calendar years of operation these numbers reach their asymptotic value of 308–512 events.

A detector placement below the submarine, modeled here and shown in Fig. 1, corresponds to about 15–20 m

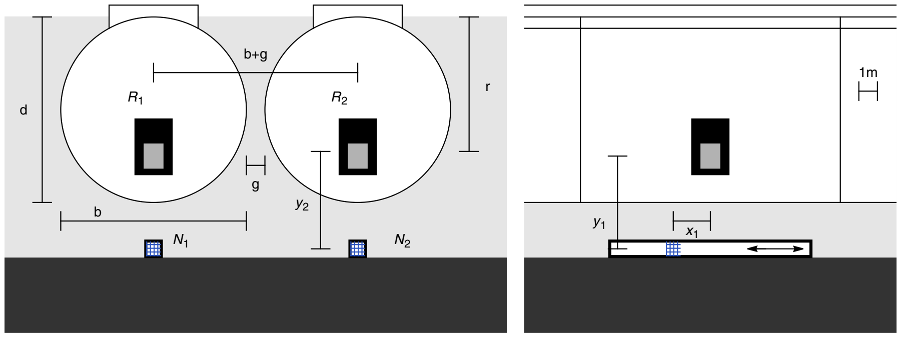

FIG. 1. Cross section (left panel) and side view (right panel) of two submarines at their berthing site. R_1 denotes reactor of vessel 1 and N_1 denotes the neutrino detector for that vessel. d is the draft, b is the beam of the vessel, and r denotes how far the center of the reactor core is below the water line. g describes the gap between vessels. y_1 is the vertical distance between the center of the reactor core R_1 and the neutrino detector N_1. x_1 is the horizontal, adjustable distance between R_1 and N_1. Water is depicted as light gray and the harbor floor as dark grey. Drawing is to scale, reactor size and position are notional.

water equivalent overburden, given a distance from the reactor core of 5–10 m and that the typical submarine has a distance from water line to bottom of the hull of about 10 m, with the reactor being somewhat below the center line of the submarine [27,28]. This is similar to the 20 m water equivalent overburden of the NEOS neutrino experiment [29]. NEOS is a 1 ton, single volume detector and observes around 80 background events per day, about half of these in the relevant region below 4 MeV. This corresponds to about 60 events per 0.1 MeV in 60 days for a 1 ton detector. Backgrounds stem from three sources: accidental coincidences, which scale with detector volume; fast neutrons, which also scale with detector volume; and cosmogenic beta-delayed neutron emitters (^{9}Li), which scale with the muon rate and, hence, detector surface area.

In a segmented detector [30,31] both volume and surface-scaling backgrounds are sharply reduced: a true inverse-beta decay event occupies a certain volume enveloped by a certain surface. For example, in the CHANDLER [31] design the detector consists of cubes measuring 6.2 cm in each direction. The coincidence volume for an inverse beta decay event is $3 \times 3 \times 3 = 27$ cubes and the corresponding top surface is $3 \times 3 = 9$ cube faces. Hence, a 1 ton detector would consist of roughly 4100 cubes and have a top surface area of about $4100^{2/3} \simeq 260$ cube faces. Therefore, the rate of volume-scaling backgrounds, like accidentals, is reduced by a factor $4100/27 \simeq 150$ and surface-scaling backgrounds by a factor $260/9 \simeq 30$. Thus, for the 1 ton detector considered here, this yields scaled background rates in the range of 0.04 to 2 per 60-day period and per 0.1 MeV. The accidental background scaling has been experimentally verified [31]. However, whether the muon related backgrounds scale with segmentation as described has not been tested, but remains a reasonable assumption. For the remainder of this study we use an intermediate value of 0.5 background events per 60 day period and 0.1 MeV, corresponding to 25 events in 60 days.

A neutrino measurement permits an effective information barrier: the owner of the vessel would want to keep the reactor full power equivalent days (FPEDs) during a patrol secret, since this number allows inferences to be made about patrol distance. The strength of the ^{144}Ce signal, being a weak function of f_{Pu239}, allows a fairly accurate measurement of the accumulated FPEDs of the vessel in the few hundred days prior to the measurement being taken. However, by varying the reactor-detector distance [32] (via changing x_1 within a fixed and known range, see Fig. 1) the owner of the vessel can effectively erase this signature: for a high FPED patrol the detector moves further away and for a low FPED patrol the detector moves closer. The actual reactor-detector distance can be concealed from the inspecting party, by design, see Fig. 1. We call the corresponding parameter the *power masking factor* $\xi = (d_{\max}/d_0)^2$, defining the degree to which FPED information can be hidden. The actual value is determined by the extent to which the owner of the vessel wants to keep the true reactor usage secret. Once total signal strength information is erased, the only remaining information is that (1) there is a significant neutrino flux, encoding the fact that a reactor with a certain minimum FPEDs is present, and (2) the ratio of ^{144}Ce to ^{106}Ru neutrinos, which encodes the accumulated fission fraction f_{Pu239}. The latter information would require a detector with a mass of around 10 tons to be effectively usable, see Supplemental Material.

Based on the event number for a fresh core (108 ton^{-1} at 5 m distance) and background numbers (25 ton^{-1}) we can compute the required detector size to verify the presence of a neutrino signal and, hence, of a nuclear reactor which produced appreciable power [34]. We employ a likelihood ratio test, but compute the probability distribution of the test statistics using Monte Carlo methods; see Supplemental Material. We require a detection probability for a diversion of 90% and a false positive rate of 5%, as is safeguards practice [35]. We also set as a figure of merit the required detector mass to attain this goal. The introduction

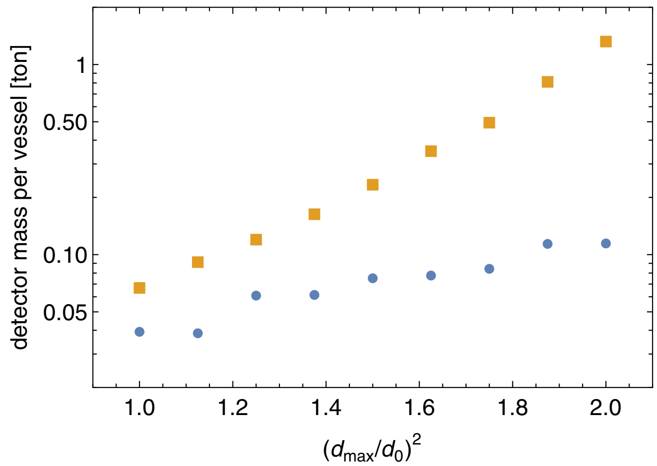

FIG. 2. Detector mass required to obtain a 90% detection probability with a 5% false positive rate as a function of the parameter $\xi = (d_{\mathrm{max}}/d_0)^2$, the average reactor power masking factor. We take $d_0 = 5$ m. The blue circles are the result for a single vessel detector, whereas the orange squares show two vessels berthed side by side.

of a variable distance as an information barrier makes the analysis more complicated and we profile the likelihood over the specific distance range corresponding to the desired power masking factor, ξ. The result for a single submarine is shown in Fig. 2 as blue circles. The case $\xi = 1$ corresponds to no information barrier and no distance variation and we find that, over the whole range for ξ, detectors of around 100 kg mass can achieve this measurement. We label this option *single boat detector*.

However, there may be several nearby mobile reactors, so the possibility of spoofing the observed submarine signal using additional reactor cores arises. As one of the most difficult cases, we consider two submarines berthed side-by-side for the duration of the measurement, depicted in the left panel of Fig. 1. We now have two reactors with unknown signal strengths and two distances that can each vary independently within ξ. The results are shown as orange squares in Fig. 2. Details of the calculation and their game-theoretical explanation can be found in the Supplemental Material. For $\xi = 1$, no information barrier, the increase in detector mass is modest, but this increase grows to more than a factor 10 for $\xi = 2$. Here we assume that both vessels have a fresh core; the increase would be larger if the vessel under inspection has a fresh core, but the side-by-side vessel has an older core. Thus, side-by-side berthing without restriction requires many large detectors, unless ξ is below 1.5. Alternatively, constrained side-by-side berthing (e.g., where the age of nearby reactor cores is prescribed) requires multiple smaller detectors, but also reliable and verifiable hull identifiers.

It is worthwhile to look beyond the individual vessel berthing concept to consider an alternative deployment covering the overall fleet: If we require $\xi = 2$ it may become more effective and impose fewer operational constraints to deploy a single, larger detector at a dedicated measurement site that performs the measurement in a short time on all submarines in the fleet, one at a time. Here, the vessel berths at the detector site by itself, but only for a few days. As we can infer from the single vessel results, a 1 ton detector without interference from the backgrounds of a side-by-side vessel could achieve a measurement in 6 days. This measurement time shortens as more patrols are conducted, since cerium reaches its equilibrium abundance. After the third patrol the time required is of the order of a day. Thus, a single ton-scale detector could serve a full fleet of vessels, an option we designate as a *whole fleet detector*. This option provides more flexibility for port operations and does not disclose the specific time period a submarine is in port. In addition, we examined the prospect of verifying core enrichment levels using CeRuLEAN and find it is also possible for larger detector masses around 10 tons; see Supplemental Material.

A concept of operation could be the inspecting party delivers a detector to the inspected party and oversees its installation at the submarine's berthing site, while the submarine is at sea. The inspected party verifies that the detector only detects neutrinos. The detector is then installed such that the inspected party can vary the reactor-detector distance, from say 5–7.1 m ($\xi = 2$), without the reactor-detector distance being ascertainable by the inspecting party. Installing a movable neutrino detector would be a one-time effort and has been demonstrated by the DANSS neutrino experiment [36,37].

When a submarine returns from patrol the vessel docks at its berthing site and the detector-reactor distance is chosen to mask the FPEDs accrued on patrol. Subsequently, the neutrino detector records its signal and transmits the data to the inspecting party. Comprehensive safeguards on naval fuel, including when fresh fuel is brought to the shipyard and before a submarine is launched at sea, are still needed. But in this naval reactor safeguards scheme using CeRuLEAN, no alteration to submarine operations or access to the submarine itself is required to safeguard the fuel loaded in an operational submarine. In the CeRuLEAN approach, no more data is revealed than can be obtained using traditional means, such as satellite imagery or safeguards inspection schedules, and patrol data inferences from the detector measurement itself are minimized.

Summary.—We propose a new technique to determine the presence and fuel enrichment level of a nuclear reactor, called the CErium RUthenium Low Energy AntiNeutrino measurement, or CeRuLEAN. In this Letter, we studied the application of CeRuLEAN to the problem of safeguarding naval reactor fuel in nuclear-powered submarines. The CeRuLEAN method uses antineutrino emissions from long-lived fission products in a shutdown reactor. It is an off-line measurement performed while a submarine is in port. The required IBD neutrino detector would be similar to demonstrated prototypes [31] and would employ a segmented plastic scintillator. Scaling from existing measured backgrounds appears to yield manageable background rates.

CeRuLEAN measurements can verify two aspects of naval reactor declarations. First, they can verify the presence of a nuclear reactor, for a fresh core after the first submarine patrol with a small detector of about 100 kg mass in a single boat detector deployment. We also considered spoofing scenarios and find that they can be dealt with using a 1–2 ton detector per boat for vessels berthed side by side. We also find that a 1–2 ton detector can serve as a whole fleet detector if prolonged close proximity (less than 20 m) to other vessels is prevented. Hence, CeRuLEAN can directly replace neutron flux tabs [1] under a wide range of scenarios. Second, CeRuLEAN could verify the type of enriched core present, LEU or HEU, requiring overall larger detectors of order 10 tons.

A key advantage of CeRuLEAN is that the neutrino signal can only be spoofed by other reactors, since it originates from the decay of $10^{16}-10^{18}$ Bq of ^{144}Ce/^{106}Ru. Thus, it provides an alternative to the naval flux monitors proposed in Ref. [1], which would likely have to be mounted in the reactor compartment. Therefore, their placement and retrieval requires onboard access to the most sensitive parts of the vessel. In contrast, naval reactor verification based on CeRuLEAN incurs no significant operational encumbrances and discloses no sensitive reactor design or operation information, beyond the core plutonium fission fraction. Most importantly, CeRuLEAN addresses the specific problem of eliminating the managed access burden of maintaining naval fuel cycle safeguards for fuel loaded in an actively deployed submarine because it requires no onboard access to the military submarine by civilian inspectors to verify reactor declarations. Therefore, CeRuLEAN may provide the first cross-over technology transfer opportunity for antineutrino detectors from high energy physics to nonproliferation monitoring.

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of the statistical calculation (Appendix A), provides a game theoretic interpretation of the results in the main text (Appendix B), provides details of the reactor parameters used as inputs (Appendix C) and provides an additional analysis using the proposed method for submarine core enrichment monitoring (Appendix D).

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