P3 1 Looking for the nuclear needle in the ocean

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Abstract

Using the interaction of reverse beta decay antineutrino reaction with protons, we determined the radii of a range of detectors for nuclear submarines to be used varied by the count rate of detection of antineutrinos and the range of which we aim to detect them. Range $50km$, rate of $1s^{-1}$ there is detector radius of $4499.14m$. Range of $50km$, rate of $0.2s^{-1}$ detector radius is $2631.11m$. Range of $10km$ and rate of $1s^{-1}$ detector radius is $1538.69m$.

Introduction

Nuclear submarines are a very powerful deterrent to navies all across the world since their nuclear reactor is far more powerful compared to the standard reactors used in the early twentieth century, but also have the added benefit of being able to produce oxygen through using excess power to electrolyse salt water. Therefore it can remain hidden underwater for extended periods of time. This ability when paired with nuclear missile launches from these submarines makes them truly an ever present danger. The non-silo-based nuclear submarines also make perfect weapons for attacking unsuspecting fleets and aircraft carriers. Therefore ways of detecting them are being propositioned. One method of this could be with the usage of antineutrino interaction with protons in the inverse beta decay equation: $\overline{\nu_e} + p \rightarrow e^+ + n$ This concept essentially uses a large balloon of proton rich fluid as a medium to interact with antineutrinos produced in as a by-product of nuclear fission via negative beta decay. So how big a detector do we need to put on an aircraft carrier to detect nuclear subs from the torpedo launch range?

Equations

There are a few things we can already assume to know about the nuclear submarine. We can assume average output of approximately $100MW$ [1][2] and that the energy produced per fission reaction is $200MeV$[3]. The first requirement we have is to know the rate at which antineutrinos are produced. We find this by finding out the rate of fission with the following equation.

$$F = \frac{P}{E}, \tag{1}$$

where F is defined as fissions per second of which we get 3.125×10^{18}. P is the power in watts and E is the energy per fission in joules.

Research indicates there are 6 antineutrinos produced per fission[4][5]. Using this, we can then model the flux of the antineutrinos per second as a function of an isotropic sphere radially expanding. We can set this to the expected range of a torpedo launch of $50km$ for it to radiate over in the following equations:

$$\phi = \frac{6F}{A}, \tag{2}$$

Where ϕ is the flux or intensity of antineutrinos per meter squared per second, and A is the surface area of a sphere in m^2 given by: $A = 4\pi r^2$ where r is the radius of the sphere in m. We get a result of 596831036.6 neutrinos$m^{-2}s^{-1}$. We then use the nuclear cross-sectional rate of the reaction equation and adapt it for antineutrino-proton interaction to find the number of protons needed for a sufficient given reaction rate.

$$\frac{R}{\phi\sigma} = N_p, \qquad (3)$$

Where σ is the antineutrino proton interaction cross section in m^2. From the Ronvo Experiment [6], we get a cross section of $6.08 \times 10^{-43}cm^2$ which is $6.08 \times 10^{-47}m^2$. So as a result we get the number of protons to be 2.755×10^{37}.

From there, we estimated the mass of the detector fluid assuming it was same as the Kam-LAND scintillating fluid, a mixture composed of dodecane to pseudocumene at a ratio of 8:2 by volume respectively [7]. The densities used were $0.75g$ g/cm^3 for dodecane [8] and 0.88 g/cm^3 for pseudocumene [9]. So we find the mass ratio to be $\frac{0.8*0.75}{0.2*0.88} = \frac{75}{22}$ Using their respective molar masses and the fact the free protons will be the hydrogen atoms in the hydrocarbon chains, we can find the mass. Dodecane is $C_{12}H_{26}$ and pseudocumene is C_9H_{12} so we use the relative abundances to get protons per gram:

$$\rho_p = N_a(\frac{P_1 * H_1}{H_1 + X_1} + \frac{P_2 * H_2}{H_2 + X_2} + ...) \qquad (4)$$

Where N_a is Avogadro's constant $6.02*10^{23}$, P is the compound's proportion of the mixture, H is the number of "free protons" or hydrogen atoms and X is the sum molar mass of the specific compound. This gives us our ρ_p or proton density to be:

$$\rho_p = N_a \cdot \left(\frac{75}{99} \left(\frac{26}{170} \right) + \frac{22}{99} \left(\frac{12}{120} \right) \right) \qquad (5)$$

8.31×10^{22} protons per gram or 8.31×10^{25} per kilogram. So for the mass of detector fluid, we simply divided our number of protons by the density of protons.

$$N_p/\rho_p = 3.32 \times 10^{11}kg = M \qquad (6)$$

M is our mass of detector fluid in kg. Using KamLAND's values for the density of the material by using the kiloton of their fluid in their $13m$ diameter to show it is $0.869kgm^{-3}$ [7]. We can determine the V, volume of the fluid m^3 and the radius, r in m if the fluid container with $\frac{M}{D} = V$, D being density of our detector[7].

$$r = (\frac{3V}{4\pi})^{\frac{1}{3}} \qquad (7)$$

We find the volume to be $3.22 \times 10^{11}m^3$ and the radius to be $4499.14m$.

Discussion

This is an excessive volume of material to work at military paces required. So we adapted the ranges and rates of interaction for more reasonable means we could find values more acceptable. Substituting the range of sonar to ($10km$) we get a radius of $1538.69m$. Setting the rate to $0.2/s$, similar to the rotation of a sonar pattern, we get a radius of $2631.11m$. This suggests that the rate of antineutrino detection is the more significant limiting factor. Applying both limitations, we get a value $899.83m$ radius a far more reasonable value.

Conclusion

While technically achievable by organisations such as the United States Navy, the required detector size makes the system impractical for deployment. For context, the largest aircraft carrier in the world, USS Gerald Ford, is only $337m$ long. An innovative design like a blood vessel or panel system could solve this by utilising a large surface area for interaction, but until then, it remains largely fantasy. Sonar is limited to tens of kilometres and can be countered by submarines descending below Halocline and Thermocline saltwater boundaries, which deflect sonar due to changes in temperature, salinity, and density[10][11]. Thus, antineutrino detection offers range advantages over sonar, though it remains currently unworkable.

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