資料 1

KEK-TH-882
RAD-D 2003/01
hep-ph/0305062
revised, June 2003

Destruction of Nuclear Bombs Using Ultra-High Energy Neutrino Beam

— dedicated to Professor Masatoshi Koshiba —

Hirotaka Sugawara* Hiroyuki Hagura† Toshiya Sanami‡

Abstract

We discuss the possibility of utilizing ultra-high energy neutrino beams of about 1 PeV (= 1000 TeV) in order to detect and destroy the nuclear bombs wherever they are and whoever possesses them.

*e-mail:sugawara@phys.hawaii.edu, *Department of Physics and Astronomy, University of Hawaii at Manoa, HI, USA*
†e-mail:hiroyuki.hagura@kek.jp, *Radiation Science Center of KEK, Tsukuba-shi, Japan*
‡e-mail:toshiya.sanami@kek.jp, *Radiation Science Center of KEK, Tsukuba-shi, Japan*

1 Introduction

Twentieth century physicists produced one of the most powerful weapons on earth [1] and they were used twice as an actual weapon with "Results Excellent."[1] The number of countries which possess or will possess nuclear weapons could increase in spite of the existence of the Non-Proliferation Treaty on Nuclear Weapons (NPT). There is no guarantee that these countries which already possess nuclear weapons always behave humanistically. Arms control negotiations may stabilize the world temporarily but, again, there is no guarantee that the long lasting peace on earth will come true in the future. We discuss in this article a rather futuristic but not necessarily impossible technology which will expose the possessors of nuclear weapons to an extreme danger in some cases.

Our basic idea is to use an extremely high-energy neutrino beam which penetrates the earth and interacts just a few meters away from a potentially concealed nuclear weapon. The appropriate energy turns out to be about 1000 TeV. This is the energy where the neutrino mean free path becomes approximately equal to the diameter of the earth. The neutrino beam produces a hadron shower and the shower hits the plutonium or the uranium in the bomb and causes fission reactions. These reactions will heat up the bomb and either melt it down or ignite the nuclear reactions if the explosives already surround the plutonium. We will calculate the intensity of the neutrino beam required and the duration of time which the whole process will take place for a given intensity.

We emphasize that the whole technology is futuristic and the reason should be clear to all the accelerator experts. Actually, even the simplest prototype of our proposal, i.e. the neutrino factory of GeV range needs substantial R & D work. We also note that a 1000 TeV machine requires the accelerator circumference of the order of 1000 km with the magnets of $\simeq$ 10 Tesla which is totally ridiculous. Only if we can invent a magnet which can reach almost one order of magnitude higher field than the currently available magnet, the proposal can approach the reality. Even if it becomes the reality, the cost of the construction is of the order of or more than 100 billion US$. Also we note that the power required for the operation of the machine may exceed 50 GW taking the efficiency into account. This is above the total power of Great Britain. This implies that no single country will be able to afford the construction of this machine and also the operation time must be strictly restricted. We believe the only way this machine may be built is when all the countries on earth agree to do it by creating an organization which may be called the "World Government" for which this device becomes the means of enforcement.

Section 2 gives a rough estimation and section 3 deals with a computer simulation using a Monte-Carlo generator MCNPX [2]. Section 4 gives a conclusion with various comments. In addition, we give the calculation of the mean free path of neutrino inside the earth in appendix A. In appendix B, we also describe a possible accelerator scheme.

[1]A coded message sent to President Harry S. Truman from Richard Nelson, the youngest crewman of Enola Gay, who died February 7, 2003 of complication of emphysema (New York Times, February 7, 2003).

2 Rough estimation

The neutrino beam is already hazardous at the energy of several TeV as have been analyzed by B. J. King [3] and N. V. Mokhov and A. Van Ginneken [4] in connection with the study of the muon colliders. If one constructs a race track shaped muon storage ring as shown in fig. 1, most of the muons decay into the two opposite directions of the straight sections. These two directions are the most hazardous directions ("hot spots") but the circular parts also emit the neutrinos which may also be hazardous in the vicinity of the storage ring.

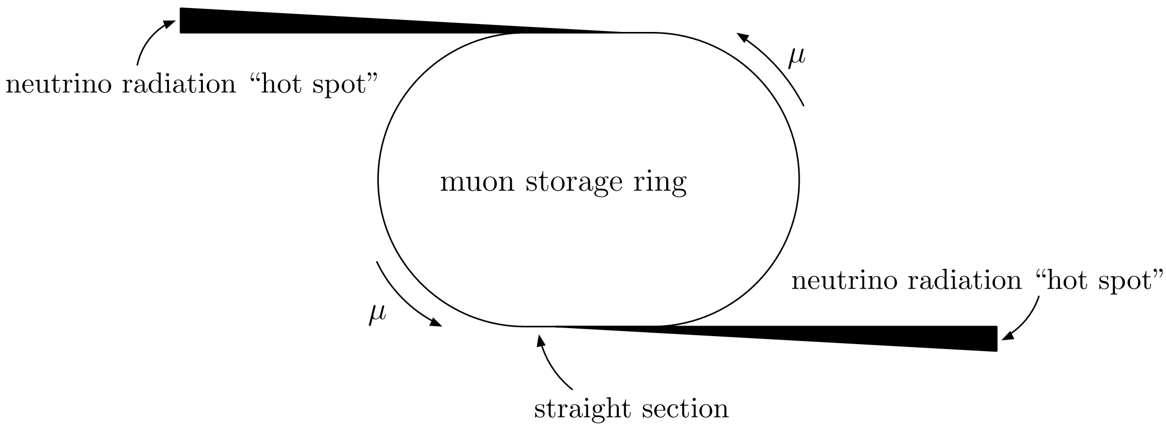

Figure 1: *Neutrino radiation from a race track shaped muon storage ring. The decay of muons will produce the neutrino radiation emanating out tangentially everywhere from the ring. In particular, the straight sections in the ring will cause radiation "hot spots" where all of the decays line up into a pencil beam.*

Here we would like to consider a situation where one of the straight lines is directed toward the nuclear bomb which is located somewhere on the opposite side of the earth (fig. 2). We must choose the energy of the neutrino beam in such a way that the mean free path of the neutrino is compatible to the diameter of the earth. Fig. 3 shows the mean free path of (anti-)neutrino vs. its energy calculated assuming that the deep inelastic cross sections dominate in the relevant energy region[2]. From fig. 3 we conclude that the energy of the neutrino beam must be about 1000 TeV to have approximately single interaction before the neutrino beam hits the bomb. When the muons of the energy $E_\mu = 10^3$ TeV are running in the ring, the size of the neutrino beams at the point of the target bomb is given by

$$r = \frac{m_\mu c^2}{E_\mu} d \simeq \frac{0.1 \text{ (GeV)} \times 10^7 \text{ (m)}}{10^6 \text{ (GeV)}} = 1 \text{ (m)} \ ,$$

where m_μ and c stand for the muon mass and the speed of light, and d is the distance from the muon storage ring to the position of the bomb which we take to be the diameter of the earth ($\simeq 10^7$ m). The beam spread due to the transverse momentum of the beam is negligible at this energy if the current value of the ionization cooling of $P_t = 1$ (MeV) is adopted. The range of the neutrino is 10^7 meters

[2] See appendix A for the detailed calculations of the mean free paths shown in fig. 3.

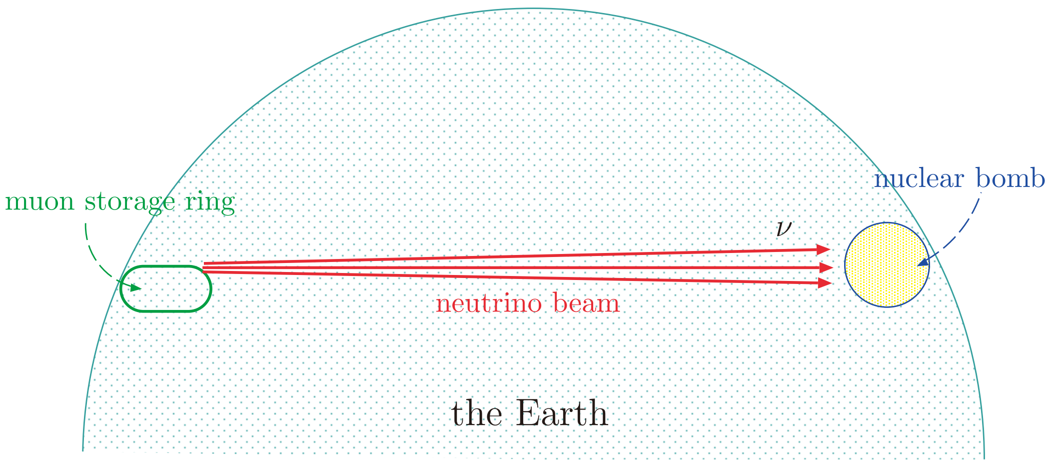

Figure 2: *Neutrino beam is aimed at the nuclear bomb that is placed on the opposite side of the earth. The beam is emitted downstream from one of the straight sections of the muon storage ring (see fig. 1), and reaches the bomb after passing through the inside of the earth.*

and the effective neutrino interaction is restricted within a few meters away from the bomb because of the interaction range of the hadrons. Therefore, the probability of getting an effective reaction from the beam is $1/10^7$. As a result, the energy deposit from the beam for the unit area (m^2) is given by

$$E_{\rm dep} = 10^{15} \times 10^{-7} \times I = 10^8 I \ \ (\mathrm{eV/sec} \cdot \mathrm{m}^2) \ \ , \tag{1}$$

where I stands for the neutrino beam intensity. For example, we get

$$E_{\rm dep} \simeq 1000 \ \ (\mathrm{Joule/sec} \cdot \mathrm{m}^2) \quad \text{for the intensity of } I = 10^{14} \ (1/\mathrm{sec})\,. \tag{2}$$

This is equivalent to about 1 $\mathrm{S_V/sec}$. We note that this value of the radiation dose is very large, compared with the U.S. Federal off-site limit of 1 $\mathrm{mS_V/year}$.[3]

The above estimation can be summarized in the following formula:

$$E_{\rm dep} = E_\nu \left(\frac{R_h}{R_\nu}\right) e^{-d/R_\nu}\, I \left(\frac{m_\mu c^2}{E_\nu} d\right)^{-2} \ \ (\mathrm{eV/sec} \cdot \mathrm{m}^2) \ \ , \tag{3}$$

where R_h and R_ν stand for the average hadron and the neutrino mean free paths. R_ν is proportional to E_ν^{-1} below 1000 TeV corresponding to $\sigma_\nu^{\rm tot}\ (\mathrm{cm}^2) \sim 10^{-38} E_\nu$ (GeV), which leads to

$$E_{\rm dep} \sim E_\nu^4 \ \ .$$

Thus, $E_{\rm dep}$ drops sharply to 0.1 Joule/s for 100 TeV neutrino energy. It is, therefore, rather crucial to keep the energy as high as 1000 TeV.

To proceed further we need to know a little about the structure of the nuclear bomb. Since no official information is available to us, we rely on popular books [5, 6] and unclassified papers [7] on the subject. As a possible model for the bomb we consider a 10 kg ball of ^{239}Pu which has the critical mass

[3] The unit $\mathrm{S_V}$ corresponds, in alternative units, to 100 rem.

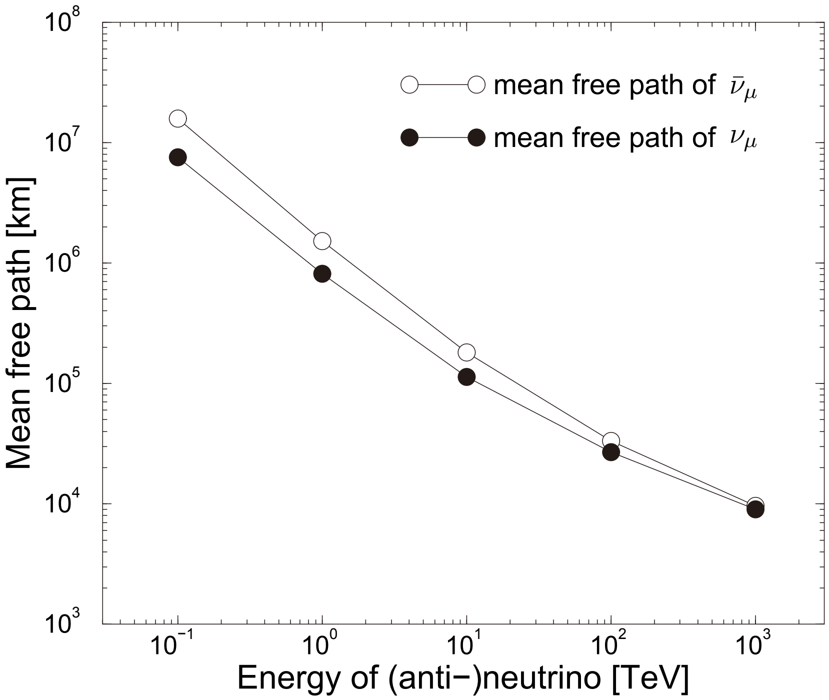

Figure 3: *Mean free path of (anti-)neutrino vs. its energy. This is calculated under the assumption that in this energy region the deep inelastic cross sections dominate. For the detail of the calculation, see appendix A.*

of 15 kg, surrounded by the ^{238}U tamper, the reflector and the explosive material (fig. 4). We also consider a system without explosive material surrounding the plutonium ball since we have no way to know how these bombs are stored. A crucial parameter in the former case is the number of fissions in the system which provides the temperature rise enough to ignite the surrounding explosives. If we assume that the explosive has the ignition temperature of 300 °C (TNT has its ignition temperature 210 °C), the number of fissions, $N_{\rm fission}$, required turns out to be about 10^{16} per 10 kg of plutonium [7]. One order of magnitude larger value 10^{17} should be enough to melt down the system in the latter case.

Let us estimate how much time it takes for this process to happen when the energy deposit from the neutrino beam is given by eq. (1). Since the tamper ^{238}U can also be regarded as the source of the fission when the neutron energy is as high as 10 MeV, which is the typical energy, $\epsilon_{\rm sp}$, of the spallation neutrons, we take the area exposed to the hadron shower to be 0.1 (m^2). In this case the total energy deposit in the bomb fission system is

$$E^{\rm T}_{\rm dep} = 0.1 \times 10^8 I = 10^{21}\ ({\rm eV/sec}) \quad {\rm for}\ \ I = 10^{14}\ (1/{\rm sec})\ \ .$$

The number of spallation neutrons, therefore, is equal to

$$n_{\rm sp} = \frac{E^{\rm T}_{\rm dep}}{\epsilon_{\rm sp}} = \frac{10^{21}}{10^7} = 10^{14}\ (1/{\rm sec})\ \ .$$

If we assume that each of the spallation neutrons causes a single fission and none of them are lost, the time required to ignite the explosive is

$$\frac{N_{\rm fission}}{n_{\rm sp}} = \frac{10^{16}}{10^{14}} = 100\ ({\rm sec})\ \ ,$$

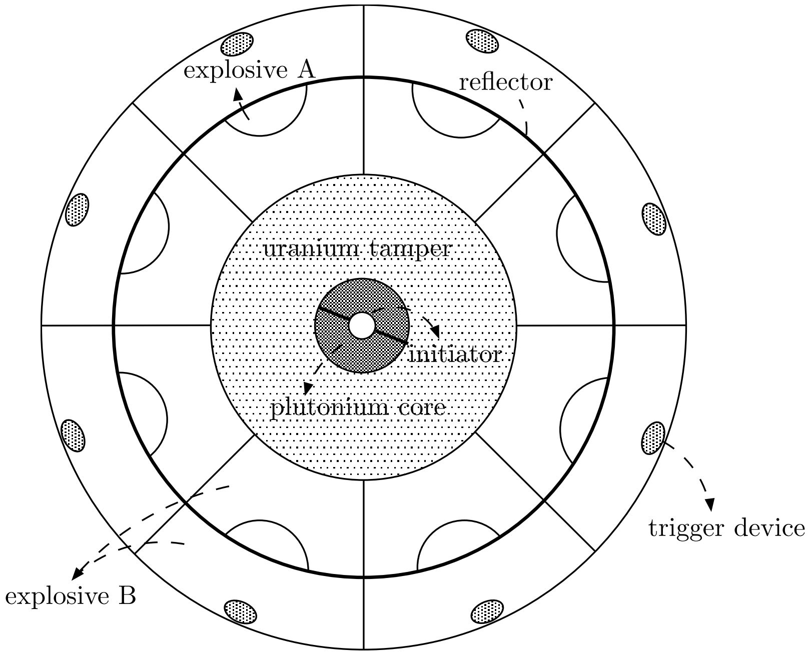

Figure 4: *A model for the plutonium bomb of implosion type* [6]. *The whole profile of the bomb is in the shape of a spherical body.*

and the melt down time is about 1000 (sec). The next question is whether we are going to have a full-fledged explosion or a kind of "fizzle explosion" in the case when the explosive sets ignited. The problem was studied in the appendix of ref. [7] by F. von Hippel and E. Lyman. This analysis shows that the neutron from the spontaneous fission which contaminates the ^{239}Pu system gives the probability P of the occurrence of "fizzle explosion" given by

$$P = 1 - e^{-cn_{\rm spon}} \ , \tag{4}$$

where $n_{\rm spon}$ is the number of neutrons from the spontaneous emission and c is a certain constant. We can replace this number $n_{\rm spon}$ by the number of spallation neutrons caused by the neutrino beam, which is 9 order of magnitude larger than the number of neutrons by the spontaneous emission of ^{240}Pu. Therefore, the probability of the "fizzle explosion" is practically equal to 1 in this case. This results in an energy yield of the explosion by the neutrino beam to be about 3% of the full explosion.

3 Simulation

Having discussed the rough estimation, let us now turn to numerical simulations to study the system in a more precise way. We divide our simulation procedure into two parts: The first part deals with a neutrino beam and its development into a hadron shower (see fig. 5). The second one follows the first one to calculate the nuclear reactions in the target bomb (see fig. 6). We give detailed discussions of the two parts separately in the subsequent sections 3.1 and 3.2.

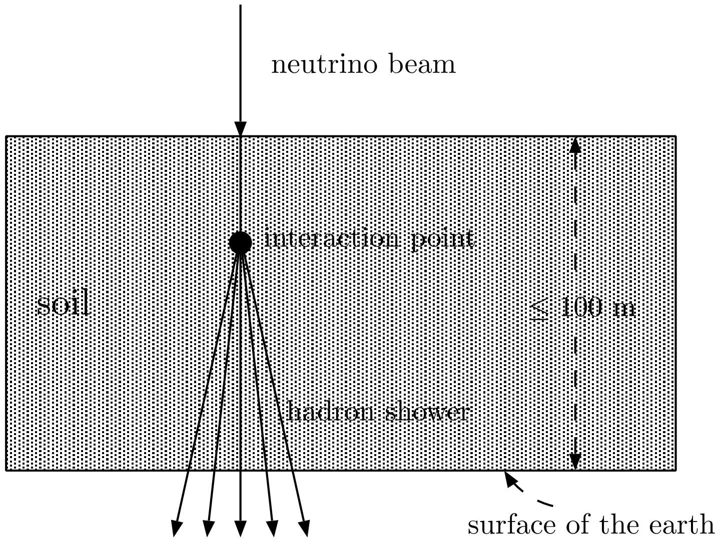

Figure 5: *Hadron shower arising near the target bomb. The neutrino beam passing through the soil interacts with nuclei near the surface of the earth, resulting in a hadron shower in a place a few meters close to the bomb.*

3.1 Incident neutrino beam and hadron shower

The first part is to start from a given neutrino beam of certain energy and intensity. We simulate the process of the neutrino beam hitting a target nucleus in the soil and follow the development of a hadron shower initiated by the neutrino interaction, as shown in fig. 5. The former process can be simulated by a generator HERWIG [8], in which we can include processes with the incident neutrino beam, such as $\nu + p$ (or n) $\rightarrow$ hadrons + leptons. In the latter process, subsequently, we simulate the interactions of the hadron shower with nuclei of the soil by using other Monte-Carlo codes GEANT4 [9] and MARS [10]. The purpose of this part is to obtain the multiplicity of the shower when the shower is going out of the earth. The neutrino interaction which occurs near the surface of the earth is relevant. We consider, therefore, a system which is shown in fig. 5.

The result of this part will appear in a separate publication [12].

3.2 Nuclear reactions inside the target

The second part of our simulation is to calculate the temperature increase of the plutonium system caused by the hadron shower. We consider a system shown in fig. 6. Our calculation of this part is carried out using the MCNPX code[4].

In order to simplify the system and save the computation time, we replace the parallel hadron shower of fig. 6 by a neutron source which is situated at the center of the ^{239}Pu core, as shown in fig. 7. We also assume that the incident neutron of its energy 1 GeV starts from a point inside the core.

[4]MCNPX has been used extensively in nuclear reactor physics and its applications, and developed for a long time since 1940's [2]. Furthermore, many physicists and programmers are still developing it for improvement even at present.

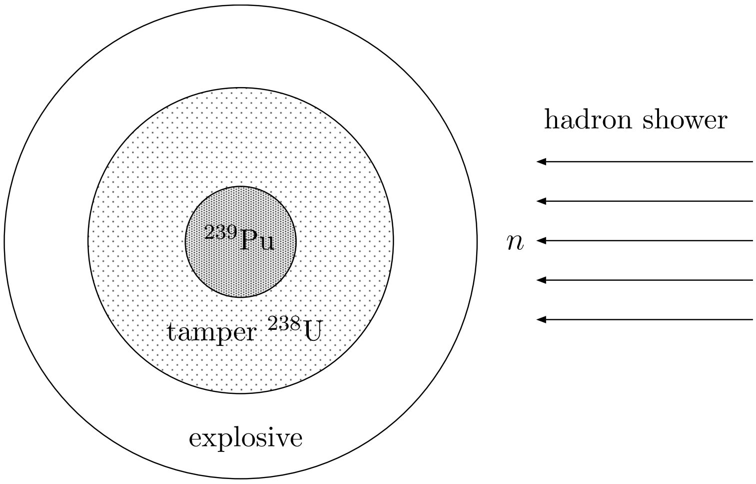

Figure 6: *A hadron shower going into the plutonium bomb. Neutrons in the shower will induce the fission reactions inside the plutonium system and cause the temperature increase as a result.*

To make clear the algorithm of the MCNPX code, we illustrate a simple example of nuclear reactions in fig. 7, where the first collision occurs at event 1 in the Pu core. The neutron is scattered in the direction shown, which is selected randomly from the physical scattering distribution. A photon is also produced and is temporarily stored, or banked, for later analysis. At event 2, fission occurs, resulting in the termination of the incoming neutron and the birth of two outgoing neutrons and one photon. One neutron and the photon are banked for later analysis. The first fission is captured at event 3 and terminated. The banked neutron is now retrieved and, by random sampling, leaks out of the core at event 4. The fission-produced photon has a collision at event 5 and leaks out at event 6. The remaining photon generated at event 1 is now followed with a capture at event 7. Note that MCNPX retrieved banked particles such that the last particle stored in the bank is the first particle taken out.

This neutron history in the core and the tamper is now complete. As more and more such histories are followed, the neutron and photon distributions become better known. The quantities of interest, such as the total energy arising in the reactions, are tallied along with estimates of the statistical precision of the results. Hence, after repeating the similar calculations, we could obtain the average value, $\epsilon_{\text{fission}}$, of the fission energy deposition:

$$\epsilon_{\text{fission}} = 0.6260 \pm 0.0032 \ (\text{MeV/g}) \ .$$

This is the contribution on the average from one incident neutron. Thus, if we prepare N_{in} neutrons incident on the ^{239}Pu core, the increase in temperature can be estimated as

$$\Delta T = \frac{N_{\text{in}}\, \epsilon_{\text{fission}}}{C_{\text{Pu}}} = 0.9547 \times 10^{-12}\, N_{\text{in}} \ (\text{K}) \ , \tag{5}$$

where C_{Pu} is the specific heat of ^{239}Pu, whose numerical value is given by

$$C_{\text{Pu}} = \frac{4.186 \ (\text{J/cal}) \times (6.0/239) \ (\text{cal/g} \cdot \text{K})}{1.602 \times 10^{-13} \ (\text{J/MeV})} = 6.557 \times 10^{11} \ (\text{MeV/g} \cdot \text{K}) \ .$$

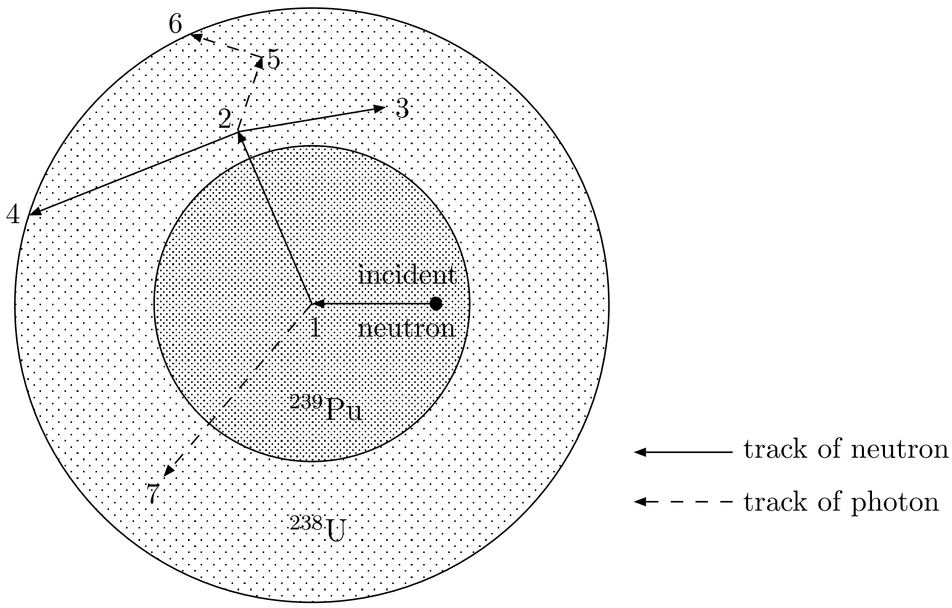

Figure 7: *A history of a neutron incident on the* ^{239}Pu *core that can undergo nuclear fission. 1. Neutron scattering and photon production in the core. 2. Fission and photon production in the* ^{238}U *tamper. 3. Neutron capture in the tamper. 4. Neutron leakage out of the tamper. 5. Photon scattering in the tamper. 6. Photon leakage out of the tamper. 7. Photon capture in the tamper.*

Therefore, in order to obtain a temperature increase $\Delta T = 250$ (K), which corresponds to the ignition temperature of TNT, the total number of the incident neutrons should be

$$N_{\text{in}} = \frac{250}{0.9547 \times 10^{-12}} = 2.619 \times 10^{14} \quad . \tag{6}$$

This value of $N_{\text{in}} \sim O(10^{14})$ is close to the estimated value in section 2, and it is not unrealistic in the future technology of the muon colliders.

To verify our results of simulation, the experiment can be devised in which a hadron beam of GeV energy hits a ball of plutonium (not necessarily of weapons-grade) and increases its temperature. The experiment is similar to the one which is performed to study the target material for the neutron spallation sources.

4 Conclusion

We have shown that it is possible to eliminate the nuclear bombs from the surface of the earth utilizing the extremely high-energy neutrino beam. When the neutrino beam hits a bomb, it will cause the fizzle explosion with 3% of the full strength. It seems that it is not possible to decrease the magnitude of the explosion smaller than this number at this stage. It is important to decrease this number to destroy bombs safely. We are not sure what this means when the plutonium or uranium is used to ignite the hydrogen bomb. We may just break the bomb or may lead to a full explosion. The whole process takes a matter of a few minutes in the case considered in this paper although, of course, it depends on the intensity of the neutrino beam. When the bombs are stored in the form of plutonium ball separated from the explosives, what we can do is to melt them down or vapor them away. It takes substantially longer time for this process to occur.

To justify the above statements we performed a detailed simulation calculation and the part of its results is explained in this paper although the full content will be published later. After the high-energy neutrino beam passes through the soil, it causes a hadron shower near the surface of the earth, and subsequently, neutrons in the shower will strike the ^{239}Pu core. In order to estimate the number of the incident neutrons which is large enough to make the temperature of the TNT surrounding the core increase to its ignition one, we have carried out the numerical simulations using MCNPX under the simplified conditions. As a consequence, we obtained the value of $N_{\rm in} \sim O(10^{14})$. This value is consistent with the estimation obtained roughly, and it is expected to be realistic in the future technology.

We utilize 1000 TeV[5] neutrino beam for our purposes and we do not have the technology yet to produce such a high energy neutrino. We may start an R & D now and proceed step by step. Yet it may take even an order of a century to achieve the goal.

We describe below a possible scenario for the whole project:

(1) First, we should construct a neutrino factory which could have substantially lower energy than even 1 TeV. The purpose is to fully understand the properties of the neutrino including mass, mixing angles, CP violating phase, Majorana property and the interactions with other particles [15].

(2) The next step is to construct a muon collider in the multi-TeV energy range. The energy should be beyond 10 TeV. These two steps still require a fair amount of R & D but we believe that they are on the straightforward extension of the currently available technology.

(3) The third step is to construct a muon collider of more than 100 TeV energy and to reach even 1000 TeV. We do not have the technology yet for this kind of machine. We may need a magnet with one to two orders of magnitude higher field than the currently available one to construct a machine of a reasonable scale. A completely new approach may be necessary to make this possible.

(4) If the third step becomes real, then the fourth step is to actually build the 1000 TeV muon collider with the movable straight sections.

We want to emphasize the importance of realizing the first two steps since the technology is within the reach and its contribution to the basic science is enormous. The study may even show that the

[5]Actually, the neutrino mean free path which leads us to consider 1000 TeV is not quite accurate. As is mentioned in appendix A, we did not include the contribution of the heavier quarks. In addition, we did not take into consideration the "neutrino transport theory" [11] at all here. The inclusion of these effects on the deep inelastic cross sections will lead to the mean free path which is almost 1/3 of the value we have used in this paper. This change will lead to the energy of 300 TeV and, therefore, we need 27 times higher intensity than considered in section 2. Of course, targeting the bomb becomes much easier.

neutrino interaction increases more rapidly with the energy owing to the large extra-dimensions as in some models [16]. In that case we need not go as far as 1000 TeV for our purposes. The last two steps require tremendous amount of effort in developing the necessary technology. It is also true that fair amount of financial and human resources will have to be introduced to accomplish the last two steps.

The neutrino beam could also be used to detect the nuclear bombs with much less energy and with much less intensity. The necessary technology is the detection of the fission products from a reasonable distance. It could be rather difficult if the bombs are stored in a deep underground location.

Another useful application of high-energy neutrino beam is to the study of the inner structure of the earth [17]. We may not need the neutrino energy to be as high as 1000 TeV in this case. The detailed study is being performed on this subject and we will describe it in a forthcoming publication.

We are certainly aware of the fact that this kind of device can not only target the nuclear bombs but other kinds of weapons of mass destruction and also, unfortunately, any kind of living object including human. But we should emphasize that the device itself is not a weapon of mass destruction. The reason is as follows: The calculation in section 2 and section 3 shows that it takes 1 second for this device to cover a 1 m^2 with the radiation dose of 1 $\mathrm{S_V}$. It takes more than a year to cover the area of 10 km^2 with this value of dose per unit area. It is extremely unlikely that no measure is taken after a few minutes of exposure of this kind. Moreover, as is emphasized in the introduction and also in the appendix B, the construction cost and the power required for the operation make it almost impossible for even the richest country to build and operate it all by itself. We strongly object to the ungrounded worry that this kind of device, even its downgraded version could be used by certain irresponsible organization as a weapon of mass destruction. On the contrary, we sincerely hope that our proposal will motivate and stimulate the revival of the old idea of "World Government" which has so far been discarded as unrealistic.

Lastly we would like to point out that at least the first two steps described in this section have nothing to do with the weapon research. They belong to the most fundamental scientific research activities. The suitable organizational structure to perform such a research, therefore, is through the world-wide collaboration. Another worry could be expressed on the neutrino hazard around the machine. It depends crucially on where one builds the machine. The concrete proposal explained in appendix B has two hazardous planes and two dangerous (P_3P_4 and Q_3Q_4) directions. "No fly zones" should be set to avoid these hazardous regions. The duration time of an operation should be minimized for the security reason and also for the reason of power consumption.

Appendices

A Mean free path of (anti-)neutrino

This section is devoted to the derivation of the mean free path of (anti-)neutrino passing through the inside of the earth. T. Abe, who is on the staff of Accelerator Laboratory of KEK, has mainly contributed to the following calculations and actually made fig. 3 under some assumptions. Here we discuss the assumptions in some detail and further derive the mean free paths in a numerical way.

First, we assume that neutrino deep-inelastic scattering on heavy nuclear targets ${}^{Z+N}_{Z}\mathrm{X}$, including the contributions of both the charged and neutral currents, dominates in the energy region between multi-TeV and 1000 TeV; the relevant cross sections for νX-scattering are given at the tree level by [13]

$$\frac{d^2\sigma^{\rm cc}_{\nu \rm X}}{dxdy} = \frac{G_{\rm F}^2 m_{\rm N} E_\nu x}{\pi}\left(\frac{M_W^2}{-q^2+M_W^2}\right)^2\left\{Zd(x)+Nu(x)+(1-y)^2\left(Z\bar{u}(x)+N\bar{d}(x)\right)\right\}, \tag{7}$$

$$\frac{d^2\sigma^{\rm cc}_{\bar{\nu} \rm X}}{dxdy} = \frac{G_{\rm F}^2 m_{\rm N} E_\nu x}{\pi}\left(\frac{M_W^2}{-q^2+M_W^2}\right)^2\left\{Z\bar{d}(x)+N\bar{u}(x)+(1-y)^2\Big(Zu(x)+Nd(x)\Big)\right\}, \tag{8}$$

$$\begin{aligned}\frac{d^2\sigma^{\rm nc}_{\nu \rm X}}{dxdy} = {} & \frac{G_{\rm F}^2 m_{\rm N} E_\nu x}{\pi}\left(\frac{M_Z^2}{-q^2+M_Z^2}\right)^2 \\ & \times\Bigg[(1-y)^2\Bigg\{\left(\frac{2}{3}\sin^2\theta_W\right)^2\Big(Zu(x)+Nd(x)\Big)+\left(\frac{1}{3}\sin^2\theta_W\right)^2\Big(Zd(x)+Nu(x)\Big) \\ & +\left(-\frac{1}{2}+\frac{2}{3}\sin^2\theta_W\right)^2\left(Z\bar{u}(x)+N\bar{d}(x)\right)+\left(\frac{1}{2}-\frac{1}{3}\sin^2\theta_W\right)^2\Big(Z\bar{d}(x)+N\bar{u}(x)\Big)\Bigg\} \\ & +\Bigg\{\left(\frac{2}{3}\sin^2\theta_W\right)^2\Big(Z\bar{u}(x)+N\bar{d}(x)\Big)+\left(\frac{1}{3}\sin^2\theta_W\right)^2\Big(Z\bar{d}(x)+N\bar{u}(x)\Big) \\ & +\left(\frac{1}{2}-\frac{2}{3}\sin^2\theta_W\right)^2\Big(Zu(x)+Nd(x)\Big)+\left(-\frac{1}{2}+\frac{1}{3}\sin^2\theta_W\right)^2\Big(Zd(x)+Nu(x)\Big)\Bigg\}\Bigg],\end{aligned} \tag{9}$$

$$\begin{aligned}\frac{d^2\sigma^{\rm nc}_{\bar{\nu} \rm X}}{dxdy} = {} & \frac{G_{\rm F}^2 m_{\rm N} E_\nu x}{\pi}\left(\frac{M_Z^2}{-q^2+M_Z^2}\right)^2 \\ & \times\Bigg[(1-y)^2\Bigg\{\left(\frac{2}{3}\sin^2\theta_W\right)^2\Big(Z\bar{u}(x)+N\bar{d}(x)\Big)+\left(\frac{1}{3}\sin^2\theta_W\right)^2\Big(Z\bar{d}(x)+N\bar{u}(x)\Big) \\ & +\left(\frac{1}{2}-\frac{2}{3}\sin^2\theta_W\right)^2\Big(Zu(x)+Nd(x)\Big)+\left(-\frac{1}{2}+\frac{1}{3}\sin^2\theta_W\right)^2\Big(Zd(x)+Nu(x)\Big)\Bigg\} \\ & +\Bigg\{\left(\frac{2}{3}\sin^2\theta_W\right)^2\Big(Zu(x)+Nd(x)\Big)+\left(\frac{1}{3}\sin^2\theta_W\right)^2\Big(Zd(x)+Nu(x)\Big) \\ & +\left(-\frac{1}{2}+\frac{2}{3}\sin^2\theta_W\right)^2\left(Z\bar{u}(x)+N\bar{d}(x)\right)+\left(\frac{1}{2}-\frac{1}{3}\sin^2\theta_W\right)^2\Big(Z\bar{d}(x)+N\bar{u}(x)\Big)\Bigg\}\Bigg],\end{aligned} \tag{10}$$

where $G_{\rm F}$, θ_W, $m_{\rm N}$ and E_ν stand for the Fermi coupling constant, the Weinberg angle, the nucleon mass and the incident neutrino energy. $u(x)$ and $d(x)$ are the parton distribution densities for u and d quarks. Z and N stand for the proton number and the neutron number inside the given nuclei, and

q denotes the momentum transfer for the processes considered. Here x and y are the usual scaling variables, defined as

$$x = \frac{-q^2}{2m_{\rm N}\,(E_\nu - E_\mu)}\,, \quad y = \frac{(E_\nu - E_\mu)}{E_\nu}\,, \tag{11}$$

where E_μ stands for the energy of the final-state muon in the charged-current processes. In case of the neutral-current processes E_μ must be replaced by the energy, E'_ν, of the final-state neutrino in eqs. (11). In eqs. (7) and (8) we take the following scattering processes into consideration at the tree level:

$$\nu_\mu + d \to \mu^- + u\,, \quad \nu_\mu + \bar{u} \to \mu^- + \bar{d}\,,$$
$$\bar{\nu}_\mu + u \to \mu^+ + d\,, \quad \bar{\nu}_\mu + \bar{d} \to \mu^+ + \bar{u}\,,$$

Here we ignored the contribution of strange quark for simplicity. Similarly, in eqs. (9) and (10) we include the following neutral current scattering processes:

$$\nu_\mu + {\rm q} \to \nu_\mu + {\rm q}\,, \quad \nu_\mu + \bar{\rm q} \to \nu_\mu + \bar{\rm q}\,,$$
$$\bar{\nu}_\mu + {\rm q} \to \bar{\nu}_\mu + {\rm q}\,, \quad \bar{\nu}_\mu + \bar{\rm q} \to \bar{\nu}_\mu + \bar{\rm q}\,,$$

where ${\rm q} = u$ or d, and again we do not include the s quark contribution at all.

Second, we adopt a set of parton distributions called CTEQ5L [14] as the structure functions of proton and neutron. Using the set, we calculate the total cross sections $\sigma^{\rm tot}_{\nu p}$, $\sigma^{\rm tot}_{\nu n}$, $\sigma^{\rm tot}_{\bar{\nu} p}$ and $\sigma^{\rm tot}_{\bar{\nu} n}$ for the $\nu_\mu p$, $\nu_\mu n$, $\bar{\nu}_\mu p$ and $\bar{\nu}_\mu n$ scattering processes, respectively. Actually, we have carried out these calculations by the Monte-Carlo method with a high precision of 0.1 %.

Finally, we obtain the mean free path of neutrino R_ν and that of anti-neutrino $R_{\bar{\nu}}$ in a usual manner. For the purpose we first must know the number density of protons, N_p, inside the earth and that of neutrons, N_n. Indeed, we can easily obtain these densities, because we know that the number of protons and that of neutrons are on the average in the ratio of 49.5 to 50.5. In addition, the average mass density of the earth, $\rho_{\rm earth}$, is measured to be 5.52×10^3 (kg/m^3). Hence, one can obtain the number densities:

$$\begin{aligned} N_p &= \frac{\rho_{\rm earth}}{m_p} \times \frac{49.5}{49.5+50.5}\ (1/{\rm m}^3)\ , \\ N_n &= \frac{\rho_{\rm earth}}{m_n} \times \frac{50.5}{49.5+50.5}\ (1/{\rm m}^3)\ , \end{aligned}$$

where m_p and m_n stand for the proton and the neutron masses. Thus, we obtain the mean free path of (anti-) neutrino

$$R_\nu = \frac{1}{N_p \sigma^{\rm tot}_{\nu p} + N_n \sigma^{\rm tot}_{\nu n}}\ ({\rm m})\ , \tag{12}$$

$$R_{\bar{\nu}} = \frac{1}{N_p \sigma^{\rm tot}_{\bar{\nu} p} + N_n \sigma^{\rm tot}_{\bar{\nu} n}}\ ({\rm m})\ . \tag{13}$$

Throughout the process of the above calculations, we did not include higher order corrections at all. However, it is plausible that if we include s and other heavier quarks into the parton distributions, the total cross sections will probably become a few times larger than those obtained here. Furthermore, QCD corrections and the "regeneration processes" [11] will also have other effects on the cross sections. Our next step is to take these effects into consideration on the basis of a detailed Monte-Carlo study, which remains to be solved in the near future.

B Possible accelerator scheme

We first look for a mountain like in fig. 8 whose surface does not touch many of the straight lines depicted as P_1P_2, P_3P_4, Q_1Q_2 or Q_3Q_4. We construct two synchrotron A and B which are both revolvable. A should be larger than B. Muon beam is injected into the synchrotron A first and accelerated to a sufficient energy. Injection system could be installed in a tunnel in the mountain. Then it is stored either in the path $P_2P_3P_4P_1P_2$ or $Q_2Q_3Q_4Q_1Q_2$ depending on the direction of the beam in the synchrotron A. The beam is either μ^+ or μ^-. The straight sections P_1P_2, P_3P_4, Q_1Q_2 and Q_3Q_4 are made of chambers separated by many bellow structures so that they can have a flexible length. We probably have to prepare several chambers to cover from the minimum to the maximum length continuously. When we rotate A or B the chambers must follow until we steer the straight section to a given target.

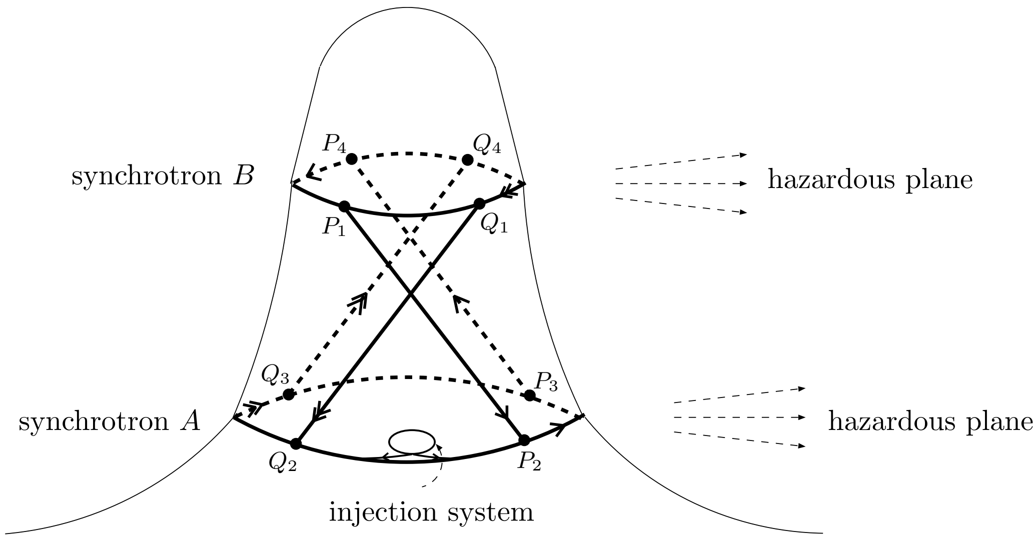

Figure 8: *Accelerator scheme.*

The next question is how precisely we can steer it. From the discussion given in the text the required accuracy is 10^{-7}. This is 1/10 micron per meter. We believe this is not an outrageous number. The current effort toward the construction of a linear collider is aiming at approximately 1 micron per meter. Future technology certainly will reach our required number sooner or later.

Another issue is the power consumption and the radiation hazard. Power required is $10^{14} \times 10^{-19} \times 10^{15}$ W $\simeq$ 10 GW. Actually, we may need something like 50 GW (considering the efficiency) which is exactly the whole capacity of Japanese nuclear power. But the energy consumption could be as small as $10^2/10^8 = 10^{-6}$ times the whole consumption of 50 GW power. This should be quite tolerable. For the radiation hazard we have two planes in fig. 8 which should not be crossed by anyone during the operation and one direction toward the sky where no one is allowed to touch. The other direction is, of course, toward the target. Almost all the energy is lost in the earth and only 10^{-7} times the whole energy hits the target. People working near the target should be warned unless they are working to conceal the weapons.

We can perform $\mu^+\mu^+$, $\mu^-\mu^-$ and $\mu^+\mu^-$ colliding experiment in this scheme by injecting two beams simultaneously although the detector should be placed on a very steep slope between A and B synchrotrons. We believe it is not unreasonable to build this kind of accelerator complex first with much lower energy beam to study the inside of the earth and simultaneously performing the muon collider experiments and also the neutrino experiments.

Acknowledgment

We are grateful to Tetsuo Abe for giving us fig. 3 of the mean free paths. We thank Masayoshi Kawai for his useful comments on MCNPX. We appreciate Yoshinobu Takaiwa for his helpful suggestion of some Monte-Carlo generators. We would like to acknowledge valuable discussions with Tokushi Shibata and members of Theory Division of KEK. The questions and comments by Yoshitaka Kimura, Sakuei Yamada, Frank von Hippel, Sydney Drell, Burton Richter and colleagues of H.S. at the University of Hawaii are deeply appreciated.

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資 料　2

February 2008

Hazardous Effects of UltraHigh-Energy Neutrinos on Fissile Systems

Junpei Fujimoto[a] *　Hiroyuki Hagura[b] †　Kiyoshi Kato[c] ‡
Yoshimitsu Shimizu[a] §　Hirotaka Sugawara[d] ¶

[a] *Graduate University for Advanced Studies, Hayama, Miura-gun Kanagawa 240-0193, Japan*
[b] *KCS Corp., Muramatsukita 2-7-25, Tokai-mura, Naka-gun, Ibaraki 319-1108, Japan*
[c] *Kogakuin University, Nish-Shinjyuku 1-24, Shinjyuku, Tokyo 163-8677, Japan*
[d] *JSPS Washington Office, 1800 K St NW, Suite 920, Washington DC 20006, USA*

Abstract

We discuss interactions of ultrahigh-energy neutrinos with fissile systems including fissionable and radiation-shielding material. Neutrino beams emitted from a huge muon accelerator of more than several hundred TeV are able to produce high-energy hadrons by deep-inelastic scattering on various nuclei in the material. We calculate mean free paths of the neutrinos, including large QCD effects at the leading and the next-to-leading orders. The produced hadrons induce exothermic nuclear reactions in the process of transport in the systems even after going through the Earth. We show it by numerical methods that the heat and the radiation caused by the reactions can be a serious danger to the systems, particularly to nuclear bombs.

*E-mail: `junpei[at]post.kek.jp`
†E-mail: `hagura[at]post.kek.jp`
‡E-mail: `kato[at]cc.kougakuin.ac.jp`
§E-mail: `shimiz[at]suchix.kek.jp`
¶E-mail: `sugawara[at]jspsusa.org`

1 Introduction

Accelerators have been giving us a lot of information on the microscopic structures of nature. Experiments at accelerators have made particle physics the most reliable science in collaboration with theoretical developments. Such a trend in particle physics will continue also in the future. A proposal for a muon storage ring, which is regarded as a neutrino factory on the energy scale of several ten GeV, has also been discussed by neutrino physicists [1]. Many projects for the next generation of accelerators are considered within the reach of the current technology or its extension.

As for the next-next generation of accelerators, however, particle physicists have no decisive project at the energy frontier in the future, although many physicists have discussed varieties of ideas. According to the linear extrapolation of the Livingston plot, physicists have potentiality of constructing a PeV-scale collider by the early 2040's, as shown in Fig. 1. Of them a large muon collider of more than 100 TeV is such a candidate for the future accelerator [2].

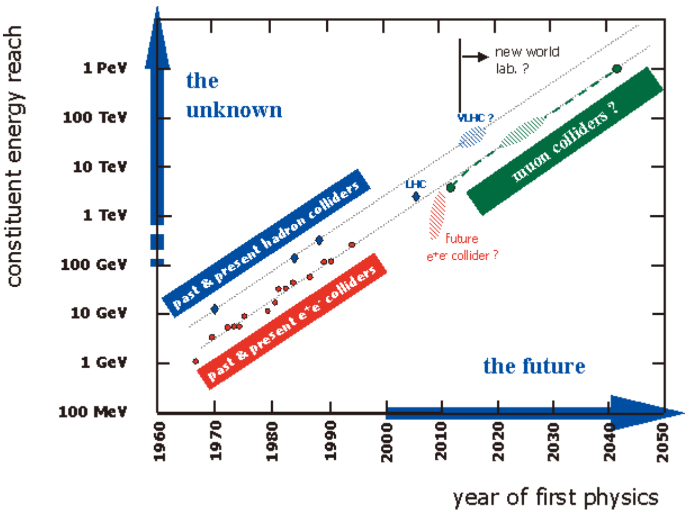

Figure 1: The Livingston plot used in Ref. [2]. It shows the historical progress in the constituent energy reach of colliders. Each point on the curve represents a collider. A possible scenario for future colliders to continue the exponential progress in hadron and lepton energy reach has been added. The definitions and data points in the plot are discussed in detail in Ref. [2], as is an optimistic scenario for future colliders.

Interestingly, such a muon collider can play another role of an intense neutrino factory because the decays of muons in the beam ring produce plenty of neutrinos along the ring. The interactions of such neutrinos with matter give rise to a serious problem of the so-called *neutrino hazards* at very high energies [3]. Intense neutrino beams are already hazardous even at the energy of several TeV as have been analyzed by B. J. King [4], N. V. Mokhov and A. Van Ginneken [5] in connection with the study of muon colliders. This is due to the properties that high-energy neutrinos have large cross sections of deep-inelastic scattering (DIS) on nuclei in matter, which are enough to produce a lot of dangerous energetic hadrons. As a result, high-energy neutrinos are able to have very hazardous effects on human bodies, environments and furthermore on fissile systems such as nuclear power reactors, nuclear weapons and so on. At any rate, there is no physical way of shielding the high-energy, neutrino-induced radiation in any cases.

If one constructs a race track shaped muon storage ring as shown in Fig. 2, most of the muons decay into the two opposite directions of the straight sections. These two directions are the most hazardous "hot spots". In addition, the circular parts also emit the neutrinos which may also be hazardous in the vicinity of the storage ring.

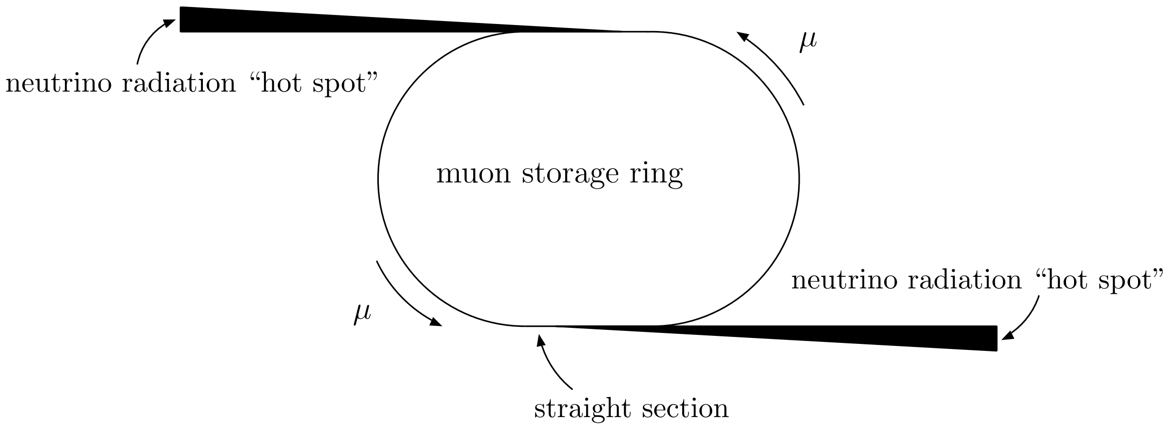

Figure 2: Neutrino radiation from a race track shaped muon storage ring. The decay of muons will produce the neutrino radiation emanating out tangentially everywhere from the ring. In particular, each straight section in the ring will cause a radiation "hot spot" where all of the decays line up into a pencil beam.

In our previous study [6], we carried out some Mont-Carlo simulations of the interactions of high-energy neutrino beams with a plutonium bomb, and concluded that the high-energy neutrino beams of 1 PeV are able to induce a fizzle explosion with more than 3 % of the full strength when they hit the core of the plutonium bomb. We also estimated the electric power required for the operation of the muon accelerator may exceed 50 GW[1], although our calculation was based on some unrealistic assumptions mainly owing to the limitations of radiation-transport codes at that time.

Now we study the same phenomena on the basis of sophisticated numerical techniques and theoretical considerations including particle, nuclear and neutron physics. This paper is organized as follows. In Section 2 we give in some detail a review on neutrino-nucleon (νN) and neutrino-nucleus (νA) deep-inelastic scattering (DIS) at (ultra-)high energies. Numerical program PDFLIB [12] is used to include QCD corrections at the leading-log (LL) and the next-to-leading-log (NLL) levels to the cross-sections for the DIS processes. Nuclear effects on νA DIS are also discussed. Then, we will calculate mean free paths of (anti-)neutrinos when passing through the inside of the Earth. Section 3 gives a rough estimation and also deals with a computer simulation using a Monte-Carlo generator HERWIG [17], a high-energy hadron transport code MARS [21] and a neutron-transport code MCNP [18]. Section 4 gives a conclusion with various comments. Appendix A is devoted to

[1]This value 50 GW is above the total power of Great Britain.

a brief review of a model for nuclear-bomb detonation. In appendix B, we explain a possible accelerator scheme.

2 Interactions of Neutrinos at Ultra-High Energies

Neutrinos are very weakly interacting particles at low energies. At ultra-high energies, however, the cross-sections for neutrino deep-inelastic scattering (νDIS) processes become large because they are nearly proportional to the energies of the neutrinos incident on nucleon/nuclear targets. First we derive the cross sections based on the parton model of nucleon. Second we discuss the effect of strong interactions known as QCD corrections. Finally we show the mean free path of $\nu, \bar{\nu}$ v.s. neutrino energy when they pass through the Earth. It is argued that the number of quark species (flavor) should be 5 rather than 2.

2.1 Parton Model Cross Sections for νDIS

In order to illustrate how νDIS (including anti-neutrino-nucleon DIS) look like, we first consider the simplest case that the nucleon is composed of only u- and d-quark: A proton is made of two u-quarks and one d-quark, and a neutron of two d-quarks and one u-quark. In addition to those basic quark components, high energy ν_μ's see a pair of virtual quarks, thus there exist also anti-quarks $\bar{u}$ and $\bar{d}$ inside a nucleon. Also there is a neutral massless boson called *gluon*, that do not interact with neutrino, but strongly with quarks in a nucleon.

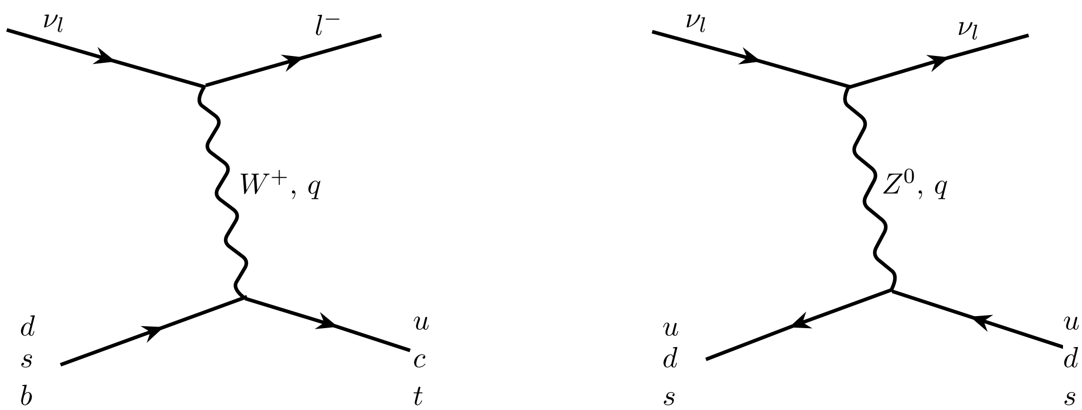

Figure 3: Neutrino deep-inelastic scattering at the tree level.

In this section we consider the tree level interaction between ν_μ and parton as shown in Fig. 3. The processes proceed by exchanging either of two heavy bosons between ν_μ and quarks. One is $W^\pm$ and the other is Z^0. Since the former is a charged particle, the corresponding process is called charged-current(CC) process, while the latter case, without charge, neutral-current(NC) process.

Then the basic processes which take place between $\nu_\mu(\bar{\nu}_\mu)$ and quarks in a nucleon are,

$$\nu_\mu + d \to \mu^- + u\,, \quad \nu_\mu + \bar{u} \to \mu^- + \bar{d}\,,$$
$$\bar{\nu}_\mu + u \to \mu^+ + d\,, \quad \bar{\nu}_\mu + \bar{d} \to \mu^+ + \bar{u}\,,$$

for CC, and

$$\nu_\mu + \mathrm{q} \to \nu_\mu + \mathrm{q}\,, \quad \nu_\mu + \bar{\mathrm{q}} \to \nu_\mu + \bar{\mathrm{q}}\,,$$
$$\bar{\nu}_\mu + \mathrm{q} \to \bar{\nu}_\mu + \mathrm{q}\,, \quad \bar{\nu}_\mu + \bar{\mathrm{q}} \to \bar{\nu}_\mu + \bar{\mathrm{q}}\,,$$

for NC, where $\mathrm{q} = u$ or d.

Corresponding to these basic processes we write down the double differential cross-sections at the leading order, namely tree level without any other corrections. We assume that νDIS on a nuclear target ${}^A_Z\mathrm{A}$, where $A \equiv Z + N$ is the mass number of the nucleus A, dominates in the energy region between multi-TeV and 1000 TeV. In this approximation the cross sections for νA DIS are simply given by adding $Z\sigma^{\rm cc}_{\nu p}$ and $N\sigma^{\rm cc}_{\nu n}$ for CC interactions, and $Z\sigma^{\rm nc}_{\nu p}$ and $N\sigma^{\rm nc}_{\nu n}$ for NC interactions. The basic formulas are given by

$$\frac{d^2\sigma^{\rm cc}_{\nu \rm A}}{dxdy} = \frac{G_{\rm F}^2 m_{\rm N} E_\nu x}{\pi}\left(\frac{m_W^2}{-q^2+m_W^2}\right)^2 \left\{ Zd(x) + Nu(x) + (1-y)^2\left(Z\bar{u}(x) + N\bar{d}(x)\right)\right\}, \tag{1}$$

$$\frac{d^2\sigma^{\rm cc}_{\bar{\nu} \rm A}}{dxdy} = \frac{G_{\rm F}^2 m_{\rm N} E_\nu x}{\pi}\left(\frac{m_W^2}{-q^2+m_W^2}\right)^2 \left\{ Z\bar{d}(x) + N\bar{u}(x) + (1-y)^2\Big(Zu(x) + Nd(x)\Big)\right\}, \tag{2}$$

$$\begin{aligned}
\frac{d^2\sigma^{\rm nc}_{\nu \rm A}}{dxdy} = {}& \frac{G_{\rm F}^2 m_{\rm N} E_\nu x}{\pi}\left(\frac{m_Z^2}{-q^2+m_Z^2}\right)^2 \\
& \times\Bigg[(1-y)^2\Bigg\{\left(\frac{2}{3}\sin^2\theta_W\right)^2\Big(Zu(x)+Nd(x)\Big) + \left(\frac{1}{3}\sin^2\theta_W\right)^2\Big(Zd(x)+Nu(x)\Big) \\
& + \left(-\frac{1}{2}+\frac{2}{3}\sin^2\theta_W\right)^2\left(Z\bar{u}(x)+N\bar{d}(x)\right) + \left(\frac{1}{2}-\frac{1}{3}\sin^2\theta_W\right)^2\Big(Z\bar{d}(x)+N\bar{u}(x)\Big)\Bigg\} \\
& + \Bigg\{\left(\frac{2}{3}\sin^2\theta_W\right)^2\Big(Z\bar{u}(x)+N\bar{d}(x)\Big) + \left(\frac{1}{3}\sin^2\theta_W\right)^2\Big(Z\bar{d}(x)+N\bar{u}(x)\Big) \\
& + \left(\frac{1}{2}-\frac{2}{3}\sin^2\theta_W\right)^2\Big(Zu(x)+Nd(x)\Big) + \left(-\frac{1}{2}+\frac{1}{3}\sin^2\theta_W\right)^2\Big(Zd(x)+Nu(x)\Big)\Bigg\}\Bigg],
\end{aligned} \tag{3}$$

$$\frac{d^2\sigma^{\rm nc}_{\bar{\nu} \rm A}}{dxdy} = \Big(\text{interchange the factor } (1-y)^2 \text{ with the factor 1 in the above expression (3)}\Big). \tag{4}$$

Here $G_{\rm F}$, θ_W, $m_{\rm N}$ and E_ν stand for the Fermi coupling constant, the Weinberg angle, the nucleon mass and the incident neutrino energy. These apparently show that the cross section is linear with the ν energy E_ν. The scaling functions $u(x)$ and $d(x)$ are the parton distribution functions(PDFs) for u- and d-quarks in a proton. In the parton model of nucleon the variable x is interpreted as a fraction of momentum of initial quark. Also we have assumed

$$\begin{aligned} d(x) \ \text{ in a neutron } &= u(x) \ \text{ in a proton,} \\ u(x) \ \text{ in a neutron } &= d(x) \ \text{ in a proton,} \end{aligned} \tag{5}$$

that is, proton and neutron are symmetric under the interchange $u \leftrightarrow d$. The functions $\bar{u}(x)$ and $\bar{d}(x)$ stand for those for anti-quarks. The momentum transfer is denoted as q for the processes considered, and x is the Bjorken's scaling variable and y the fraction of the energy transferred to the hadrons, defined as

$$x = \frac{Q^2}{2m_{\mathrm{N}}\,(E_\nu - E_\mu)}\,, \quad y = \frac{(E_\nu - E_\mu)}{E_\nu}\ , \tag{6}$$

where $Q^2 \equiv -q^2$ and E_μ stands for the energy of the final-state muon in the CC processes. In the case of NC processes E_μ in Eq. (6) must be replaced by the energy of the final-state neutrino, E'_ν. The variables x, y run in the region

$$0 < x < 1 \quad \text{and} \quad 0 < y < 1, \tag{7}$$

assuming $E_\mu \gg m_{\mathrm{N}}$. Actually the model that a nucleon is composed of only u- and d-quark is not sufficient; one has to include the contribution from other quark pairs which are created virtually from gluon. To this end it is enough to replace the distribution functions in the following way:

$$\begin{aligned} Zu(x) &\rightarrow Z(u(x) + c(x)), \\ Zd(x) &\rightarrow Z(d(x) + s(x) + b(x)), \\ Z\bar{u}(x) &\rightarrow Z(\bar{u}(x) + \bar{c}(x)), \\ Z\bar{d}(x) &\rightarrow Z(\bar{d}(x) + \bar{s}(x) + \bar{b}(x)), \end{aligned} \tag{8}$$

and

$$\begin{aligned} Nu(x) &\rightarrow N(u(x) + s(x) + b(x)), \\ Nd(x) &\rightarrow N(d(x) + c(x)), \\ N\bar{u}(x) &\rightarrow N(\bar{u}(x) + \bar{s}(x) + \bar{b}(x)), \\ N\bar{d}(x) &\rightarrow N(\bar{d}(x) + \bar{c}(x)), \end{aligned} \tag{9}$$

where c, s, b stand for charm-quark, strange-quark and bottom-quark. Since those quarks are produced by pair creation, one can assume

$$c(x) = \bar{c}(x), \quad s(x) = \bar{s}(x), \quad b(x) = \bar{b}(x). \tag{10}$$

2.2 QCD Effects on νN DIS

According to the theory of Quantum Chromodynamics(QCD), the Bjorken's scaling behavior of the parton distribution functions is violated, that is, not constant against Q^2 but is broken owing to radiating gluons. As a result, the QCD effect leads to the explicit Q^2-dependence of the functions, which is governed by the so-called Altarelli-Parisi equations. The dependence is taken into account perturbatively; the lowest corrections are called Leading-Log(LL) approximation and the next one Next-to-Leading-Log(NLL) approximation.

Let us denote the distribution function of a quark species q in a nucleon as $f_{N/q}(x, Q^2)$. Here q runs u, d, c, s, b (5 flavor). Then, for example, u-quark distribution in a proton is given by

$$f_{p/u}(x, Q^2) = u(x) + \delta^{(LL)}u(x, Q^2) + \delta^{(NLL)}u(x, Q^2) + \cdots , \tag{11}$$

where two added terms represent corrections. For simplicity we present in this section how the LL corrections are calculated. For this end we have to introduce a notion: flavor Non-Singlet quark and flavor Singlet quark. This is defined by the combinations

$$\begin{aligned} q^{NS}(x, Q^2) &= f_{N/q}(x, Q^2) - f_{N/\bar{q}}(x, Q^2), \\ q^{S}(x, Q^2) &= \sum_{q=u,d,\cdots} [f_{N/q}(x, Q^2) + f_{N/\bar{q}}(x, Q^2)], \end{aligned} \tag{12}$$

where the sum over quark species is taken to the total number of flavor $N_f = 5$. In the previous section we assumed that a nucleon is made of u- and d-quarks. Real nucleon is, however, not so much simple object. It contains further s, c, b-quark pairs created from the vacuum. Another classification of quarks is valence quark and sea quark. In this case

$$\begin{aligned} q_v(x, Q^2) &= q^{NS}(x, Q^2), \\ q_s(x, Q^2) &= \frac{1}{2}[f_{N/q}(x, Q^2) + f_{N/\bar{q}}(x, Q^2) - q_v(x, Q^2)] = f_{N/\bar{q}}(x, Q^2). \end{aligned} \tag{13}$$

Now the Q^2 evolution is determined by the Altarelli-Parisi equations. Originally they are given by a set of differential equations, but their equivalents are given by an integral form [9]: For Non-Singlet quark or valence quark the evolution is

$$q^{NS}(x, Q^2) = \int_x^1 \frac{\mathrm{d}z}{z} K^{NS}(x/z, \bar{s}) q^{NS}(z, Q_0^2) \qquad (q = u, d, s, c, \cdots) . \tag{14}$$

Here, $K^{NS}(x, \bar{s})$ is called Non-Singlet Kernel function which is determined by the theory and

$$\bar{s} = \ln \frac{\ln(Q^2/\Lambda^2)}{\ln(Q_0^2/\Lambda^2)}, \tag{15}$$

where Q_0^2 is the squared reference momentum transfer, which one may choose as one likes, and Λ is a universal constant parameter that should be fixed by experimental data. This formula implies that once one knows the distribution $q^{NS}(x, Q^2)$ at $Q = Q_0$, then one can predict its value at higher energy $Q > Q_0$. For the case of singlet quark it can be mixed with gluon in the course of evolution, thus the evolution is given by

$$\left(\begin{array}{c} q^S(x,Q^2) \\ G(x,Q^2) \end{array}\right) = \int_x^1 \frac{\mathrm{d}z}{z} \left(\begin{array}{cc} K_{qq}(x/z,\bar{s}) & K_{qG}(x/z,\bar{s}) \\ K_{Gq}(x/z,\bar{s}) & K_{GG}(x/z,\bar{s}) \end{array}\right) \left(\begin{array}{c} q^S(z,Q_0^2) \\ G(z,Q_0^2) \end{array}\right). \tag{16}$$

Here four kernel functions appear, K_{qq}, K_{qG}, K_{Gq} and K_{GG}. These are similar to K^{NS}, but different. Also they are fixed by the theory.

In the NLL approximation the mechanism of Q^2 evolution is basically th same as LL, but the formulas are by far complicated. We do not give them here, but in the numerical estimations that we present later we include those effects as well as LL.

2.3 Nuclear Effects on νA DIS

A nucleus is made of nucleons: Nucleus A is composed of Z protons and N neutrons giving a mass number $A = Z+N$. Thus the most crude approximation would be to regard these nucleons are independent; a nucleus is simply their collection without any interaction as we have described. Of course this is too much simplified picture. The electron(e^-) and muon(μ) deep inelastic scattering experiments on various target nuclei, it turned out that the structure functions of a heavy nucleus is different from those of deuteron($^2_1$D). The ν-nucleon DIS cross section for CC, shown in Fig 4, is generally written in the form

$$\frac{d^2\sigma^{\rm cc}_{\nu\rm N}}{dxdy} = \frac{G_{\rm F}^2 m_{\rm N} E_\nu}{\pi}\left(\frac{m_W^2}{Q^2+m_W^2}\right)^2 \Big\{ xy^2 F_1^{\nu\rm N}(x,\,Q^2) \;+\; (1-y)F_2^{\nu\rm N}(x,\,Q^2) \\ +\; y(1-\frac{y}{2})xF_3^{\nu\rm N}(x,\,Q^2)\Big\}\;, \tag{17}$$

This form is derived from only taking all kinematic conditions, like spin of nucleon, into account. It is quite general and irrelevant to how a nucleon is composed of quarks. A similar formula can be given to the case of a nucleus.

Collecting all the experimental observations by e^- and μ scatterings, it has been shown that the ratio of structure functions(each of which is normalized by dividing the atomic number A)

$$R_{\rm A/D}(x,Q^2) = \frac{F_2^{e\rm A}(x,Q^2)}{F_2^{e\rm D}(x,Q^2)}, \tag{18}$$

deviates from unity but looks like a curve depicted in Fig. 5. When x is small the nuclear effect is called *nuclear shadowing*, and when x is close to 1, *Fermi motion*. Physical meaning of these two is rather simple. The former reflects the fact that e^-/μ beam is easy to hit nucleons on the surface of the nucleus rather than those located deep inside of nucleus. The latter is explained by the Fermi motion of nucleon inside the nucleus. Inbetween these two a bit complicated structure is seen, which is called EMC effect. The detail of this effect is not fully clarified. The shape of $R_{\rm A/D}$ is rather common among various nuclei. Though the ratio rather varies in x space, but only weak Q^2 dependence is experimentally seen. How to incorporate with those effects into our calculation will be discussed in the near future.

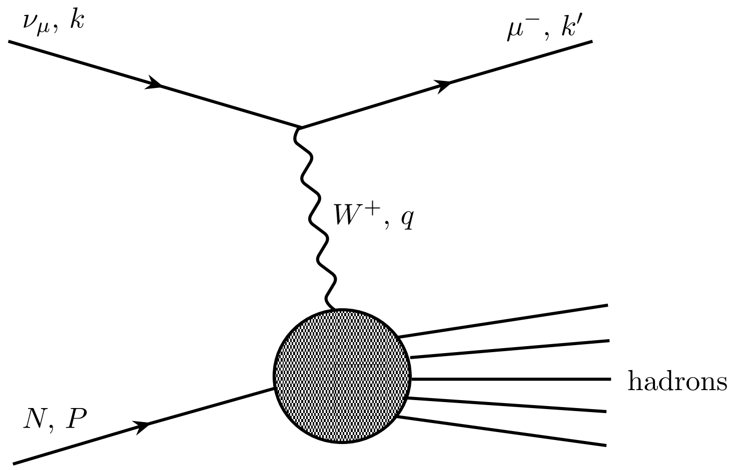

Figure 4: Deep-inelastic neutrino scattering off a nucleon target by the charged-current interaction.

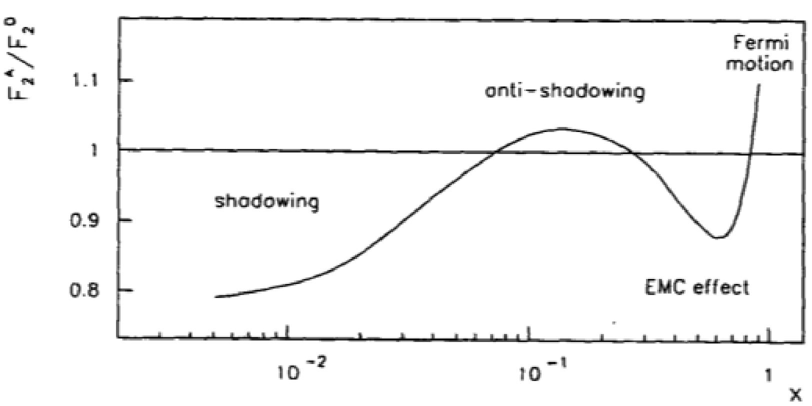

Figure 5: Schematic explanation of nuclear effects in structure functions [13].

2.4 Mean Free Paths of Neutrinos Inside the Earth

This section is devoted to the derivation of the mean free paths of (anti-)neutrinos passing through the inside of the Earth.

Suppose we have a material of sufficiently large volume, which is composed of some target particles distributed uniformly with the number density n. When the cross section of a projectile particle on the target particle, σ, is known, the mean free path is defined as

$$R = \frac{1}{n\sigma}. \tag{19}$$

When a beam of projectiles with a uniform velocity hits the material, the beam intensity, I, decreases with respect to the distance l from the surface where the beam gets in the material as

$$I(l) = I_0 \exp\left(-\frac{l}{R}\right) \tag{20}$$

where I_0 is the initial beam intensity. The damping of the intensity is caused by scattering of projectile by target. Hence, to get the mean free path of neutrino inside the Earth, one should know the cross section of neutrinos against atomic nuclei that compose the Earth.

Taking the simplest assumption that all the nuclei that compose the Earth can be regarded as a collection of free protons and neutrons, first we have to calculate the total cross sections $\sigma_{\nu p}^{\rm tot}$, $\sigma_{\nu n}^{\rm tot}$, $\sigma_{\bar{\nu} p}^{\rm tot}$ and $\sigma_{\bar{\nu} n}^{\rm tot}$ for the $\nu_\mu p$, $\nu_\mu n$, $\bar{\nu}_\mu p$ and $\bar{\nu}_\mu n$ scattering processes, respectively. As we have discussed earlier these cross sections are expressed by parton distribution functions. We adopt two sets of parton distributions CTEQ5L [10] and MRST [11] in PDFLIB[12] for the proton and neutron structure functions. These two sets are provided by different groups based on a number of experiments carried at SLAC, DESY and CERN. By using different sets of distributions we may estimate the errors included.

Let us evaluate the mean free path of neutrino R_ν and that of anti-neutrino $R_{\bar{\nu}}$ as explained. First we have to know the number density of protons, N_p, inside the Earth and that of neutrons, N_n. Indeed, we can easily obtain these densities, because we know that the number of protons and that of neutrons are on the average in the ratio of r_p to $(1 - r_p)$, where $r_p = 0.495$. In addition, the average mass density of the Earth, $\rho_{\rm E}$, is measured to be 5.52×10^3 (kg/m^3). Hence, one can obtain the number densities:

$$\begin{aligned} N_p &= \frac{\rho_{\rm E} r_p}{m_p r_p + m_n(1-r_p)} = 1.632 \times 10^{30} \ \ (1/{\rm m}^3) \ , \\ N_n &= \frac{\rho_{\rm E}(1-r_p)}{m_p r_p + m_n(1-r_p)} = 1.665 \times 10^{30} \ \ (1/{\rm m}^3) \ , \end{aligned}$$

where m_p stands for the proton mass and m_n for the neutron mass.

Thus, we obtain the mean free path of (anti-) neutrino inside the Earth environment

$$R_\nu^{(\rm e)} = \frac{1}{N_p \sigma_{\nu p}^{\rm tot} + N_n \sigma_{\nu n}^{\rm tot}} \ \ ({\rm m}) \ , \tag{21}$$

$$R_{\bar{\nu}}^{(\rm e)} = \frac{1}{N_p \sigma_{\bar{\nu} p}^{\rm tot} + N_n \sigma_{\bar{\nu} n}^{\rm tot}} \ \ ({\rm m}) \ . \tag{22}$$

We show in Fig. 6 the mean free path versus the energy of neutrino. Here we would like to make some comments. In the previous paper [6] we have included only u- and d-quarks in the calculation (2 flavor model). However, it turned out that this is not enough and we have to take account of the contribution from other quarks, s, c, b (5 flavor model). This is mainly because the energy of ν_μ is so high that one cannot ignore the heavy quark pair creation by gluon from the vacuum. Since other quarks contribute, the cross section increases, thus leading to decreasing of the mean free path. Roughly speaking, to get $R_\nu \sim R_{\bar{\nu}} \sim 10^4$ km only $E_\nu \sim 500$ TeV is needed while $E_\nu \sim 1000$ TeV for 2 flavor model. We show two cases with LL QCD corrections and NLL ones. The difference is not so much, but for all range of E_ν, NLL give a distance $\sim 200 - 300$ km smaller than LL case.

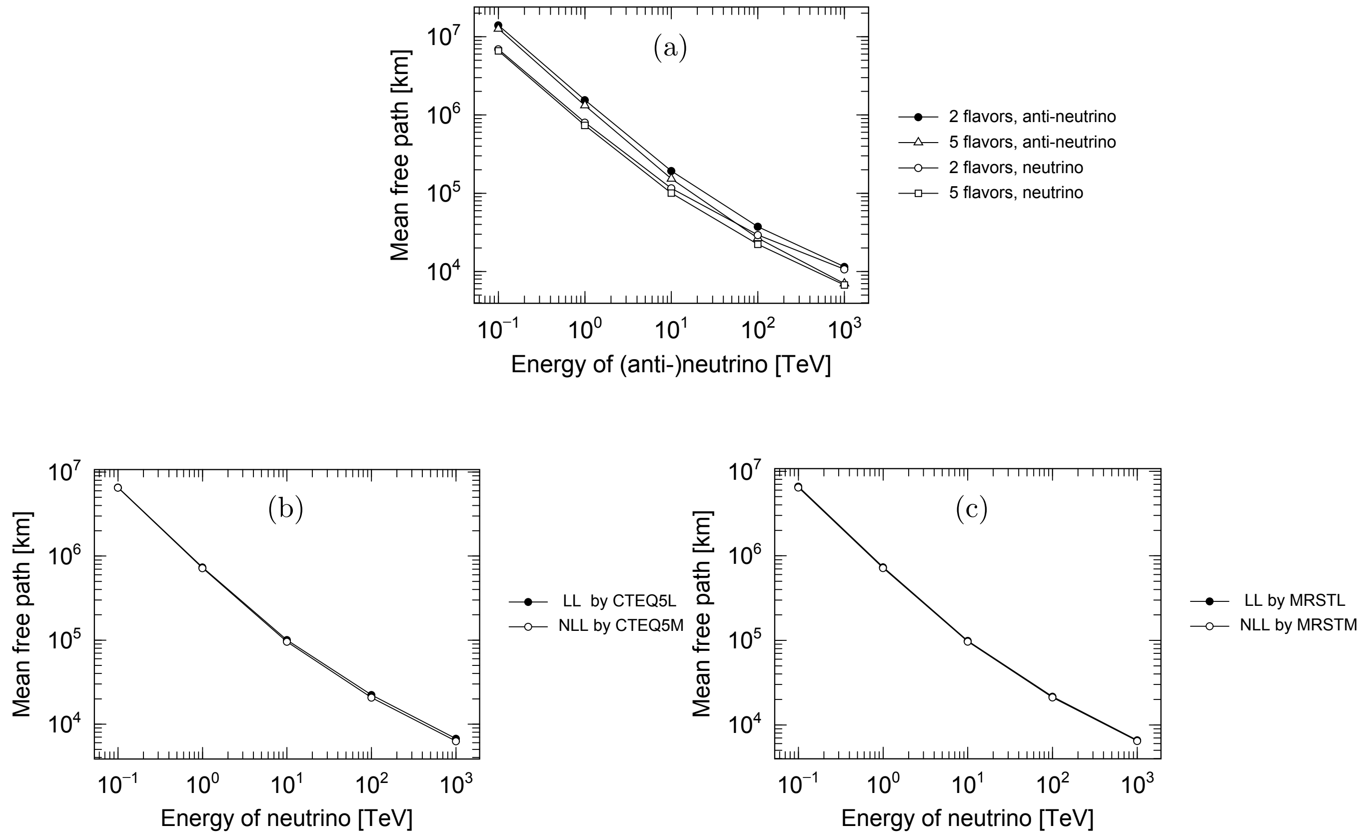

Figure 6: Mean free paths of (anti-)neutrinos vs. its energy. (a) Comparison of 2- and 5-flavor contributions to LL calculations using CTEQ5L. (b) LL and NLL calculations using CTEQ5L and CTEQ5M. (c) LL and NLL calculations using MRSTL and MRSTM.

2.5 Mean Free Paths of Neutrinos Inside the Material

After traveling the long journey inside the Earth (see Fig. 7), the neutrino beam of intensity $I_0 e^{-l/R}$ will cause hazardous hadron showers in the environment near a target bomb just before hitting the target. In addition, therefore, we need to calculate other mean free paths in the soil and the radiation-shielding material around the bomb, and those in the fissionable material in the core of the bomb. They are needed to estimate the radiation dose and the energy deposition in the target bomb. As a result, it is necessary for us to know the following three sets of mean free paths of (anti-)neutrinos.

1. The first set is mean free paths, $R_\nu^{(\mathrm{e})}$, inside the Earth, which we have alread calculated at the LL and NLL approximations. They are already given by Eq. (21) and needed to know the reduction of the initial beam intensity from I_0 to $I_0 e^{-l/R_\nu^{(\mathrm{e})}}$.
2. The second one is mean free paths inside the radiation-shielding material, as shown in Fig. 8. Many hadrons will be produced by νDIS in each shielding material near the target. The beam intensity I_i just before going into the i-th shielding material s_i of thickness l_i will

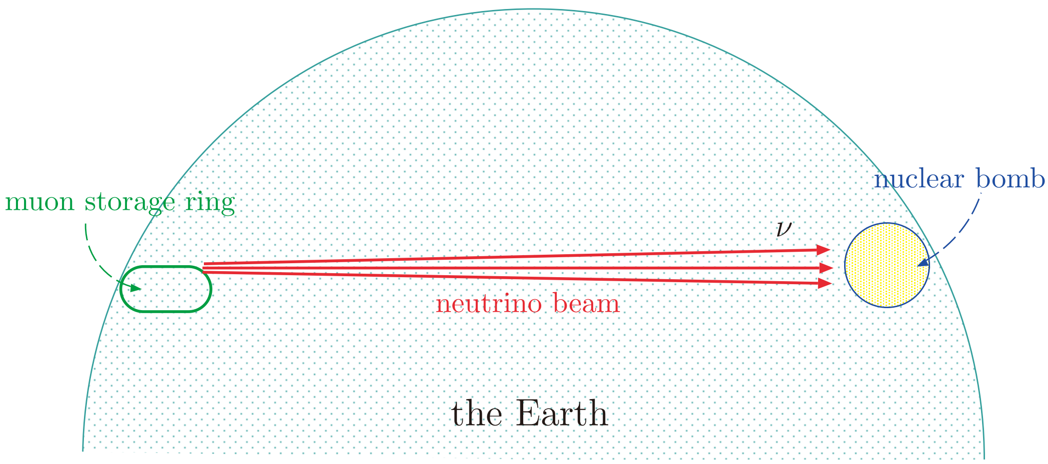

Figure 7: Neutrino beam is aimed at a nuclear bomb that is placed on the opposite side of the Earth. The beam is emitted downstream from a straight section of the muon storage ring (see Fig. 2). After traveling a distance l, the beam intensity reduces by $e^{-l/R}$, where R is the mean free path of the neutrinos.

reduce to $I_i e^{-l_i/R_\nu^{(s_i)}}$ when it exits the i-th material, where $R_\nu^{(s_i)}$ is the mean free path in the i-th material s_i.

3. The third one is the mean free paths, $R_\nu^{(c)}$, inside the bomb core. They are needed to estimate the number of the direct interactions of (anti-)neutrinos with the fissinable material, as shown also in Fig. 8. Very energetic hadrons will be produced directly by the neutrino-plutonium (or -uranium) DISs in the ^{239}Pu core and the ^{238}U tamper[2].

Needless to say, mean free paths, $R_{\bar{\nu}}^{(e)}$, of anti-neutrinos also are necessary and calculated in the same way.

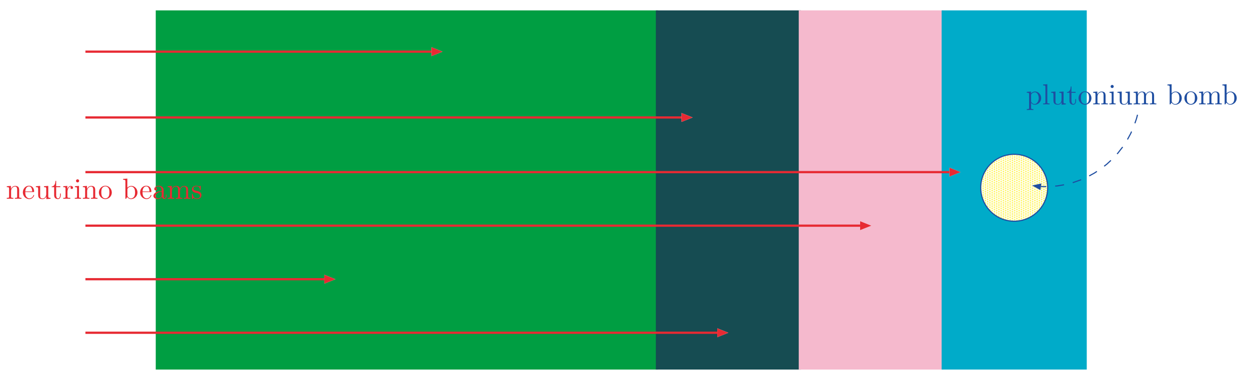

Figure 8: The neutrino beam passing through the Earth interacts with nuclei in the environment and the radiation-sheilding material a few ten meters close to the target bomb, and it causes many hadrons by νDIS in the material and the target.

[2]The profile of a plutonium bomb will be explained later in Fig 9.

As a result, we have the above three sources of energetic hadrons. The hadron shower will deposit some amount of their energies to the bomb core in the processe of transport inside the environment near the bomb. This is the reason why we are calculating the cross sections for νDIS processes in the environment. In order to estimate precise values of the energy depositions, we need the mean free paths inside the environment. Once we ignore completely the nuclear effects on νDIS for simplicity, the total cross section for νDIS on ^{239}Pu, $\sigma^{\rm tot}_{\nu{\rm Pu}}$, is estimated as follows,

$$\sigma^{\rm tot}_{\nu{\rm Pu}} = \sigma^{\rm cc}_{\nu{\rm Pu}} + \sigma^{\rm nc}_{\nu{\rm Pu}} \simeq Z\left(\sigma^{\rm cc}_{\nu p} + \sigma^{\rm nc}_{\nu p}\right) + N\left(\sigma^{\rm cc}_{\nu n} + \sigma^{\rm nc}_{\nu n}\right) \quad \text{for } Z = 94,\ N = 145\,. \tag{23}$$

In case of $E_\nu = 1\,(\text{PeV})$, we obtain using the CTEQ5M parton distributions at NLO,

$$\sigma^{\rm tot}_{\nu{\rm Pu}} = 1.0161 \times 10^{5}\,(\text{pb}) = 1.0161 \times 10^{-31}\,(\text{cm}^2)\ , \tag{24}$$

The density of ^{239}Pu is known to be $\rho_{\rm Pu} = 19.8\,(\text{g/cm}^3)$ at a normal temperature, we obtain the number density, $N_{\rm Pu}$, of plutonium nucleus

$$N_{\rm Pu} = \frac{\rho_{\rm Pu}}{m_{\rm Pu}} = \frac{19.84\,(\text{g/cm}^3)}{239 \times 1.6605 \times 10^{-24}\,(\text{g})} = 4.999 \times 10^{22}\,(1/\text{cm}^3) \tag{25}$$

Now we can straightforwardly write down the mean free path of the neutrino inside the core without the nuclear effects as,

$$R^{(\rm c)}_{\nu} = \frac{1}{N_{\rm Pu}\sigma^{\rm tot}_{\nu{\rm Pu}}} = 1.9687 \times 10^{6}\,(\text{m}) \quad \text{at } E_\nu = 1\,\text{PeV}\ . \tag{26}$$

3 Numerical Simulations

Here we turn to Monte-Carlo studies, including so many physical processes over wide energy scales $E_{\rm scale}$, namely over eighteen orders of magnitude ranging from PeV down to meV regions. The definitions of *very low*-, *low*-, *intermediate*-, *high*- and *ultra-high*-energy physics are greatly influenced by the background of the physicist[3]. For our purpose, we roughly classify the whole processes of various scales into four regions as follows.

1. *Ultra-high energy*: $100\,\text{TeV} \lesssim E_{\rm scale} \lesssim 1\,\text{PeV}$
   The beam energy of incident neutrinos from the muon strage ring is assumed to be about 1 PeV down to 100 TeV, where νDIS processes are dominant. Phenomenology of particle physics, including both QCD and nuclear effects with high precision, is important in this energy region.
2. *High energy*: $5\,\text{GeV} \lesssim E_{\rm scale} \lesssim 100\,\text{TeV}$
   Hadronic interactions and hadron-transport processes in matter are important in this region. Energies of the hadrons produced by νDIS processes distribute from several hundred TeV

[3]In reactor physics, for example, a 14-MeV neutron released by a fusion process is considered high-energy, but to particle physicist, such an energy is extremely low.

down to several GeV, and the hadrons are transported and scattered many times through hard, semi-hard, or soft scattering processes. Physics of high-energy hadron transport is of main concern.

3. *Intermediate energy*: $100\,\mathrm{MeV} \lesssim E_{\mathrm{scale}} \lesssim 5\,\mathrm{GeV}$
   Varieties of nuclear reactions will occur in this energy region. Phenomenology of nuclear physics will be important, including For example, spallation reactions, high-energy fisson and other ones take place in this region. See Ref. [19] to know the intermediate interaction physics in more detail.
4. *Low energy*: $100\,\mathrm{meV} \lesssim E_{\mathrm{scale}} \lesssim 100\,\mathrm{MeV}$
   In this region, low-energy nuclear reactions are very complicated. Photo-nuclear interactions with nuclei are dominat down to about 10 MeV, in addition to spallation reactions, in which several neutrons are emitted in the final state.
5. *Very-low energy*: $E_{\mathrm{scale}} \lesssim 100\,\mathrm{meV}$
   This energy scale is the so-called the thermal region, in which scatterd neutrons are called a *thermal neutrons*[20]. Nuclear reactor physics is important here in connection with neutron-transport in some material, particularly in fissile (or fissionable) ones.

From now on we will discuss all the processes explained above by the Monte-Carlo method, within the limitations of current event generators and radiation-transport codes.

3.1 Some Estimation

Before going into detailed numerical simulations, we give a brief estimation to the physical processes with various different scales. We consider a situation where one of the straight lines is directed toward the nuclear bomb which is located somewhere on the opposite side of the Earth (Fig. 7). We must choose the energy of the neutrino beam in such a way that the mean free path of the neutrino is compatible to the diameter of the Earth. Fig. 6 shows the mean free path of (anti-)neutrino vs. its energy calculated assuming that the deep inelastic cross sections dominate in the relevant energy region. From Fig. 6 we conclude that the energy of the neutrino beam must be about several hundred TeV to have approximately single interaction before the neutrino beam hits the bomb. The size of the beam at the point of the bomb is given by

$$r_{\mathrm{b}} = \frac{m_\mu c^2}{E_\mu} d \simeq \frac{0.1\,(\mathrm{GeV}) \times 10^7\,(\mathrm{m})}{10^6\,(\mathrm{GeV})} = 1\,(\mathrm{m}) \ ,$$

where m_μ and c stand for the muon mass and the speed of light, and d is the distance from the muon storage ring to the position of the bomb which we take to be the diameter of the Earth ($\simeq 10^7\,\mathrm{m}$). The beam spread due to the transverse momentum of the beam is negligible at this energy if the current value of the ionization cooling of $P_t = 1$ (MeV) is adopted. The range of the neutrino is 10^7 meters and the effective neutrino interaction is restricted within a few meters

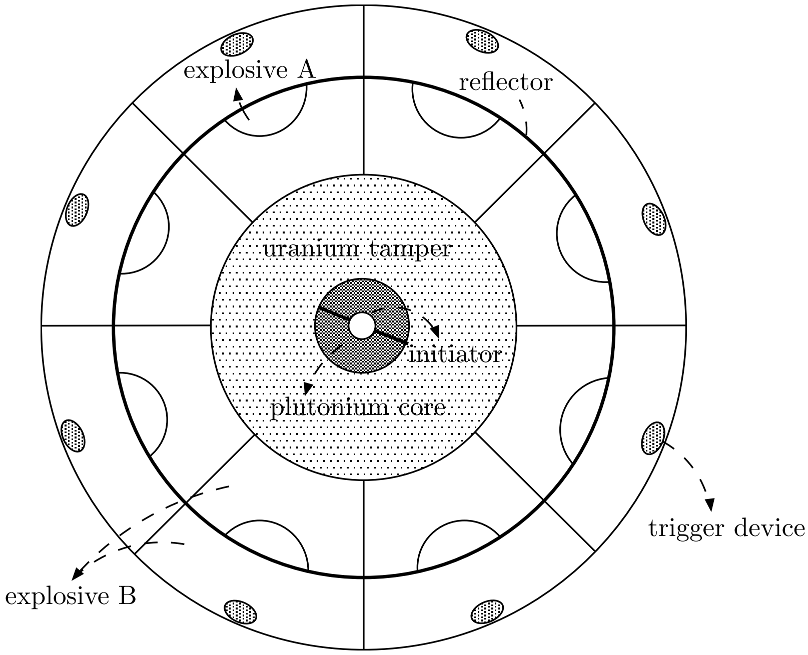

Figure 9: A model for the plutonium bomb of implosion type [14]. The whole profile of the bomb is in the shape of a spherical body.

away from the bomb because of the interaction range of the hadrons. Therefore, the probability of getting an effective reaction from the beam is $1/10^7$.

More precisely, the above estimation can be summarized as follows. The energy deposition per the unit volume from the Earth environment near the bomb core is

$$\begin{aligned} E^{(\mathrm{e})}_{\mathrm{dep}} =& \ \epsilon^{(\mathrm{e})}_{\nu} I_0 \Delta t \, e^{-d/R^{(\mathrm{e})}_{\nu}} \int_0^{R^{(\mathrm{e})}_{\mathrm{h}}} \frac{dx}{R^{(\mathrm{e})}_{\nu}} \, e^{-x/R^{(\mathrm{e})}_{\nu}} \\ \simeq& \ \epsilon^{(\mathrm{e})}_{\nu} I_0 \Delta t \, e^{-d/R^{(\mathrm{e})}_{\nu}} \left(\frac{R^{(\mathrm{e})}_{\mathrm{h}}}{R^{(\mathrm{e})}_{\nu}} \right) \quad (\mathrm{eV/cm^3}) \ , \end{aligned} \tag{27}$$

where $R^{(\mathrm{e})}_{\mathrm{h}}$ stands for the average hadron mean free path in the Earth environment near the target bomb, and $R^{(\mathrm{e})}_{\nu}$ for the neutrino mean free paths inside the Earth that was calculated in Secion 2 (see Fig. 6) and $\epsilon^{(\mathrm{e})}_{\nu}$ $(\mathrm{eV/cm^3})$ is the average energy deposition of one neutrino incident on the Earth environment, which will be estimated later by the numerical method.

To proceed further we need to know a little about the structure of the nuclear bomb. Since no official information is available to us, we rely on a textbook [14], several popular books [15] and unclassified papers [16] on the subject. It is very helpful for us to know the theory of the nuclear-bomb detonation, which is briefly reviewed in Appendix A. As a possible model for a nuclear bomb we consider a 10 kg ball of ^{239}Pu which has the critical mass of 15 kg, surrounded by the ^{238}U tamper, the reflector and the explosive material (Fig. 9). We also consider a system without explosive material surrounding the plutonium ball since we have no way to know how these bombs are stored. A crucial parameter in the former case is the number of fissions in the system which provides the temperature rise enough to ignite the surrounding explosives.

Now let us estimate the direct energy deposition in the core of the bomb. Using the mean free path $R_\nu^{(c)}$ shown in Eq. (26), one can estimate the energy deposition per unit volume in the core, $E_{\rm dep}^{(c)}$, in a way similar to the above one:

$$\begin{aligned} E_{\rm dep}^{(c)} = &\ \epsilon_\nu^{(c)} I_0 \Delta t\, e^{-d/R_\nu^{(e)}} \int_0^{2r_c} \frac{dx}{R_\nu^{(c)}}\, e^{-x/R_\nu^{(c)}} \\ \simeq &\ \epsilon_\nu^{(c)} I_0 \Delta t\, e^{-d/R_\nu^{(e)}} \left(\frac{2r_c}{R_\nu^{(c)}} \right) \quad ({\rm eV/cm^3}) \ , \end{aligned} \tag{28}$$

where $r_c = 6\,({\rm cm})$ is the radius of the Pu core we use here. $\epsilon_\nu^{(c)}\,({\rm eV/cm^3})$ is the average energy deposition of one neutrino incident directly on the bomb core. From the two hadron sources, which are neutrons from the hadron shower in the Earth and ones from the direct νDIS in the Pu core, we obtain a rough estimation of the ratio, T_r, of two energy depositions as

$$T_r = \frac{E_{\rm dep}^{(c)} \cdot \pi r_c^2}{E_{\rm dep}^{(e)} \cdot \pi r_b^2 \left(\frac{\pi r_c^2}{\pi r_s^2} \right)} = \left(\frac{\epsilon_\nu^{(c)}}{\epsilon_\nu^{(e)}} \right) \left(\frac{2r_c}{R_h^{(e)}} \right) \left(\frac{R_\nu^{(e)}}{R_\nu^{(c)}} \right) \left(\frac{r_s^2}{r_b^2} \right) \ . \tag{29}$$

Here r_s is the size of the hadron shower after the transport through the Earth environment, namely, $r_s \sim 3\,({\rm m})$ in our case[4]. Once we put some numerical values into Eq. (29), we obtain the following rough estimation

$$T_r \sim O(\epsilon_\nu^{(c)}/\epsilon_\nu^{(e)}) \ . \tag{30}$$

Our calculation here is simply based on the geometric sizes of the hadron showers produced by the νDIS processes before and after the hadron transport. Physically, it is too simple to determine the heat deposition in the Pu core. That is the reason why we need a precise simulation in the next section.

3.2 Monte-Carlo Simulation

Now let us now turn to numerical simulations to study the system in a more precise way. Basically, we can divide our simulation processes into two parts: the first part deals with νDIS in the Earth environment near a target bomb, as shown in Fig. 8, and the second one follows the first one to calculate the nuclear reactions in the target bomb, as as shown in Fig. 11. As a result, we will obtain the temperature increase of the plutonium core caused by nuclear reactions induced by hadrons and photons.

The first part is to start from a given neutrino beam of certain energy and intensity. We simulate the process of the neutrino beam hitting a target nucleus in the soil and follow the development

[4]See Fig. 12 (a) and its caption.

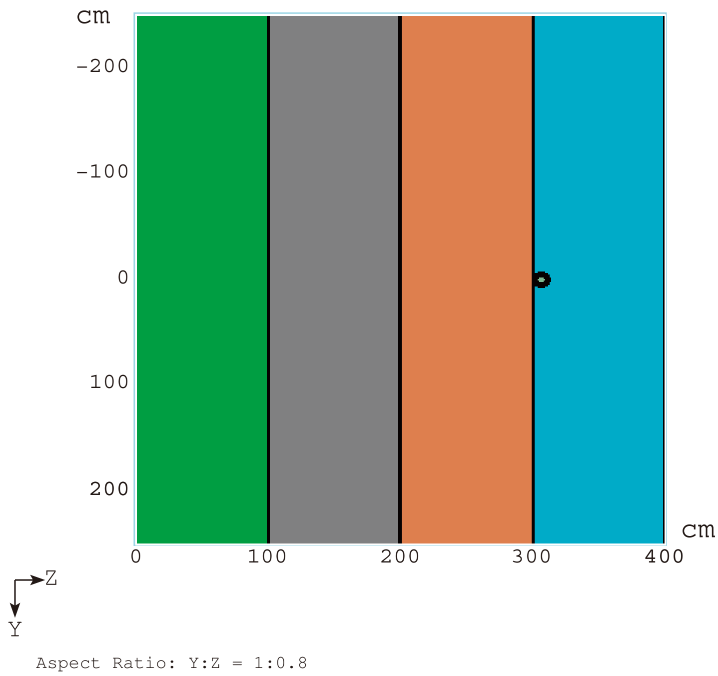

Figure 10: Geometry of our simulation system used in MARS code.

of a hadron shower initiated by the neutrino interaction, as shown in Fig. 8. The former process can be simulated by a generator HERWIG [17], in which we can include processes with the incident neutrino beam, such as $\nu + p$ (or n) $\rightarrow$ hadrons + leptons. In the latter process, subsequently, we simulate the interactions of the hadron shower with nuclei of the soil by using other Monte-Carlo code MARS [21]. The purpose of this part is to obtain the multiplicity of the shower when the shower is going out of the Earth. The neutrino interaction which occurs near the surface of the Earth is relevant. We consider, therefore, a system which is shown in Fig. 8.

The second part of our simulation is to calculate the temperature increase of the plutonium system caused by the hadron shower. We consider a system shown in Fig. 10. Our calculation of this part is carried out using the MARS code[5]. As for the transport calculation of high-energy hadrons, it adopts Quark-Gluon String Model. But MARS has no neutron-transport at energies below 20 MeV. If low-energy neutron is produced through the process of hadron-transport, MARS passes it to another code MCNP [19].

To make clear the algorithm of radiation-transport codes, we illustrate a simple example of nuclear reactions in Fig. 11, where the first collision occurs at event 1 in the Pu core. The neutron is scattered in the direction shown, which is selected randomly from the physical scattering distribution. A photon is also produced and is temporarily stored, or banked, for later analysis. At event 2, fission occurs, resulting in the termination of the incoming neutron and the birth of two outgoing neutrons and one photon. One neutron and the photon are banked for later analysis.

[5]MARS has been used extensively in radiation-shielding calculations and developed for a long time since 1970's [21].

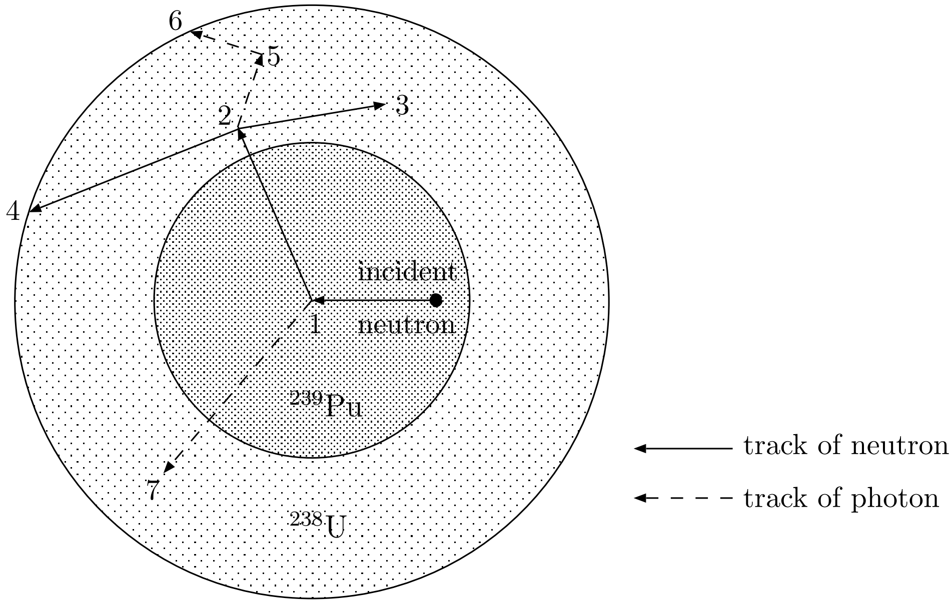

Figure 11: A history of a neutron incident on the ^{239}Pu core that can undergo nuclear fission. 1. Neutron scattering and photon production in the core. 2. Fission and photon production in the ^{238}U tamper. 3. Neutron capture in the tamper. 4. Neutron leakage out of the tamper. 5. Photon scattering in the tamper. 6. Photon leakage out of the tamper. 7. Photon capture in the tamper.

The first fission is captured at event 3 and terminated. The banked neutron is now retrieved and, by random sampling, leaks out of the core at event 4. The fission-produced photon has a collision at event 5 and leaks out at event 6. The remaining photon generated at event 1 is now followed with a capture at event 7. Note that MCNPX retrieved banked particles such that the last particle stored in the bank is the first particle taken out.

This neutron history in the core and the tamper is now complete. As more and more such histories are followed, the neutron and photon distributions become better known. The quantities of interest, such as the total energy arising in the reactions, are tallied along with estimates of the statistical precision of the results.

Hence, after repeating the similar calculations, we could obtain the average value, $E^{(\mathrm{Pu})}_{\mathrm{fission}}$, of the fission energy deposition in the Pu core:

$$E^{(\mathrm{Pu})}_{\mathrm{dep}} = 35.1287 \pm 15.7699 \ (\mathrm{MeV/g}) \ . \tag{31}$$

In addition, the fission energy deposition in the uranium tamper is

$$E^{(\mathrm{U})}_{\mathrm{dep}} = 13.1842 \pm 9.2451 \ (\mathrm{MeV/g}) \ . \tag{32}$$

These are the contributions on the average from one incident neutrino of 1 PeV. If we irradiate, in an interval Δt (sec), $I_0 \Delta t$ neutrinos, at the Pu bomb, the number of neutrinos, N_{int}, that interact

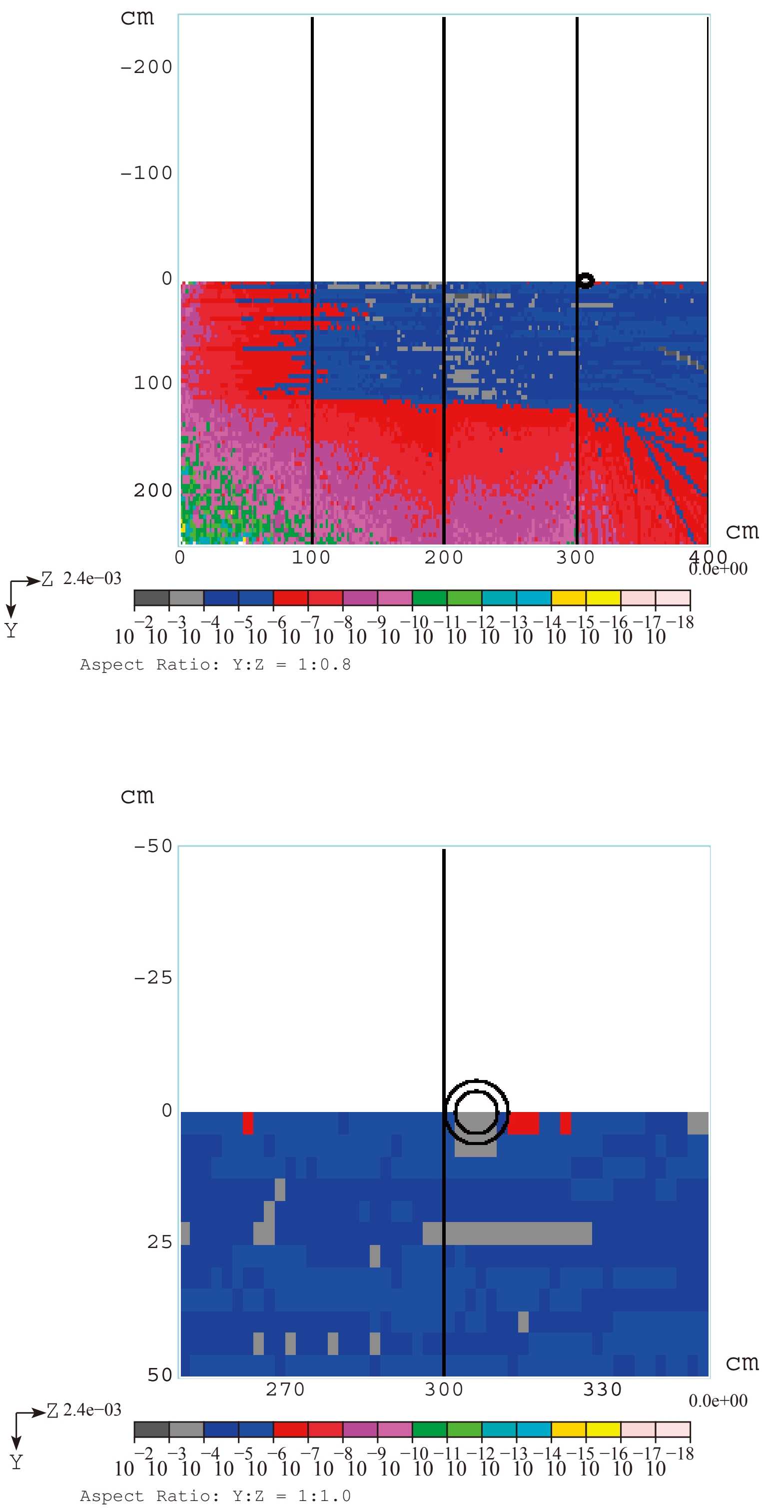

Figure 12: Heat deposition through transportation by the MARS code.

in the transport region of size $R_{\rm h}^{(\rm e)}$ will be

$$N_{\rm int} = I_0 \Delta t \, e^{-d/R_\nu^{(\rm e)}} \left(\frac{R_{\rm h}^{(\rm e)}}{R_\nu^{(\rm e)}} \right) \quad . \tag{33}$$

The increase in temperature inside the ^{239}Pu core and the ^{238}U tamper can be estimated as

$$\Delta T = \frac{N_{\rm int} \, (E_{\rm dep}^{(\rm Pu)} + E_{\rm dep}^{(\rm U)})}{C_{\rm Pu}} \, , \tag{34}$$

where $C_{\rm Pu}$ is the specific heat of ^{239}Pu, whose numerical value is given by

$$C_{\rm Pu} = \frac{4.186 \text{ (J/cal)} \times (6.0/239) \text{ (cal/g} \cdot \text{K)}}{1.602 \times 10^{-13} \text{ (J/MeV)}} = 6.557 \times 10^{11} \text{ (MeV/g} \cdot \text{K)} \quad .$$

Therefore, in order to obtain a temperature increase $\Delta T = 210$ (K), which corresponds to the ignition temperature of TNT, the total number of the interacting neutrinos required is

$$N_{\rm int} = \frac{C_{\rm Pu} \, \Delta T}{E_{\rm dep}^{(\rm Pu)} + E_{\rm dep}^{(\rm U)}} = \frac{(6.557 \times 10^{11}) \times 210}{35.1287 + 13.1842} = 2.8501 \times 10^{12} \quad . \tag{35}$$

Instituting typical numerical values, namely $R_\nu^{(\rm e)} = 6.259 \times 10^6 \,(\rm m)$, $d = R_\nu^{(\rm e)}$ and $R_{\rm h}^{(\rm e)} = 100 \,(\rm m)$ into Eq. (33), we get

$$N_{\rm int} = 5.8776 \times 10^{-6} I_0 \Delta t = 2.8501 \times 10^{12} \quad . \tag{36}$$

Therefore, we obtain the total number of incident neutrinos required

$$I_0 \Delta t = \frac{2.8501 \times 10^{12}}{5.8776 \times 10^{-6}} = 4.849 \times 10^{17} \quad . \tag{37}$$

If we assume the intensity of the incident neutrino beam I_0 to be 10^{14} (1/sec), then the required irradiation time can be estimated as

$$\Delta t = 4.849 \times 10^3 \,(\text{sec}) = 1.347 \,(\text{h}) \quad . \tag{38}$$

These values of $I_0 \sim O(10^{14})$ and $\Delta t \sim O(10^3)$ are compatible with those estimated in the previous work [6], although we have omitted the direct energy deposition in the plutonium core.

4 Conclusion and Discussions

We have shown that it is possible to eliminate the nuclear bombs from the surface of the Earth utilizing the extremely high-energy neutrino beam. When the neutrino beam hits a bomb, it will cause the fizzle explosion with more than a few % of the full strength. This result is quite consistent with our previous one [6]. But in this paper, we have achieved some new observations.

Firstly, we have calculated the mean free paths of neutrinos, including the QCD effects within the LL and NLL approximations. The paths get shorter than those of previous ones [6], for example, R_ν already becomes about 10^4 km at $E_\nu \sim 500$ TeV. For all range of E_ν, NLL QCD corrections give a distance about 200 up to 300 km smaller than LL ones.

Secondly, we performed detailed numerical simulations, using three different Monte-Carlo codes: HERWIG6 for the νN DIS in the Earth environment near the target, MARS15 for the hight-enerygy hadron transport in the Earth and shielding environment, and MCNP for (very-)low-energy neutron transport, including exothermic nuclear reactions inside the Pu core and the U tamper. After the high-energy neutrino beam passes through the Earth, it causes hadron showers near the opposite side of the Earth, and subsequently, neutrons in the showers will strike the ^{239}Pu core. In order to estimate the number of the incident neutrons which is large enough to make the temperature of the TNT surrounding the core increase to its ignition one, we have carried out the numerical simulations using the three codes under more realistic conditions, compared with the previous ones. As a consequence, we obtained the values of $I_0 \sim O(10^{14})$ [1/sec] and $\Delta t \sim O(10^3)$ [sec]. These numerical values are compatible with those estimated in the previous work [6], although we have omitted the direct energy deposition in the plutonium core. We expect that they will be realistic in the future technology of accelerator.

Lastly, we point out the importance of the direct νDIS on the fissionable material such as ^{239}Pu, ^{235}U and ^{238}U. As shown in Eq. (30), the energy deposition from this direct interaction of high-energy neutrino with ^{239}Pu is considered to be much higher than the indirect one with the Earth environment, although only the latter case was calculated precisely in our study.

Finally, we desire precise experiments in order to measure the energy (heat) depositions coming from the ν-Pu (or U) DIS. In addition to our proposal, other useful application of high-energy neutrino beams is to the study of the inner structure of the Earth [22]. We may not need the neutrino energy to be as high as 1 PeV in this case. These ideas towards the applications of neutrinos will be realized step by step because they are useful to global security, even for our daily life, beyond the most fundamental scientific research activities.

Acknowledgment

We would like to acknowledge meaningful discussions with members of Theory Center of KEK, particularly on theoretical consideration. We are grateful to Keijiro Tobimatsu for his continuous encouragement and also to Tadashi Ishikawa for his careful reading of our manuscript. We address special thanks to Tetsuo Abe at Accelerator Laboratory of KEK for his contribution to numerical calculations at the initial stage of our study. We appreciate Yoshimasa Kurihara for his helpful suggestion of some Monte-Carlo generators. We would like to acknowledge valuable discussions

with Toshiya Sanami on nuclear reactor physics at Radiation Science Center of KEK.

Appendices

A Theory of Nuclear-Bomb Detonation

Here we give a brief review of theory of pre-detonation, which is based on a famous text book on atomic bombs [14] and the appendix of Ref. [16]. After describing the behavior of neutrons in fission systems, we will derive probabilities of different bomb yields, including both the full-fledged and incomplete "fizzle" explosions.

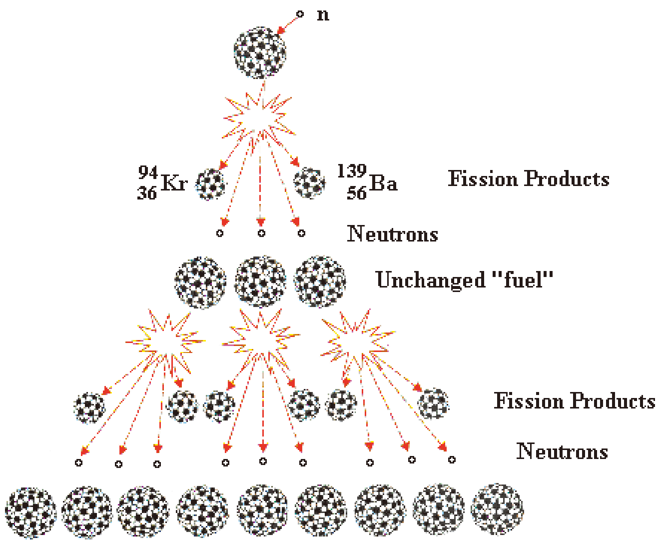

Figure 13: Fission chain reactions.

A.1 Neutron Chain Fission Reactions

Fissile nuclides, such as ^{235}U, ^{238}U and ^{239}Pu release several neutrons in experiencing nuclear fissions. When ^{235}U absorbs a neutron, it splits into two daughter particles of uneven mass and releases an average of 2.5 neutrons, for example, as follows:

$$^{235}_{92}\mathrm{U} + n \rightarrow {}^{139}_{56}\mathrm{Ba} + {}^{94}_{36}\mathrm{Kr} + 3n \ , \tag{39}$$

If fissions occur successively, the whole process of the successive reactions is called a *chain reaction*, as shown in Fig. 13. When we zoom up fission neutrons in such a chain-reaction system, the ratio of the number of neutrons in a certain generation to that of neutrons in the previous generation is called the *neutron multiplication constant*, denoted by k (see Fig. 14):

$$k \equiv \frac{\text{number of neutrons in the current generation}}{\text{number of neutrons in the previous generation}} \ . \tag{40}$$

The fission systems are classified, corresponding to the value of k, into three cases: super-critical in case of $k > 1$, critical $k = 1$ and sub-critical $k < 1$. Using the neutron balance in the chain-reaction system, One can re-write k as

$$k = \frac{\text{neutron production rate in the system}}{\text{neutron loss rate in the system}} = \frac{P(t)}{L(t)} \ . \tag{41}$$

A time scale τ of the neutrons in the chain-reaction system, within which neutrons are lost from/in the system, can be written

$$\tau = \frac{N(t)}{L(t)} \ , \tag{42}$$

where $N(t)$ stands for the number of neutrons at t in the system. In other words, τ means the 'life time' of neutrons in the system. So the time-dependence of the number of neutrons is

$$\frac{dN(t)}{dt} = (\text{neutron production rate}) - (\text{neutron loss rate}) = P(t) - L(t) \ , \tag{43}$$

or one can re-write from (41), (42) and (43) as

$$\frac{dN(t)}{dt} = \frac{(k-1)}{\tau} N(t) \equiv \alpha(t) N(t) \ , \tag{44}$$

Therefore one obtains the solution:

$$N(t) = N_0 \exp\left\{\frac{k-1}{\tau} t\right\} \ . \tag{45}$$

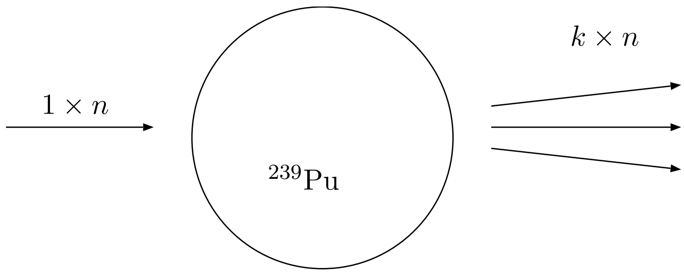

Figure 14: Neutron multiplication rate in fissile material. One neutron (n) incident on the material (^{239}Pu) will increase to k neutrons. k is called the *neutron multiplication constant.*

A.2 Mark's Model for Detonation

As an example of fission chain reaction systems, we briefly review Mark's simplified model for detonation of nuclear bombs, which is discussed in Ref. [16]. This model assumes a linear growth of the neutron multiplication rate from zero at time $t = 0$ to unity at the time of maximum super-criticality $t = t_0$:

$$\frac{k-1}{1} = \frac{t}{t_0} \ , \tag{46}$$

The left-hand side of Eq. (46) stands for the rate of neutron increase. The neutron time constant, $\alpha(t)$, for the chain reaction defined in (44) is then

$$\alpha(t) = \frac{k-1}{\tau} = \frac{t}{t_0 \tau} \ . \tag{47}$$

For instance, a 1 MeV neutron has its 'life time' $\tau \sim 10^{-8}$ seconds, for which it runs about 15 cm in the system. For simplicity we assume that each neutron induces a fission reaction only once. Then, from (44) and (47) one obtains (the logarithm of) the total number of neutron-induced fissions during an interval $(t_f - t_i)$ as follows:

$$\ln\left(\frac{N(t_f)}{N(t_i)}\right) = \int_{t_i}^{t_f} \alpha(t)dt = \frac{1}{2t_0\tau}\left(t_f^2 - t_i^2\right) \ . \tag{48}$$

Mark's criterion for pre-detonation [16] is that the neutron-induced chain reaction be initiated at a time t_i early enough so that approximately e^{45} fissions have occurred before maximum criticality is achieved, i.e.,

$$\frac{N(t_f)}{N(t_i)} = e^{45} \ , \tag{49}$$

when $t_f < t_0$. Solving (48) and (49) for t_f gives

$$t_f = \sqrt{t_i^2 + 90 t_0 \tau} \ , \tag{50}$$

When $t_f \geq t_0$, the bomb yield Y will be the designed one Y_0 or

$$\text{bomb yield } \ Y = Y_0 \, , \quad \text{when } \ t_i \geq t_0\sqrt{1 - \frac{90\tau}{t_0}} \equiv t_i^{\text{crit}} \ . \tag{51}$$

For Mark's values, $t_0 = 10^{-5}$ and $\tau = 10^{-8}$ seconds, this corresponds to $t_i^{\text{crit}} = 0.954 \times 10^{-5}$ seconds. In this case, the full explosion will be achieved.

Based on the approximation derived in Ref. [14], furthermore, Mark also relates the reduced predetonation yield Y to the designed Y_0:

$$Y = \ (1 - k_f)^3 \, Y_0 = \left(\frac{t_f}{t_0}\right)^3 Y_0 \, , \quad \text{for } \ t_f < t_0 \, , \tag{52}$$

where $k_f \equiv k(t_f) = 1 + t_f/t_0$. From Eqs. (50) and (52) the minimum value of Y/Y_0 is given by

$$\frac{Y}{Y_0} = \left(\frac{t_i^2}{t_0^2} + \frac{90\tau}{t_0}\right)^{3/2} \geq \ \left(\frac{90\tau}{t_0}\right)^{3/2} = 0.027 \ . \tag{53}$$

Finally, we estimate the probabilities for the designed and the reduced yields to occur. Spontaneous fissions in the plutonium generate neutrons at a rate of N per second. Now we calculate the probability that the neutrons induce a chain reaction by time T. Since the expected value that one of the neutrons will start a chain reaction is $(k-1)$, the probability that a reaction occurs during the j-th interval $(t_j,\, t_{j+1})$, where $t_j \equiv j\Delta t$ and $\Delta t \equiv T/M$ with M being a large integer, is

$$P(t_j < t < t_{j+1}) = \Big(1 - N(k-1)\Delta t\Big)^j \cdot N(k-1)\Delta t\,. \tag{54}$$

Therefore, the probability of $P(t < T)$ of a chain reaction having been initiated by time T is obtained as

$$\begin{aligned} P(t<T) &= \sum_{j=0}^{M-1} P(t_j < t < t_{j+1}) \simeq \sum_{j=0}^{M-1} \Big(1 - N(k-1)_{\rm av}\Delta t\Big)^j \cdot N(k-1)_{\rm av}\Delta t \\ &= N(k-1)_{\rm av}\Delta t \cdot \frac{1 - \Big(1 - N(k-1)_{\rm av}\Delta t\Big)^M}{1 - \Big(1 - N(k-1)_{\rm av}\Delta t\Big)} = 1 - \Big(1 - N(k-1)_{\rm av}\Delta t\Big)^M\,, \end{aligned} \tag{55}$$

where we have used the linear-growth property of $(k-1)$

$$(k-1)_{\rm av} = \frac{1}{2}(k-1) = \frac{1}{2}\left(\frac{T}{t_0}\right)\,. \tag{56}$$

When M is large enough, one obtains from (55) the simple expression for $P(t < T)$

$$P(t<T) = 1 - \exp\Big\{-NT(k-1)_{\rm av}\Big\} = 1 - \exp\left\{-\frac{1}{2}NT\left(\frac{T}{t_0}\right)\right\}\,. \tag{57}$$

From Eq. (51) and (57), the probability of a full explosion is then

$$1 - P(t < t_i^{\rm crit}) = \exp\left\{-\frac{1}{2}N(t_0 - 90\tau)\right\}\,. \tag{58}$$

B Possible accelerator scheme

We first look for a mountain like in Fig. 15 whose surface does not touch many of the straight lines depicted as P_1P_2, P_3P_4, Q_1Q_2 or Q_3Q_4. A candidate for the mountain is Mt. Vinson Massif which is 4,892 meters in height, the summit of the Antarctica.

We construct two synchrotron A and B which are both revolvable. A should be larger than B. Muon beam is injected into the synchrotron A first and accelerated to a sufficient energy. Injection system could be installed in a tunnel in the mountain. Then it is stored either in the path $P_2P_3P_4P_1P_2$ or $Q_2Q_3Q_4Q_1Q_2$ depending on the direction of the beam in the synchrotron A. The beam is either μ^+ or μ^-. The straight sections P_1P_2, P_3P_4, Q_1Q_2 and Q_3Q_4 are made of chambers separated by many bellow structures so that they can have a flexible length. We probably have to prepare several chambers to cover from the minimum to the maximum length continuously. When we rotate A or B the chambers must follow until we steer the straight section to a given target.The next question is how precisely we can steer it. From the discussion given in the text the required accuracy is 10^{-7}. This is 1/10 micron per meter. We believe this is not an outrageous number. The current effort toward the construction of a linear collider is aiming at approximately 1 micron per meter. Future technology certainly will reach our required number sooner or later.

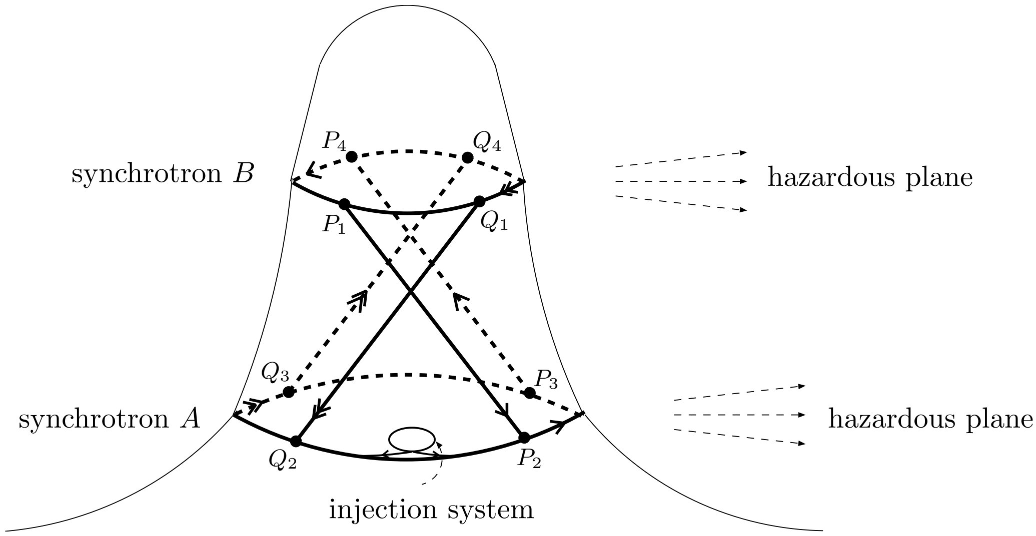

Figure 15: Accelerator scheme.

Another issue is the power consumption and the radiation hazard. Power required is $10^{14} \times 10^{-19} \times 10^{15}$ W $\simeq 10$ GW. Actually, we may need something like 50 GW (considering the efficiency) which is exactly the whole capacity of Japanese nuclear power. But the energy consumption could be as small as $10^2/10^8 = 10^{-6}$ times the whole consumption of 50 GW power. This should be quite tolerable. For the radiation hazard we have two planes in fig. 15 which should not be crossed by anyone during the operation and one direction toward the sky where no one is allowed to touch. The other direction is, of course, toward the target. Almost all the energy is lost in the earth and only 10^{-7} times the whole energy hits the target. People working near the target should be warned unless they are working to conceal the weapons.

We can perform $\mu^+\mu^+$, $\mu^-\mu^-$ and $\mu^+\mu^-$ colliding experiment in this scheme by injecting two beams simultaneously although the detector should be placed on a very steep slope between A and B synchrotrons. We believe it is not unreasonable to build this kind of accelerator complex first with much lower energy beam to study the inside of the earth and simultaneously performing the muon collider experiments and also the neutrino experiments.

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