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The Physical Basis of Nuclear Weapon Design

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Abstract. This document delves into the theoretical foundation and design principles of nuclear weapons, commencing with an exploration of the characteristics of fissile materials. Due to the high level of confidentiality of nuclear weapons, their specific details cannot be known by the vast majority of people, but this article focuses solely on their theoretical analysis. It elucidates the fundamental mechanisms of nuclear reactions, introducing the concept of nuclear criticality—the point at which a chain reaction can be sustained. Through intricate mathematical modeling, it describes the diffusion patterns of neutrons within nuclear fuel and surrounding reflector layers. Furthermore, the article presents a comprehensive design approach required to attain a supercritical state, inclusive of a driving apparatus and remote control systems. A pivotal component discussed is the neutron tube, which serves as the primary source of initiation neutrons. In essence, this paper offers profound insight into the sophisticated mechanics and operational principles underlying nuclear armament design.

Keywords: Atomic Physics, Nuclear Bombs, Nuclear Fission, Neutron Tubes.

1. Introduction

The development and design of nuclear weapons since their mid-20th century inception have significantly impacted global politics and international relations. Understanding the theoretical and practical aspects of these weapons is vital for devising national defense strategies and international security measures. Key discoveries in the late 1930s and early 1940s, including the understanding of fission and nuclear energy release mechanisms, laid the groundwork for advancing nuclear technology from basic atomic bombs to sophisticated thermonuclear devices [1]. This technological progression not only reflects scientific advancement but also prompts profound ethical and philosophical discussions.

This article employs intricate mathematical models to elucidate the neutron diffusion patterns within nuclear fuel and reflector layers, detailing the integrated designs necessary for achieving supercritical states. While general information about nuclear weapons is widely accessible, specific details on design principles remain scarce. By thoroughly analyzing the design and operational mechanisms of nuclear bombs, this study aims to enhance our comprehension of nuclear technology, aiding in the refinement of national security policies and international non-proliferation endeavors. Such insights are crucial for both scientists and policymakers to foster innovative technological developments and effective nuclear policies.

2. Understanding Fissile Materials

According to the picture of cosmic physics, the universe was born at a singularity, where there was initially no matter, only energy and strings. Photons were produced at the intersection of strings and energy, and high-energy photons split into positive and negative electron pairs. As the strings fluctuated and entangled with energy, various substances such as hadrons, electrons, neutrinos, etc. were born. These substances, such as quarks, electrons, etc., combined in a finely symmetrical form to form stable groups, which are known as various elements. In the center of massive celestial bodies such as stars, lighter elements such as hydrogen undergo fusion reactions under enormous pressure to produce new and heavier elements such as helium and lithium, while releasing energy [2]. This self-sustaining fusion combustion reaction is effective for elements with atomic numbers before iron.

The material after iron may be the product of the collapse and explosion of a star in its later years, resulting in a decrease in equilibrium, if the atomic nucleus is disturbed by new particles such as neutrons or protons, the potential barrier of the new group will be higher than the binding energy of the nucleus. The nucleus will split apart and release excess binding energy, which is the source of nuclear energy. A nuclear bomb is a weapon that utilizes fissile elements for a chain reaction, converting the depleted mass into energy in the form of shock waves, radiation, etc. [3]. using the mass-energy equation:

$$\mathrm{E} = \mathrm{m}c^2 \tag{1}$$

Where E represents energy, m represents mass, and c represents the speed of light， and releasing it in a few millionths of a second, causing massive destruction [4, 5].

3. Introduction to Nuclear Reactions

Nuclear reaction is the core process of material energy conversion. Here, the author mainly explores nuclear reactions triggered by neutrons. When a free neutron is incident near the atomic nucleus, reactions will occur according to different probabilities [6].

3.1. Elastic Scattering (EL)

It only changes their speed and direction of motion. They can be understood through classical mechanics.

3.2. Non-Elastic Scattering (NON)

When inelastic scattering occurs, neutrons are first absorbed by the atomic nucleus to form excited composite nuclei, which then emit gamma rays to release neutrons and return to the ground state. The prerequisite for this reaction is that the kinetic energy of neutrons must reach the first excited state of the atomic nucleus.

3.3. Absorption (INL)

Absorption reaction refers to the absorption of neutrons by atomic nuclei, resulting in an unstable composite nucleus. By emitting various substances such as γ, α, hydrogen ions, etc., excess energy is consumed to return to the ground state. There is a type of element that has a high probability of splitting into several smaller atomic nuclei, which is X and Y in (2), and releasing two or more neutrons (ν) after absorbing low-energy neutrons, triggering a new round of fission reaction. The reaction equation is:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow [^{236}_{92}U]^{*} \rightarrow ^{A1}_{Z1}X + ^{A2}_{Z2}Y + \nu^{1}_{0}n \tag{2}$$

This element is called a fissile element and has important significance in nuclear reaction engineering, such as U-235 and Pu-239 [7].

When neutrons of different energies are incident on different substances, the probability of each reaction occurring is different, which is called the nuclear reaction cross section. There are now detailed evaluation nuclear databases available on the internet for us to use [8].

4. Nuclear Criticality and Core Design

Now let's officially enter the theoretical design work of nuclear bombs. It is known that the explosion of nuclear bombs comes from the enormous energy released by the chain reaction (2). To make (2) continue, the concept of "nuclear criticality" needs to be introduced, which means that the number of neutrons passing through a single volume per unit time remains constant, that is, neutron flux conservation [9]. In the absence of an external neutron source, the neutron diffusion equation inside nuclear fuel is:

$$\frac{\partial\varphi}{\partial \mathrm{t}} = D\nabla^2\varphi - \sum\nolimits_a \varphi \tag{3}$$

Among them, “φ” is the neutron flux density, defined as the number of neutrons passing through a unit area perpendicular to the direction of neutron motion per unit time. “D ”is the diffusion coefficient of neutrons, which describes the diffusion ability of neutrons in a medium. “∑a” is the macroscopic absorption cross-section, which describes the ability of a medium to absorb neutrons. This equation describes the diffusion process of neutrons in a medium, especially in the absence of an external neutron source, where the change in neutron flux density is mainly influenced by neutron diffusion and absorption. Under steady-state conditions (i.e. neutron flux does not vary with time), this equation can be simplified as:

$$\mathrm{D}\nabla^2\varphi - \sum\nolimits_a \varphi = 0 \tag{4}$$

Outside the reflection layer, the neutron diffusion equation is:

$$\nabla^2\varphi_c(r) + B_c^2\varphi_c(r) = 0 \tag{5}$$

Inside the reflection layer, the neutron diffusion equation is:

$$\nabla^2\varphi_r(r) + k_r^2\varphi_r(r) = 0 \tag{6}$$

At the interface between nuclear fuel and the reflector, there must be equal neutron flux and neutron leakage, boundary conditions:

$$\varphi_c(r) = \varphi_r(r) \tag{7}$$

$$\lim_{r\to\infty} \varphi_c < \infty \tag{8}$$

$$D_c\varphi_c' = D_r\varphi_r' \tag{9}$$

$$\varphi_r = 0|_{r=R+T} \tag{10}$$

Firstly, equation (4) has a general solution:

$$\varphi_c(r) = \mathrm{A}_c\frac{\cos Br}{r} + C_c\frac{\sin Br}{r} \tag{11}$$

From condition (8), it is known that AC=0, therefore there is:

$$\varphi_c(r) = C\frac{\sin Br}{r} \tag{12}$$

In the reflective layer (5), there is a general solution:

$$\varphi_r(r) = \mathrm{A}_r \frac{\cosh(k_r r)}{r} + C_r \frac{\sinh(k_r r)}{r} \tag{13}$$

Due to boundary condition (9), there are:

$$A_r = -C_r \tanh[k_r(R+T)] \tag{14}$$

Therefore, there are:

$$\varphi_r = \frac{A \sinh[k_r(R+T-r)]}{r} \tag{15}$$

Where A is the new parameter.

From conditions (6) and (8), it can be concluded that:

$$\mathrm{C}\frac{\sinh(B_c R)}{R} = \mathrm{A}\frac{\sinh(k_T T)}{R} \tag{16}$$

$$D_c A\left[\frac{B_c \cos(B_c R)}{R} - \frac{\sin(B_c R)}{R^2}\right] = D_r C\left[-\frac{k_r \cosh(k_r T)}{R} - \frac{1}{R^2}\sinh(k_T T)\right] \tag{17}$$

By dividing the above two equations, the critical equation for a spherical nuclear bomb with a reflector layer can be obtained":

$$D_c\left[1 - B_c R\cot(B_c R)] = D_r[1 + \frac{R}{L_r}\coth\left(\frac{T}{L_r}\right)\right] \tag{18}$$

provides the relationship between the physical properties of various materials and their radii for a core with a reflective layer at nuclear criticality.

5. Integrated Design

To operate safely, a set of driving devices (i.e. a power device that can quickly change the core from a subcritical state to a supercritical state) and a corresponding remote control system are needed [10].

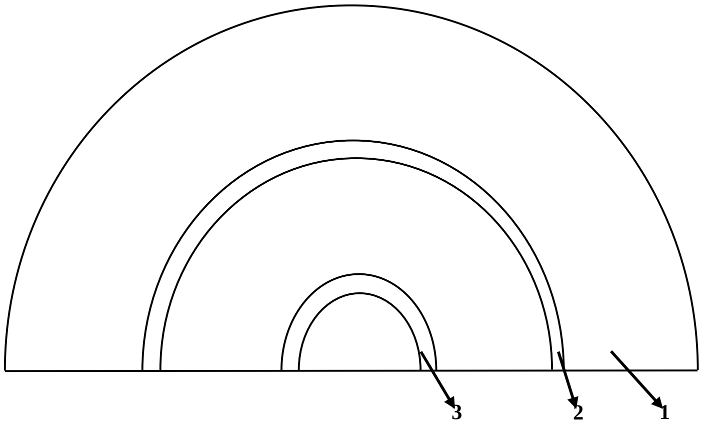

Fig. 1 The schematic diagram of the spherical detonation driving device (Picture credit: Original).

Fig. 1 is a schematic diagram of a spherical detonation driving device. The principle of this device is that a group of explosive lenses arranged on the outermost side uniformly detonate the main explosive column 1 to generate a centripetal detonation wave, pushing the neutron reflector layer 2 to rapidly compress towards the uranium-235 fuel ball 3. When the reflector layer is tightly combined with the nuclear fuel, the delay circuit activates the neutron tube to release neutrons to ignite the nuclear fuel in a supercritical state, thereby triggering a chain reaction. To achieve a good detonation compression effect, each process and parameter must be calculated carefully [11].

Firstly, the maximum acceleration that the neutron reflector layer needs to be determined, i.e. the flying plate, can achieve after being driven by explosive 1, as well as the acceleration time. Assuming t=0, the explosive with density, length, mass, and detonation velocity D is uniformly detonated at the periphery. At $\mathrm{t} = \frac{l}{D}$, the detonation wave reaches the surface of the reflector layer M. The velocity v of the particles satisfies the relationship:

$$v = D\left(1 + \frac{x-1}{\tau x} - \frac{l}{Dt}x\right) \tag{19}$$

Where:

$$\mathrm{x} = \left[1 + 2\eta\left(1 - \frac{l}{Dt}\right)\right]^{-\frac{1}{2}} \tag{20}$$

$$\tau = \frac{16m}{27M} \tag{21}$$

It can be calculated that the limit value of v is approximately D/3. To improve the compression effect as much as possible, m/M should be around 7-8. The flight cavity should not be too long, otherwise it will cause significant deformation [12]. In addition, its symmetry should be ensured in the design to ensure an even distribution of energy during explosion, to achieve the expected focusing effect. Then, material selection is also crucial: materials that can withstand extreme conditions should be chosen while considering any potential effects they may have during the reaction. The final security mechanism design needs to include security measures to prevent premature or unplanned detonation.

6. The Use of Neutron Tubes

The neutron tube is a key component that provides a neutron source for nuclear bombs. It uses the Penning discharge principle to accelerate hydrogen ions through an extraction electrode and bombard the target material with high voltage, performing D-D and D-T reactions:

$$^{2}_{1}D + ^{3}_{1}T \rightarrow ^{4}_{2}He + ^{1}_{0}n + 17.6MeV \tag{22}$$

$$^{2}_{1}D + ^{2}_{1}D \rightarrow ^{3}_{2}He + ^{1}_{0}n + 3.8MeV \tag{23}$$

Thereby generating neutrons of 17Mev or 3Mev, which is one of the most important indicator for nuclear dedicated neutron sources [13].

7. Conclusion

This article provides an overview of the design principles and manufacturing process of nuclear bombs. Firstly, it explains the basic principle of nuclear bombs converting mass into energy through a chain reaction of fission elements. Subsequently, the article delves into the origin of matter in the universe, as well as the types of nuclear reactions such as elastic scattering, inelastic scattering, and absorption reactions. Of particular importance is the introduction of how to achieve sustained chain reactions by controlling nuclear criticality and designing the core. In addition, the importance of overall design and safe operation was emphasized, including the design of the drive device and remote control system. Finally, the critical role of neutron tubes in providing initial neutron sources was discussed. This series of theoretical and practical aspects together constitute the scientific foundation for the design and manufacture of nuclear weapons. In summary, although nuclear bombs are highly destructive weapons, in the future, the author looks forward to the safer and more peaceful use of technology and nuclear science, while strengthening international cooperation to maintain global nuclear security.

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