JOINT INSTITUTE FOR NUCLEAR RESEARCH

Dzhelepov Laboratory of Nuclear Problems

FINAL REPORT ON THE START PROGRAMME

Analysis of cross sections of collisions of light nuclei

Supervisor:
Jurabek Khushvaktov
Russia, Joint Institute for Nuclear Research

Student:
Saidov Shokhrukh , Nationality
University of Uzbekistan named after Mirzo Ulugbek

Participation period:
March 10 – April 27,
Winter Session 2024

Dubna 2024

Table of Contents

Abstract

As we all know, the construction of TOKAMAK is the main problem of plasma physics nowadays. In TOKAMAK , we usually use deuterium and tritium. In fact, there are several other cores available for use in TOKAMAK . But their effectiveness is worse than the first reaction. In this work, we talk about the efficiency of some reactions in terms of their interaction cross sections.

The purpose this work

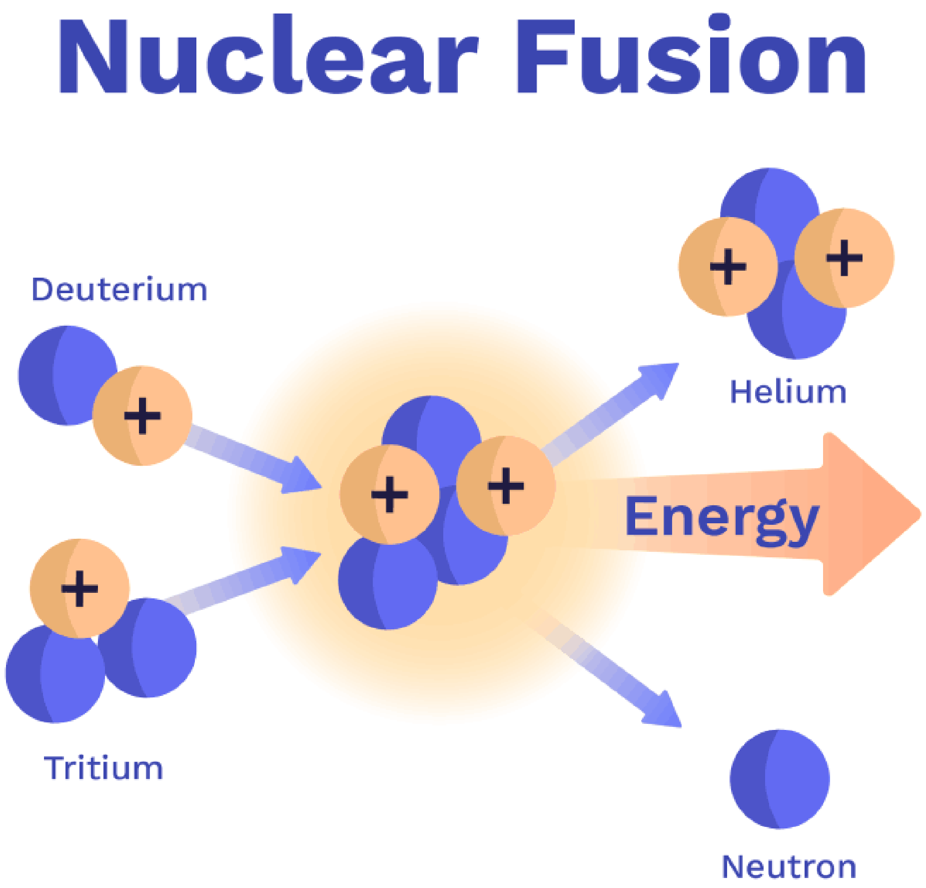
As stated above , we consider four fusion reactions in this work. More generally , we consider them by their interaction cross sections. These reactions are deuterium tritium , deuterium deuterium , deuterium helium and tritium tritium . We try analysis each reaction and to conclude for us. We make collision simulations among these nuclears in GEANT4. And we compared our simulation results with experiment data.

Introduction

In this work we will consider 4 reactions. These reactions deuterium tritium , deuterium deuterium , deuterium helium and tritium tritium.Cross-sections of these reactions were found in GEANT4 and compared to experimental results in the database. Explanations are given about each of them. In this paper, we will examine how useful each reaction is as a fusion reactor fuel.

Nuclear fusion

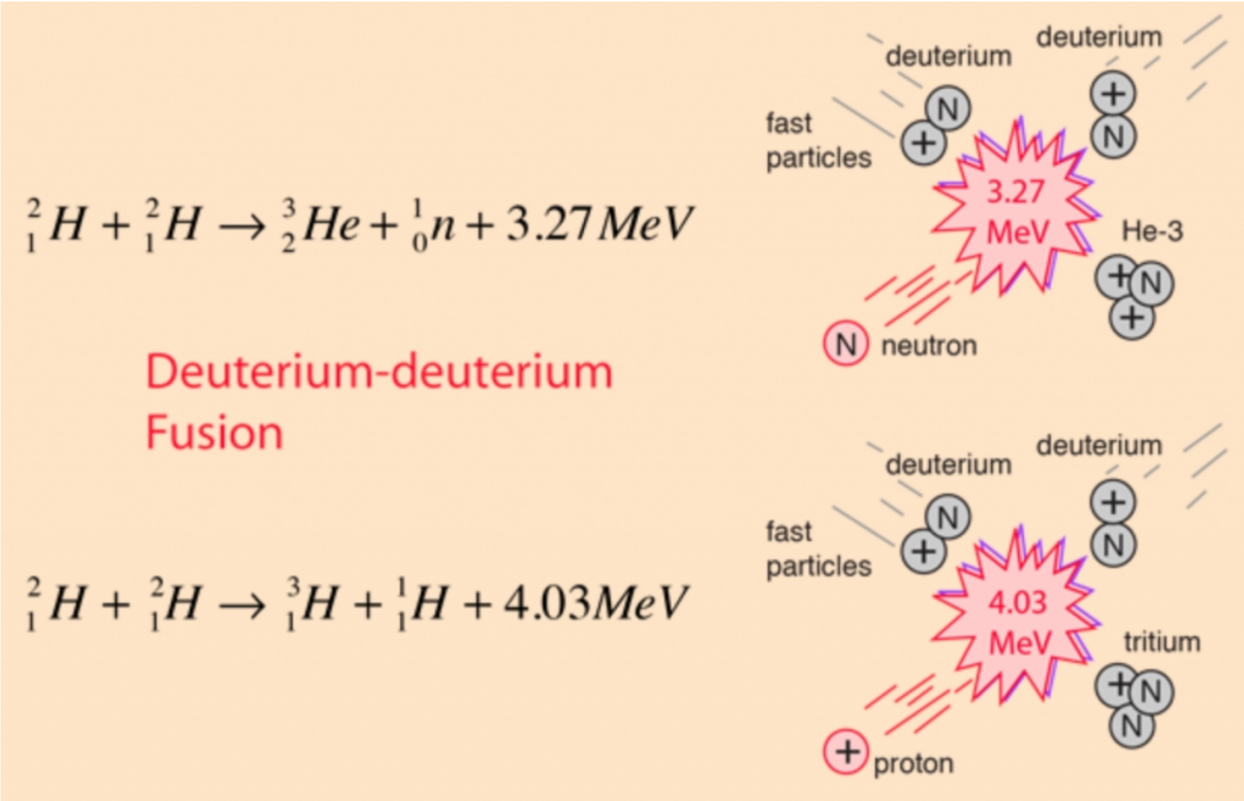
In a ground-breaking development, scientists have made significant progress in nuclear fusion research, bringing humanity one step closer to harnessing the immense energy potential of this process. Nuclear fusion is a reaction in which two or more atomic nuclei combine to form different atomic nuclei and subatomic particles, resulting in the release of massive amounts of energy. The key to nuclear fusion lies in the difference in mass between the reactants and the products. When atomic nuclei, usually deuterium and tritium, combine, the resulting atomic nuclei have a smaller mass and a larger binding energy per nucleon. This release of energy makes nuclear fusion a highly promising method for powering stars and other high-magnitude celestial bodies. The recent breakthrough in fusion research focuses on producing atomic nuclei lighter than iron-56 or nickel-62. This particular fusion process has been found to consistently release energy, making it an exothermic reaction. In contrast, fusing heavier atomic nuclei results in the retention of energy by the product nucleons, making it an endothermic process. This new development is a significant step forward as it demonstrates the potential for harnessing fusion energy in a more efficient manner. Nuclear fusion utilizes lighter elements, such as hydrogen and helium, which are generally more fusible. On the other hand, heavier elements like uranium, thorium, and plutonium are more suited for nuclear fission. This difference in fusibility explains why fusion reactions that produce lighter elements release energy, while reactions involving heavier elements require energy to sustain the reaction. The implications of this breakthrough in fusion research are immense. If scientists can master controlled nuclear fusion, it could provide a clean, abundant, and practically limitless energy source. Unlike nuclear fission, which produces harmful radioactive waste, fusion reactions produce minimal waste and are environmentally friendly. Furthermore, the extreme astrophysical event of a supernova has shown that it is possible to fuse atomic nuclei into elements heavier than iron. This opens up the possibility of producing such elements through controlled nuclear fusion, leading to advancements in various fields such as material science and nuclear medicine. Fusion energy is emerging as a promising and potentially sustainable solution for the world's growing energy needs. Many researchers consider it a "natural" energy source for the long term, with a host of advantages over other forms of energy production. Proponents of fusion reactors for electricity generation outline several key arguments in their favor that make it an attractive option. One of the primary advantages of fusion energy is the virtually inexhaustible reserves of fuel it offers. Hydrogen, which fuels fusion reactions, can be extracted from seawater, making it accessible from any coast around the world. This eliminates the possibility of one country or group of countries monopolizing fuel resources, ensuring a fair and equal distribution of resources. In addition, fusion reactions have a minimal probability of an emergency explosive increase in reaction power. This makes them inherently safer than other forms of nuclear energy, reducing the risk of accidents or disasters. Furthermore, fusion reactions do not produce any combustion products, eliminating harmful emissions such as greenhouse gases and air pollutants. This makes fusion energy a clean and environmentally sustainable option. Another advantage of fusion energy is its inherent security. Unlike traditional nuclear reactors, fusion reactors do not require materials that could be used to produce nuclear explosive devices. This eliminates the possibility of sabotage or terrorism, providing a higher level of safety and security. Compared to traditional nuclear reactors, fusion reactors produce radioactive waste with a short half-life. This reduces the long-term storage and disposal issues associated with nuclear waste, making fusion energy a more attractive option from a waste management perspective. However, critics argue that the cost-effectiveness of fusion energy remains uncertain. A study commissioned by the UK Parliament's Office of Science and Technology suggests that the cost of producing electricity using fusion reactors may be at the higher end of the cost spectrum compared to traditional energy sources. The future development of technology, market structures, and regulations will play a crucial role in determining the cost of electricity generation from fusion. The cost of electricity also depends on factors such as the efficiency of use, the duration of operation, and the cost of reactor disposal. These variables need to be carefully considered and optimized to ensure that fusion energy becomes a viable and affordable option for widespread electricity production. Despite these potential challenges, fusion energy holds immense promise as a sustainable and clean energy source for the future. Ongoing research and development efforts are focused on overcoming the current limitations and making fusion energy a commercially viable and economically competitive option for meeting the world's energy demands.Scientists have long been fascinated by the potential of nuclear fusion, a process that holds the key to clean and abundant energy. A recent study has shed light on the mechanisms behind the release of energy through fusion and its vast implications. The release of energy through fusion is the result of two opposing forces at play. The first force is the nuclear force, a manifestation of the strong interaction which tightly holds protons and neutrons together in the atomic nucleus. The second force is the Coulomb force, which causes the positively charged protons in the nucleus to repel each other. Lighter nuclei, which are smaller and proton-poor, allow the nuclear force to overcome the Coulomb force. This is because the attractive nuclear force is able to act over short distances and is stronger than the repulsive Coulomb force within smaller nuclei. As a result, when lighter nuclei fuse, the extra energy is released due to the net attraction of particles. This process of fusion powers stars and is responsible for the creation of virtually all elements through a process known as nucleosynthesis. In the case of our Sun, nuclear fusion of hydrogen nuclei into helium is what generates its energy. In the Sun's core, around 620 million metric tons of hydrogen fuse to form 616 million metric tons of helium every second. The fusion of lighter elements in stars not only releases energy but also leads to a decrease in mass. For example, when two hydrogen nuclei fuse to form helium, 0.645% of the mass is carried away in the form of kinetic energy or other forms of energy. This release of energy accompanies the formation of new elements. However, it is important to note that it requires a significant amount of energy to force nuclei to fuse, even for the lightest element, hydrogen. Nuclei need to be accelerated to high speeds to overcome the electrostatic repulsion and bring them close enough for the attractive nuclear force to take over. Once the nuclei are close enough, the fusion process occurs, resulting in the generation of energy. This fusion of lighter nuclei generally releases more energy than it takes to force them together, making it an exothermic process that can sustain itself. The energy released in nuclear fusion reactions is much greater than in chemical reactions, primarily due to the higher binding energy that holds a nucleus together compared to the energy that holds electrons to a nucleus. Fusion reactions have an energy density many times greater than nuclear fission, although individual fission reactions are often more energetic than individual fusion reactions. In fact, only the direct conversion of mass into energy, as seen in matter-antimatter collisions, can surpass the energy released in nuclear fusion. This recent research provides further insight into the processes of nuclear fusion and its immense energy potential. As scientists continue to unravel the mysteries of fusion, the dream of harnessing this clean and abundant source of energy moves closer to becoming a reality.



1-figure. Deuterium-tritium reaction.

Result of Deuterium-deuterium reaction

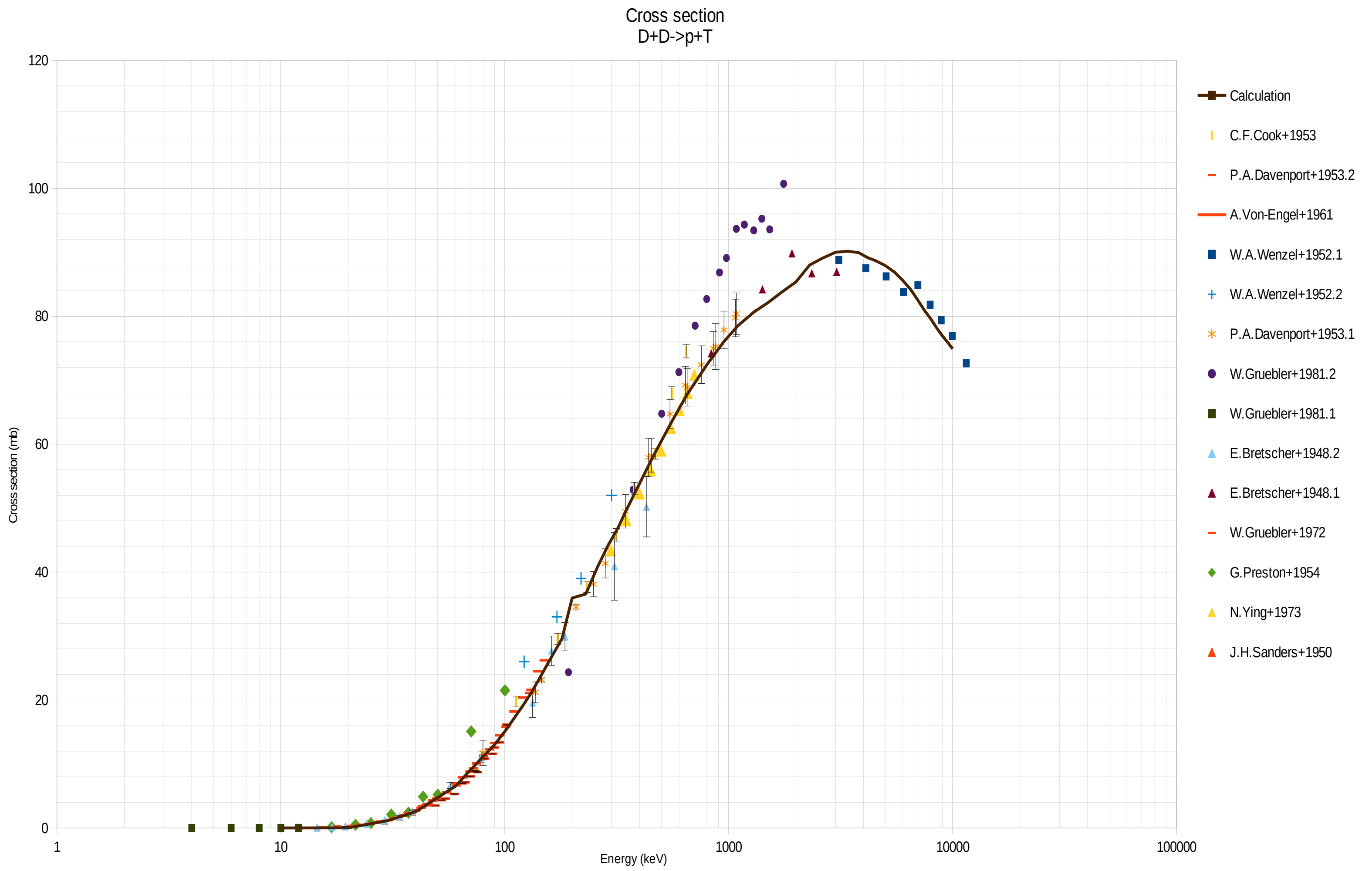
Let us first consider the following reaction. This is a box which has deuterium. Their density $0.1 g/sm^3$. It may be altered. And this box is bombarded with deuterons. The consequence of this work can go on 2 different directions.(2-picture)



2-picture. Deuterium-deuterium fusion.

The possibility of both reactions is almost equally 50%. We may see products of fusion reaction by second chart. In first reaction , the Helium-3 and neutron are formed as well as 3.27MeV energy too. In second reaction,tritium(hydrogen-3) and hydrogen are formed and with 4.03MeV.

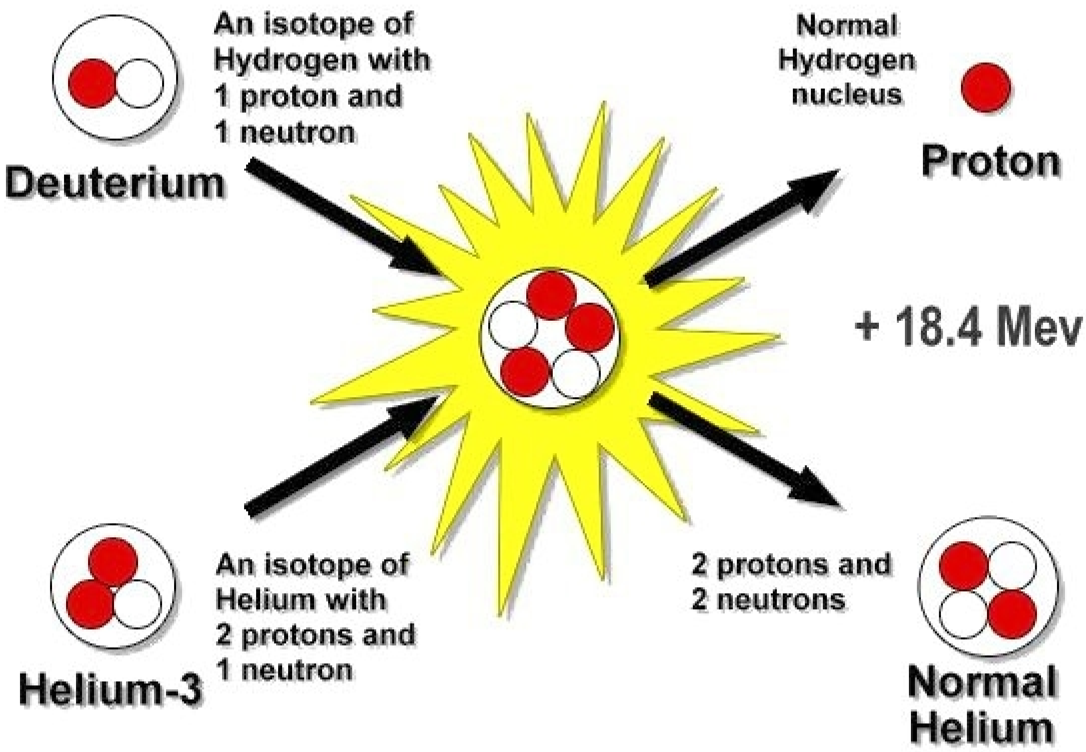
Let us consider cross section of this reaction(3-figure). We may see that the line graph is my simulation result. And other points are experimental results. This chart shows second type of reactions. The most important part for us is the cross section of the reaction. It can be seen that the largest cross section is equal to 90mb. It is much smaller. If the cross section of reaction is small , the effectiveness of collisions of the reaction is small too. So that, this reaction is not mate to us. Because there are other fusion reaction which have high effectiveness rather than.



3-figure. Cross section of D+D reaction

Result of Deuterium Helium3

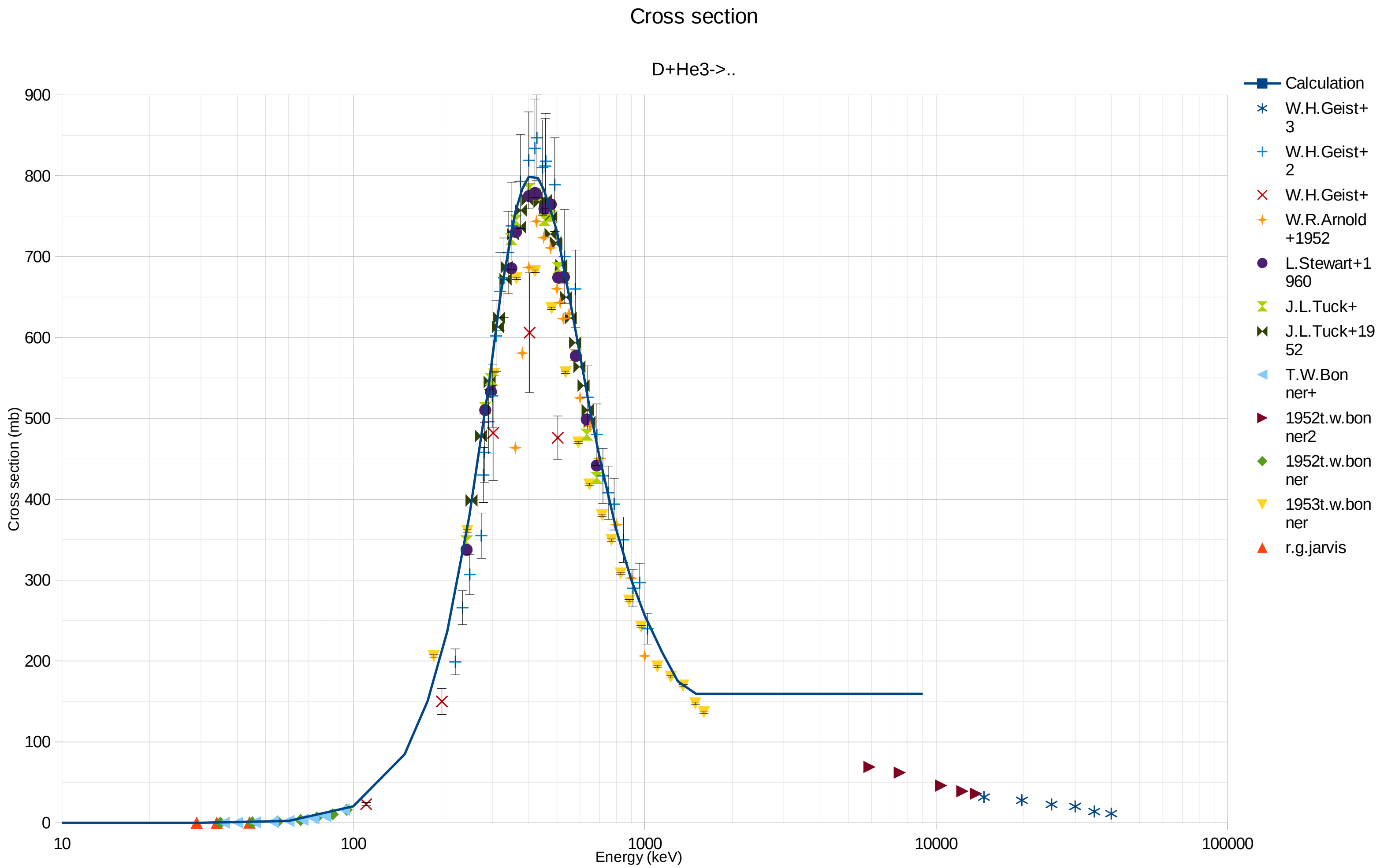
Let us consider next reaction. We can see this reaction on following chart(4-figure).



4-figure.Deuterium Helium-3 reaction.

All of the above are understandable. Below is a cross section of this reaction.(5-figure) . The largest section corresponds to 800 mb. The cross section for the rest of the energy values can be seen from the graph.

In addition, the energy to reach the maximum cross-section was also considered an important factor. Because the greater this energy, the more it is necessary to raise the plasma temperature.



5-figure.Cross section of Deuterium Helium-3 reaction.

Result of Tritium tritium reaction

In this reaction, the largest cross section is equal 140mb. The cross section is also slightly smaller in this reaction, which gives us less energy release in the reaction. We cannot use this reaction as a possible fusion reactor fuel.

For this reaction to be effective, the temperature must be raised to very high values. Because we see that in order to achieve the maximum cross-section in this reaction, the value of the energy should be around 2 MeV. In order to have this energy, we need to heat the plasma to several billion degrees. More precisely, as follows

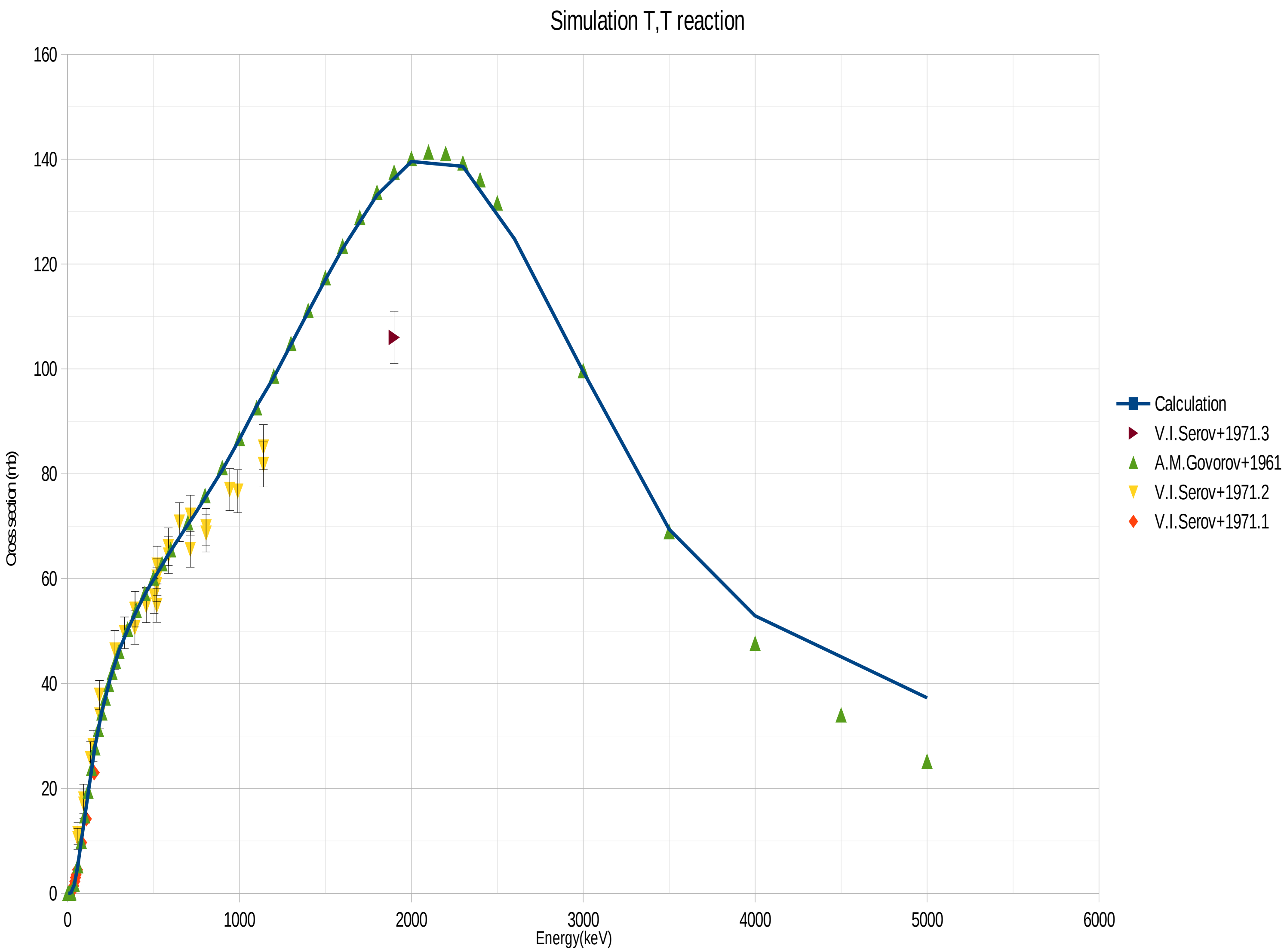
$$E = \frac{3}{2}kT$$

$$T = \frac{2E}{3k} = \frac{2 \cdot 2MeV}{3 \cdot 1.38 \cdot 10^{-23}} = 1.545 \cdot 10^{10}K$$

Nowadays the high temperature in the world is aproximately 150 million Kelvin.

It is very difficult to create such a high temperature and maintain it. Even if we reach such a temperature, the energy generated will be very small.

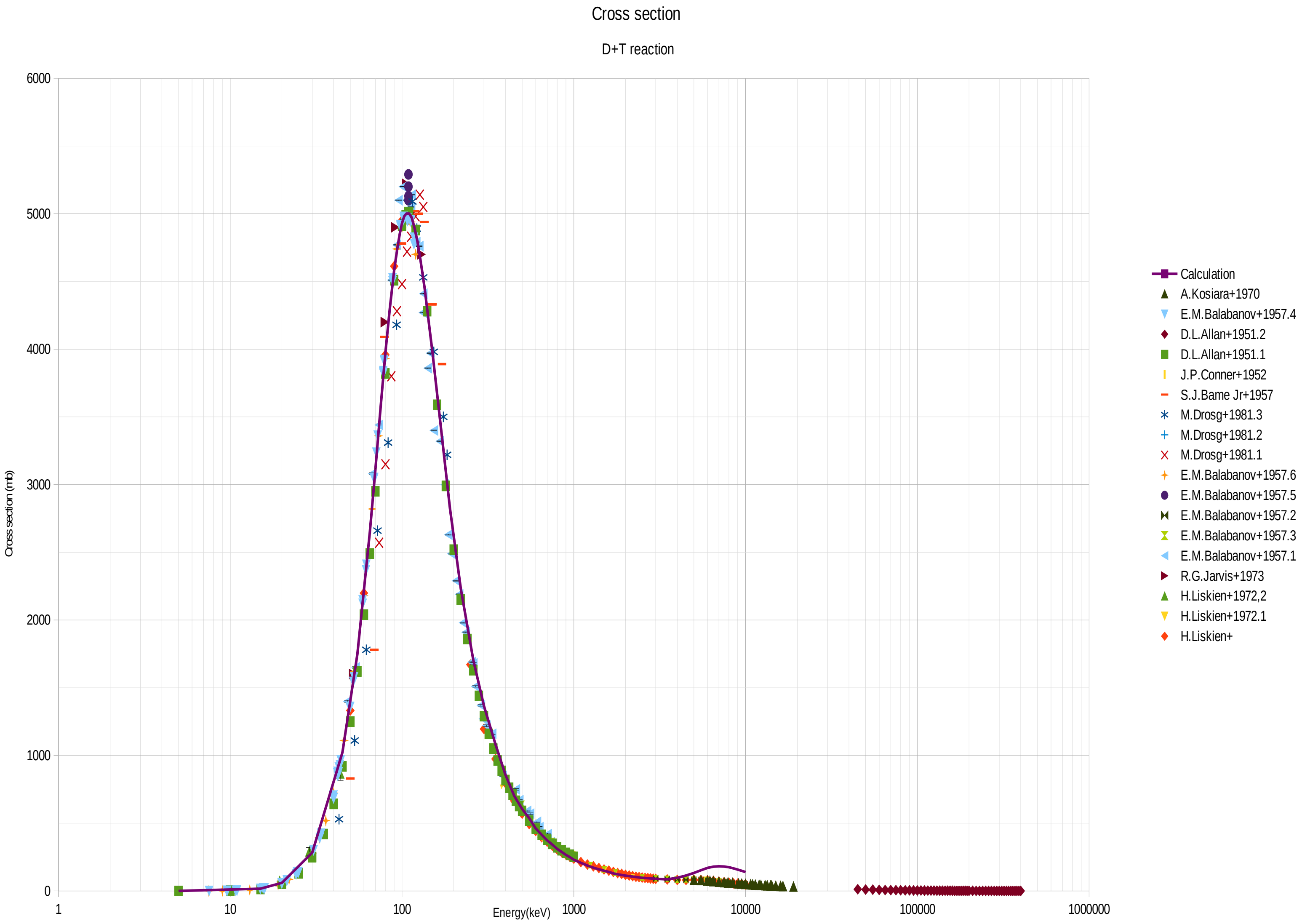
Cross section values for different energies can be obtained from the 6-graph.



6-figure. Cross section of Tritium tritium reaction.

Result of Deuterium Tritium reaction

This reaction is more effectiveness than others. Deuterium-tritium fusion, known as D+T fusion, is a type of nuclear fusion reaction where a deuterium nucleus combines with a tritium nucleus, resulting in the formation of a helium nucleus, a free neutron, and 17.6 million electronvolts (MeV) of energy. This reaction is recognized as the most well-known fusion reaction used in fusion devices due to its energy output and feasibility for fusion applications. One of the critical aspects of D+T fusion is the presence of tritium, one of the reactants needed for the reaction. Tritium is a radioactive isotope, and in fusion reactors, a structure known as a 'breeding blanket,' typically made of lithium, is positioned on the reactor walls. When lithium interacts with energetic neutrons produced during the fusion reaction, tritium is generated through a nuclear transmutation process. In the context of deuterium-tritium fusion, the fusion of one deuterium nucleus with one tritium nucleus leads to the production of a helium nucleus, a free neutron, and an energy release of 17.6 MeV, which results from a mass difference of approximately 0.02 atomic mass units (AMUs). The energy liberated in the fusion reaction is determined by the mass-energy equivalence, famously described by Einstein's equation $E=mc^2$. Around 80% of the energy released (equivalent to 14.1 MeV) is converted into the kinetic energy of the neutron, causing it to travel at about 1/6th the speed of light. The discovery of the deuterium-tritium fusion reaction traces back to 1938 when evidence of this reaction was first identified at the University of Michigan by Arthur Ruhlig. Ruhlig's experiment involved observing neutrons with energies above 15 MeV in tritium secondary reactions. These tritium reactions were produced through deuteron beam interactions with a heavy phosphoric acid target, leading to the creation of neutron+helium nuclei. Despite the initial detection, the significance of this discovery was only recently appreciated. While deuterium is relatively abundant and can be readily sourced, with about 1 in every 5,000 hydrogen atoms in seawater being deuterium, tritium poses sourcing challenges due to its radioactivity. To address this, lithium acts as a key element in the tritium generation process in fusion reactors. By exposing lithium to energetic neutrons generated during deuterium-tritium fusion, tritium nuclei are produced. Moreover, the deuterium-tritium reaction itself emits a free neutron, which can be utilized to initiate a reaction with lithium. The incorporation of a 'breeding blanket' containing lithium within fusion reactors facilitates tritium breeding, whereby the free neutrons released during the fusion process interact with lithium to create more tritium, ensuring a sustained supply of this crucial reactant.



7-figure.Cross section of Deuterium-tritium reaction

Conclusion

In this work I considered the interaction of light nuclei and simulated it in GEANT4. The results were as shown above. Now to conclude, the highest efficiency is the last reaction, that is, the deuteron tritium reaction. Because it can be seen that the reaction is much higher than that of the others. This is an important factor. Because the larger the cross-section of the reaction, the greater the number of reactions, and as a result, the amount of energy produced is also very large. The ratio was considered useless due to the small cross-section of the remaining reactions, some of which are rare in nature.

References

1. Geant4 Installation Guide Documentation Release 11.2
2. https://en.wikipedia.org/wiki/Nuclear_fusion
3. https://www-nds.iaea.org/exfor/
4. Agostinelli, S., Allison, J., Amako, K., et al., 2003. Geant4 – a simulation toolkit. Nucl.Instrum. Methods Phys. Res. A 506, 250–303. http://dx.doi.org/10.1016/S0168-9002(03)01368-8.