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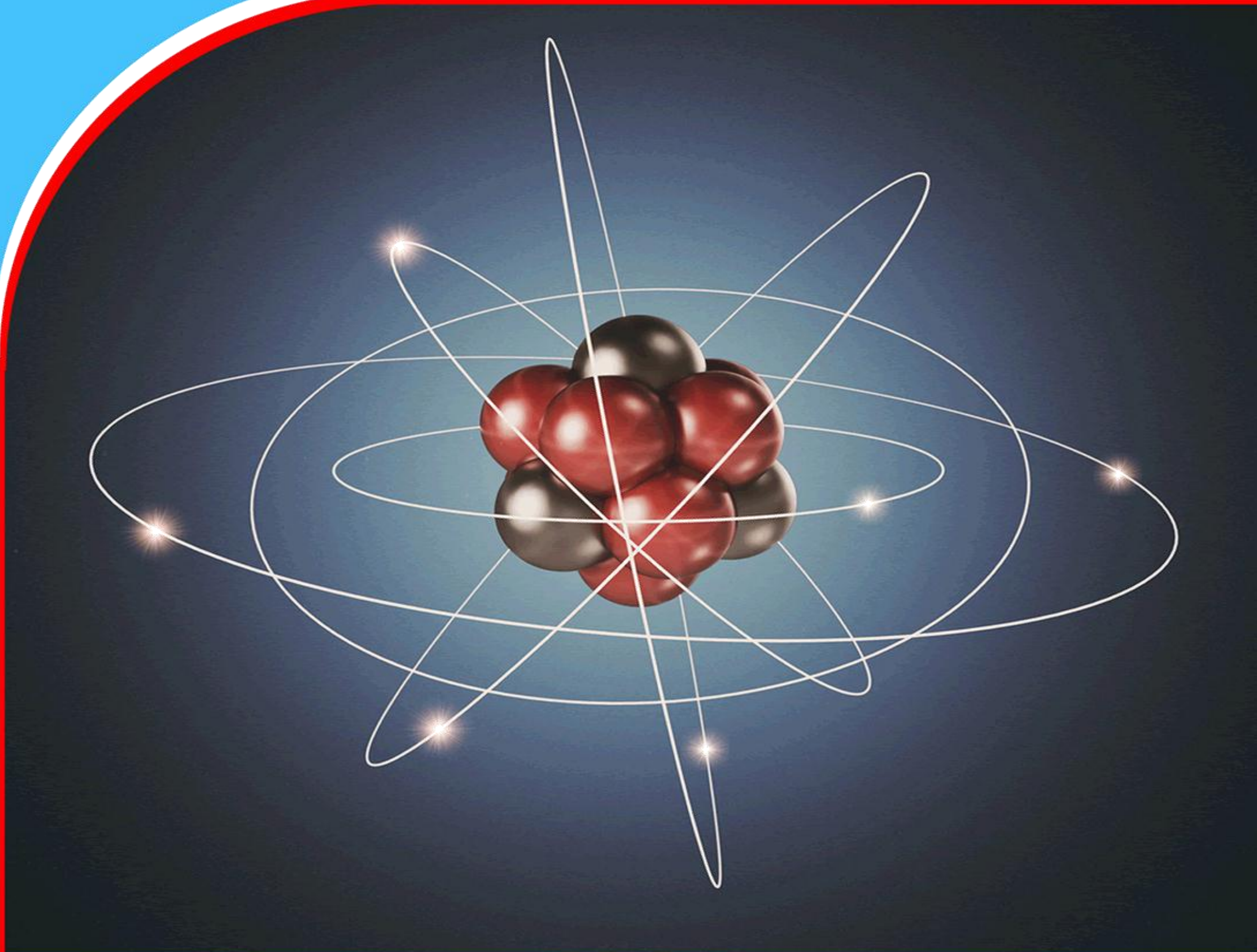

DEUTERON INDUCED FUSION REACTION TARGET FOR INERTIAL CONFINEMENT FUSION (ICF)

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DEUTERON INDUCED FUSION REACTION TARGET FOR INERTIAL CONFINEMENT FUSION (ICF)

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ABSTRACT

Objective: Energy efficiency enhancement is one of the most effective ways to achieve Fast ignition (FI) in inertial confinement fusion ICF. High energy output gain is essential for ICF reactors and greater energy efficiency can reduce energy costs. The injection of Ion beam is one method used to achieve FI fusion reaction in ICF. A fusion of deuteron with lithium-6 isotope, DLi^6 is reviewed in this work alongside the fusion of Deuterium – Tritium (DT), Deuterium – Deuterium (DD), Deuterium – Helium-3 (DHe^3) and Proton – Boron-11 (PB^{11}).

Materials and Methods: In this work, it is proposed the projection of laser-driven deuteron beam in the FI scheme for ICF in the DLi^6 plasma. Fusion occurs as the projected deuteron ion beam hits the lithium-6 target in the thermonuclear fusion reaction.

Results: The results show that the fusion reactions of DD, DHe^3 and PB^{11} all require high input kinetic energy (Mega-electronvolts) for the fusion process to occur because of higher Coulomb barrier and the probability of fusion increases by increasing the input energy drive with low output energy gain. DT fusion which require low input kinetic energy of about 400 KeV with high cross section and generated considerable high output energy gain of about 17.59 MeV, However this fusion reaction require large tritium inventory and tritium does not occur naturally, therefore the need for tritium breeding. When the energy of deuteron beam is projected at 200 keV to lithium-6 isotope target, although $D + Li^6$ has a low total cross section of about 19.409 mbarn, the stopping power of the electrons would be more than ions, nuclear stopping power is considerable at very low deuterons energies, the Coulomb interaction of deuteron and lithium-6 occurs with output energy gain of about 22.373 MeV.

Conclusion: The investigations indicate that fusion target energy gain efficiency is independent of lithium-6 numerical density. The highest value of energy efficiency gain occurs with lower input kinetic energy of deuteron beam of about 200 KeV to lithium-target.

Recommendation: This findings contribute to the core mission of NIF in achieving fast ignition with low ignition energy input to achieve Lawson break-even or "ignition" point of the fusion fuel pellet, where it gives off 100% or more energy than it absorbs. However the simulation results were based on programmed model of Geant4 Hadr03. This results can be validated with the appropriate experimental design of the Hadr03 process.

Keywords: *Inertia Confinement Fusion (ICF), Fast Ignition (FI), Mega-electronvolts (MeV), Kilo-electronvolts (KeV), Cross-section, Coulomb Interaction.*

1.0 INTRODUCTION

Fusion is the combination of two light nuclei to form a heavy one. Atomic nuclei are positively charged, and thus repel each other due to the electrostatic force. Overcoming this repulsion to bring the nuclei close enough requires an input of kinetic energy, known as the Coulomb barrier or fusion barrier energy. Inertial Confinement Fusion (ICF) is considered as an alternative to Magnetic Confinement Fusion to achieve controlled thermonuclear fusion reaction (Kawata et al., 2020). The main goal of ICF is to exploit the energy released from thermonuclear fusion reactions to produce electric energy (Moreno et al., 2014). In ICF approach there is no need using high magnetic fields to restrict the plasma, the confinement involves only the inertia of the compressed fuel(Bahmani, 2021). The major difficulties with target efficiency in the idea of inertia fusion, includes; laser - plasma instabilities, asymmetric laser illumination, hydrodynamic instabilities during the shell implosion, and insufficient target energy gain have all been solved through years of investigation (Bahmani, 2021).

Unlike fission, all fusion reactions require extremely high temperatures, tens to hundreds of million degrees Celsius. At these temperatures matter is gaseous and decomposes into atoms; the atoms, in turn, are s tripped of their outer electrons and thus become ionized. This state is referred to as a plasma, that is, an ionized gas distinguished from ordinary gases by its ability to conduct electricity easily and to respond readily to electric or magnetic forces. For practical purposes, it will be necessary for a fusion reactor to achieve conditions where the appropriate fuel is raised to these elevated temperatures and held there long enough so that a significant fraction of the fuel can undergo fusion reactions. The amount of energy recovered in the process will have to exceed the amount of energy invested, and exceed it by some measure, in order for the fusion reactor to be of practical interest (Harvey, 1978).

Fusion fuel cycles, might be considered for terrestrial purposes. The fusion energy will be released in a combination of three forms: radiation, kinetic energy of charged particles, and fast neutrons. The distribution of energy among these three forms depends on the fuel cycle selected and hence will affect the engineering aspects of a fusion plant as well as its potential applications. The reaction involving the deuterium (D) and tritium (T) isotopes of hydrogen requires by far the least stringent plasma conditions and is therefore receiving the most attention today. Deuterium is found in nature along with ordinary hydrogen in the proportion of 1 to 6,500, and is readily recoverable from the waters of the earth (Harvey, 1978).

The concept of fast ignition approach in ICF reactor is to achieve a minimum input kinetic energy and obtain large output energy gain thereby reducing input driver energy. In order to operate a typical ICF reactor, one would require an output energy of the order of 400 MJ per implosion (Tahir & Hoffmann, 1994). From Tahir and Hoffmann one-dimensional calculations, this predict that an output energy of the order of 700-800 MJ can be achieved using direct drive as well as indirect drive targets. Various studies of inertial fusion reactors have specified the amount of tritium needed per day in the target factory. However, the evacuation of unburnt tritium from the reactor chamber is also a difficult task for operators. Tahir and Hoffmann computer simulations of the burn of DT targets using volume ignition and central ignition models only focus on the influence variations of the fraction of deuteron and tritium on the energy output but fails to consider the contribution of target gain.

The supply of the required energy to achieve fast ignition is one of great concern in a fusion reactor. High amount of energy is needed for the ignition of DD, DHe^3,PB^{11} and He^3He^3 reaction fuel in a fusion reactor which is due to the losses of radiation and the requirement for high-temperature electrons and ions(Bahmani, 2020). The main purpose of this work is to propose an alternate ignition fusion reaction fuel that will generate high output energy enough to power a typical ICF reactor with low ignition energy input which is pure and generate neither neutron nor tritium, therefore increasing energy gain and reducing ignition energy in ICF reactors. In addition to also investigate the required minimum kinetic energy for the projection of deuteron beam to lithium-6 target for coulomb interaction of Deuteron – lithium (D6Li) fuel, used in a thermonuclear reaction through Monte Carlo simulation using Geant4 software toolkit.

2.0 THEORETICAL BACKGROUND

This section contains the list of thermonuclear fusion reaction equations, the relation of the probability of Coulomb interaction of deuteron with lithium-6 isotope and the description of the simulation software.

2.1 Fusion reaction equations

The fusion reactions equations that are currently considered relevant to generate energy to power ICF reactors are given in equation (i) to (v):

$$\boldsymbol{D + T \rightarrow n + He^4 + 17.60\ MeV} \quad \text{(i)}$$

$$\boldsymbol{D + D \rightarrow n + He^3 + 3.25\ MeV} \quad \text{(ii).a}$$

$$\boldsymbol{D + D \rightarrow T + p + 4.01 MeV} \quad \text{(ii).b}$$

$$\boldsymbol{D + He^3 \rightarrow p + He^4 + 18.35\ MeV} \quad \text{(iii)}$$

$$\boldsymbol{p + B^{11} \rightarrow He^4 + He^4 + He^4 + 8.68\ MeV} \quad \text{(iv)}$$

$$\boldsymbol{D + 6Li \rightarrow 4He + 4He + 22.371\ MeV} \quad (v)$$

$$\boldsymbol{D + 6Li \rightarrow p + T + 4He + 2.257\ MeV} \quad (v).a$$

$$\boldsymbol{D + 6Li \rightarrow p\,(4.397\ MeV) + 7Li\,(0.628\ MeV)} \quad (v).b$$

$$\boldsymbol{D + 6Li \rightarrow n\,(2.958\ MeV) + 7Be\,(0.423\ MeV)} \quad (v).c$$

$$\boldsymbol{D + 6Li \rightarrow n\,(\sim 0.66\ MeV) + 4He + 3He + 1.794\ MeV} \quad (v).d$$

$$\boldsymbol{D + 6Li \rightarrow 5Li + t + 0.59 MeV} \quad (v).e$$

$$\boldsymbol{D + 6Li \rightarrow 3He + 5He + 0.9 MeV} \quad (v).f$$

Fusion reaction equations (i – v) are considered as fusion fuel cycles, the reaction of Deuteron – Deuteron has two pathways and the reaction of Deuteron – Lithium-6 isotope has seven pathways(Stork et al., 2017).

2.2 Thermonuclear Reactivity

Thermonuclear reactivity relates to a fusion reaction can be determined by the following equation:

$$< \sigma v > = \int_0^\infty v F(v)\, \sigma(v) dV \quad (1)$$

Where ν is the relative velocity between the interacting species in Centre of Mass frame of reference, F(ν) is the relative velocity distribution and $\sigma(\nu)$ is the microscopic fusion cross section for a particular fusion reaction as a function of the Centre of Mass energy for that reaction system.

2.3 Probability of nuclear fusion reaction equation

The probability of nuclear fusion reactions depends on the cross-section and the stopping power of the fast deuteron in the D6Li and is obtained through the following relation;

$$\boldsymbol{P(T) = \int_0^R n_{Li}\sigma dx = \int_{ED}^{Eth} n_{Li}\,\sigma(E)\frac{1}{(\frac{dE}{dx})_{total}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(2)}$$

Where n_{Li} is the numerical density of lithium, and σ is the cross-section of the D6Li fuel, which is a function of the kinetic energy of the deuterons, R is the range of deuterons and ED and Eth is the initial kinetic energy and thermal energy of deuterons.

2.4 Simulation Softwares

The simulation framework is called Geant4 Hadr03. Hadr03 not only automates the process but also generates detail information of the reaction results. Geant4 Hadr03 is written in the C++ scripting language and addresses file management, Monte Carlo execution, and image generation. Geant4 Hadr03 also contains a Graphical User Interface (GUI) which allows for the input of many parameters that control both the Monte Carlo simulation and computed visualization.

The Geant4 Hadr03 GUI interface is shown in Fig. 1. The GUI allows rapid iteration of the micro commands parameters so that the user can quickly evaluate various concepts. Geant4 has four main parts: (1) Micro commands controls (2) Visualization of geometry and particle track, (3) Simulation result and output files display, (4) User inputs and input file generation.

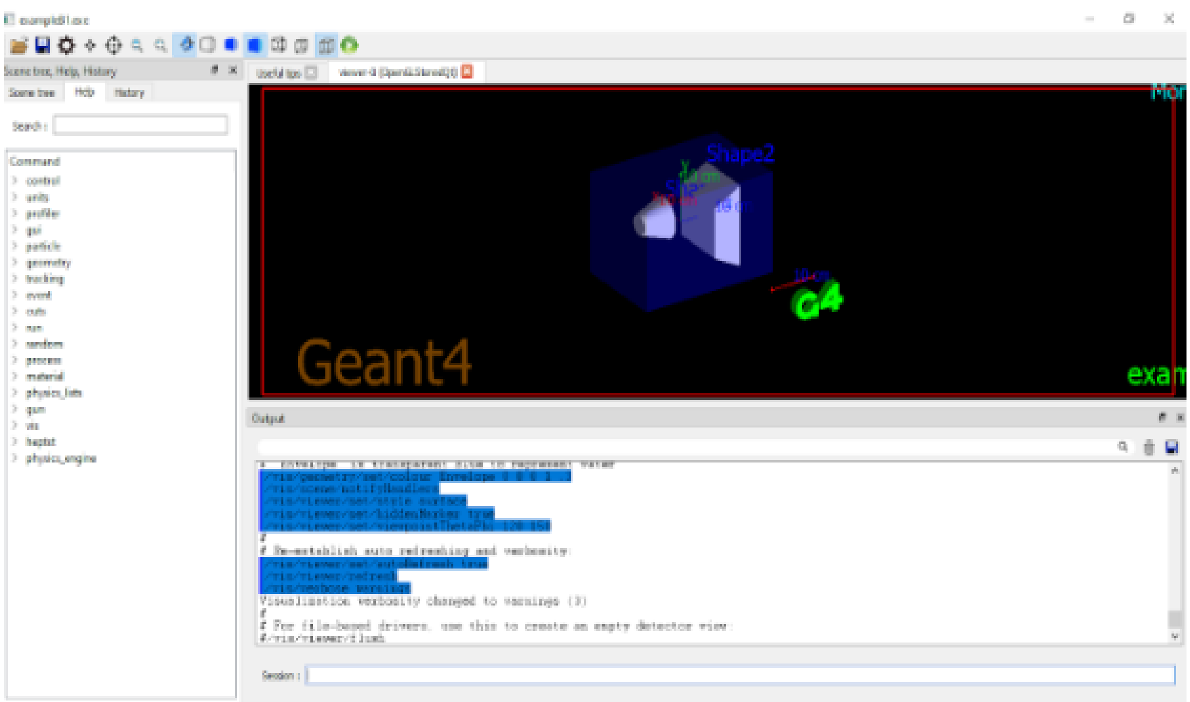

Figure 1: Geant4 GUI.

2.5 Literature review

Proposals have been made to design ICF reactors that can be operated by imploding deuterium targets that contain a small amount of DT at the center(Rofifah, 2020), The DT reaction will ignite first and the thermonuclear energy produced in the ignitor will be used to ignite D + D reactions in the deuterium. It is seen from the reaction equations [i, ii, iii, iv and v] that the energy produced in a D + T reaction is about five times higher than that produced in a D + D reaction. However, the evacuation of unburnt tritium from the reactor chamber is also a difficult task for operators.

Research has been carried out on Heavy ion Fusion (HIF) which demonstrated the production of single ion beams with the required emittance, current, and energy, suitable for injection into an induction linac (beam accelerator)(Berkeley, 1980). The repetition rate for these sources was low, and the total operating hours and the number of extracted pulses were still well below the number of pulses required in a driver in 1 yr at ≈10 Hz. Kawata (2020) worked on the improvement of fuel implosion uniformity by using dynamic smoothening approach to a spherical DT fuel target, also demonstrated the effectiveness of the wobbling frequency in obtaining a higher fusion energy gain but not much on the reduction input driver energy (Kawata et al., 2020). Similar work by Uchibori which mainly focused on the effect of the rising time of the main pulse (Δtbeam) has on the fuel implosion and an irradiation timing error (Δt) of each driver beam induces an enhancement of the implosion non-uniformity which in turn degrades fusion output energy gain, yet not much done on input driver energy(Uchibori et al., 2020).

Bahmani (2021) presented a work on "Reduction in inertial confinement fusion ignition energy of 3He-3He plasma by laser-accelerated deuterons" which reduces ignition energy and increases energy gain. However, deuteron require an approximate high acceleration energy in (MeV) for the fusion process to occur because of higher coulomb barrier of the He^3 + He^3 fuel, and also lower cross sections, higher ion temperature than DT, lack of the availability of He^3, and increased radiation losses. Bahmani also carried out a thorough investigation on D^2 + Li^6 plasma. The investigation shows that increasing electron temperature can be employed to increase the energy production efficiency due to additional heating resulting in fusion fast deuteron particles with deuterium and lithium-6 ions in the D6Li plasma, since the probability of D6Li fusion reaction is extremely sensitive to cross-section and stopping power, increasing the temperature greatly increases the rate of fusion(Bahmani, 2021). However, his investigation fails to state the required minimum kinetic energy for the projection of deuteron beam for coulomb interaction of D6Li Plasma and also ignored the thermal velocity of lithium fuel.

3.0 MATERIALS INSTRUMENTATIONS AND METHODS

This section contains the materials used in building the Geant4 toolkit, methods used in building the Hadr03 GUI and the hadronic process of running the Monte Carlo Simulation

3.1 Materials

To successfully install Geant4; one will need some software packages for building of source code and installation these are:

i. Windows 10 Operating System
ii. Cmake 3.21.2 app: used for generating and configuring of the Geant4 source code.
iii. Microsoft Visual Studio 2019 with C++ packages: used for building Geant4 source code; geant4 codes are written in C++ codes.

iv. Qt 5.9.9 (MSVC 2013 64-bits): used for compilation of source code and installation of Geant4 application program to my system.
v. Geant4 Open source code: Geant4_10_07_02 (patch 02) and Data libraries.
vi. Laptop system with at least 4 Gigabyte Ram and 2.30 Hz Processor

3.2 Methodology

This sub-section contains the method used in building the Geant4 Hadro03 GUI and the hadronic process used in running the Monte Carlo simulation.

3.2.1 Building of Geant4 Hadr03

In this study, to model the fusion interactions, the Geant4 Hadr03 (fusion hadronic Process) was built into the Geant4 toolkit using Cmake, Microsoft Visual Studio 2019 and Qt5.9.9 application software's simultaneously. The Hadr03 interaction uses G4HadronPhysicsQGSP_BIC_HP physics list implemented in the simulation, and the command "/run/initialize" was used for registration of the newly developed physics process. Customizing the fusion interaction process into the simulation requires the implementation of the micro commands displayed in figure 2. The deuteron beam particle tracks resulted from fusion interaction are recorded by a detector geometry relative to the beam direction.

3.2.2 Hadronic Process

The initial steps of the hadronic process use only a single thread because loading and generating the input files requires little time even with thousands of projections.

Step 1. The fusion.mac code was executed from the Hadron03 micro files through Hadro03 GUI. This was accomplished by starting the geant4 Hadron03 application environment for the specified thread with the first environment opened being the head of the stack as shown in figure 1.

Step 2. Then the input micro commands were passed to the thread GUI as shown in figure 2. The thread then, acting like an independent program which writes the input file to disk, executes Monte Carlo Simulation of the fusion reaction, and extracts the require data from the Geant4 data files. This process happens simultaneously with all other threads until all of the input files have been executed and tally data extracted.

Step 3. Then the input micro command "/run/beamOn" was also passed to run the simulation. The particle track images are then display in the visualization screen and the reaction data result displayed in the output screen, histogram results written in .root file format to the release data folder. Which can then be extracted for analysis. Fig 2 shows flow chart of the list of micro commands that was used during fusion hadronic process execution.

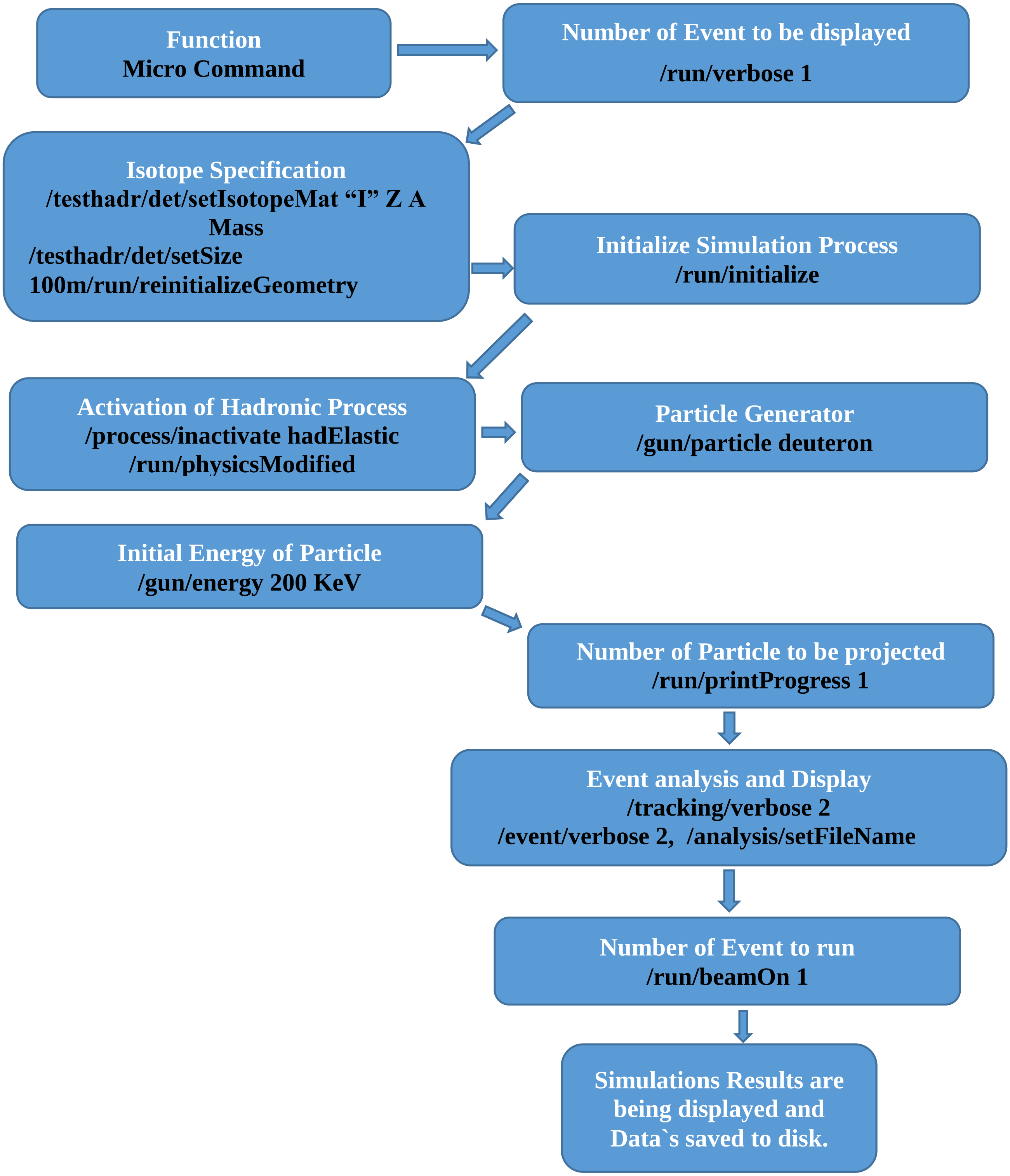

Figure 2: Hadr03 Flow chart

4.0 RESULTS AND DISCUSSION

This section contains the detailed results output of the hadronic processes and discussion of results.

4.1 Simulation of Deuterium – Tritium Fusion Reaction

After running the Monte Carlo simulation of DT fusion reaction on Geant4 Hadr03 GUI the following results were obtained.

Table 1: DT reaction result for 1 Deuteron beam.

Fusion Reactant	Input Energy	Particles Generated	Cross Section(mbarn)	Output Energy Gain (Q)	Mean Energy of Particles Generated
D	400 KeV	Alpha	851.26	17.59 MeV	4.6635 MeV
T		Neutron			13.326 MeV

T (D, n) α: Q: 4.6635 MeV (α) …………………………………………………. (i)

13.326 MeV (n).

Deuteron beam track information;

Number of Particles = 1

Particle = deuteron, Track ID = 1, Parent ID = 0

```
*****************************************************************
Step Process    X      Y      Z      KineE    dEStep   StepLeng TrakLeng   Volume
*****************************************************************
0          -50 m    26.1m    22.3 m   400 keV   0 eV     0 fm      0 fm    tritium   initStep
1          -49 m    26.1m    22.3 m   0 eV      0 eV   99.5 cm   99.5 cm   tritium   dInelastic
*****************************************************************
```

DT fusion reactions has high cross section of 0.010051 cm^{-1} and cross-section per atom of 503.46 mbarn with total cross section of 851.26 mbarn. When deuteron is projected with input kinetic energy of 400 KeV to tritium target, fusion reaction occurs, it produces a substantial amount of energy of 17.59 MeV considerably enough to power a typical ICF reactor and it also generates high number of neutrons, it is to be noted that in order to operate a typical ICF reactor one would require an output energy of about 400 MJ per implosion. However, reactor based on this system of fusion reaction will require large amount of tritium inventory. Tritium is radioactive, decaying with the emission of soft beta particle, it does not occur naturally therefore the need for tritium breeding. From table 1, the DT reaction generated alpha particle with a mean energy of 4.6635 MeV and neutron with a mean energy of 13.326 MeV all in 160.7 Nano seconds.

4.2 Simulation of Deuteron – Deuteron Fusion Reaction

After running Monte Carlo simulation of DD fusion reaction on Geant4 Hadr03 GUI the following results were obtained.

Table 2: DD reaction result for 100 Deuteron beam.

Fusion Reactant	Input Energy	Particles Generated	Cross Section(mbarn)	Output Energy Gain (Q)	Mean Energy of Particles Generated
D	10 MeV	Helium-3	157.57	3.2696 MeV	5.5648 MeV
D		Neutron			7.7049 MeV

D (D, n) ^{3}He: Q: 5.5648 MeV (α) ………………………………………………………. (ii)

7.7049 MeV (n).

Table 3: DD reaction result for 100 Deuteron beam.

Fusion Reactant	Input Energy	Particles Generated	Cross Section(mbarn)	Output Energy Gain (Q)	Mean Energy of Particles Generated
D	10 MeV	Proton	157.57	4.033 MeV	11.012 MeV
D		Triton			3.0205 MeV

D (D, t) p: Q: 11.012 MeV (p) ………………………………………………………. (iii)

3.0205 MeV (n).

Deuteron beam track information;

Number of Particles = 100

Particle = deuteron, Track ID = 1, Parent ID = 0

```
**************************************************************
Step Process    X       Y       Z       KineE   dEStep  StepLeng TrakLeng   Volume
**************************************************************
0       -50 m   12.9m   -14.9 m  10 MeV  0 eV    0 fm     0 fm     tritium  initStep
1       -50 m   12.9m   -14.9 m  0 eV    0 eV    4.68 cm  4.68 cm  tritium  dInelastic
**************************************************************
```

DD fusion reactions has a cross-section of 0.0050927 cm^{-1} and cross section per atom of 170.33 mbarn with total cross-section of 157.57 mbarn, produces small number of neutrons and tritium in comparison with DT reactions. However the fusion reactions require enormous amount of energy for coulomb interaction to occur i.e. high ignition energy input (in MeV). From the Monte Carlo simulation of DD fusion reaction shown in table 2 and 3, generated particles; first from table 2, helium-3 with mean energy of 5.5648 MeV plus neutron with mean energy of 7.7049 MeV all with an average energy gain of 3.2696 MeV. Then secondly from table 3, proton with mean energy of 11.012 MeV plus triton with mean energy of 3.0205 MeV all with an average energy gain of 4.033 MeV all generated in 1.519 Nano Seconds. This fusion reaction only took place when high input kinetic energy of 10MeV was supplied to project deuteron to deuterium target which is much difficult to achieve with present day technology.

4.3 Simulation of Deuteron – Helium-3 Fusion Reaction

After running Monte Carlo simulation of DHe^3 fusion reaction on Geant4 Hadr03 GUI the following results were obtained.

Table 4: DHe^3 reaction result for 1 Deuteron beam.

Fusion Reactant	Input Energy	Particles Generated	Cross section(mbarn)	Output Energy Gain (Q)	Mean Energy of Particles Generated
D	1 MeV	Alpha	256.44	18.353 MeV	4.1532 MeV
He^3		Proton			15.2000 MeV

He^3 (D, p) α: Q: 4.1532 MeV (α) …………………….……………………………… (iv)

15.20000 MeV (p).

Deuteron beam track information

Number of Particles = 1

Particle = deuteron,   Track ID = 1,   Parent ID = 0

```
*************************************************************
Step Process    X       Y       Z      KineE   dEStep  StepLeng TrakLeng   Volume
*************************************************************
0            -50 m   -3.15 m  23.8 m  1 MeV    0 eV     0 fm     0 fm     helium  initStep
1            -42 m  -3.15 m  23.8 m  0 eV     0 eV   7.96 m   7.96 m     helium  dInelastic
*************************************************************
```

Deuteron + Helium-3 fusion reaction has a cross-section of 0.0077969 cm^{-1} and cross-section per atom of 390.6 mbarn with total cross-section of 256.44 mbarn, this reaction produces protons and helium particles with a considerable high output energy gain. However, the fusion reaction require high amount of input kinetic energy for Coulomb interaction i.e. high ignition energy input (in MeV) although smaller than the energy require for D + D fusion reaction. Running the Monte Carlo simulation of DHe^3 fusion reaction on Geant4 hadronic process with input energy of 1MeV, results output from table 4 shows that the fusion of deuteron and helium-3 generated proton and alpha particles with an output energy gain of 18.353 MeV. This reaction require a minimum of

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1MeV energy to take place and particles generated; alpha with mean energy of 4.1532 MeV and proton mean energy of 15.2 MeV all in 258.2 Nano seconds.

4.4 Simulation of Proton – Boron Fusion Reaction

After running Monte Carlo simulation of PB^{11} fusion reaction on Geant4 Hadr03 GUI the following results were obtained.

Table 5: PB^{11} reaction result for 1 Proton beam.

Fusion Reactant	Input Energy	Particles Generated	Cross section(mbarn)	Output Energy Gain (Q)	Mean Energy of Particles Generated
p	10 MeV	Helium-3	195.37	8.6829 MeV	4.509 MeV
B^{11}		Helium-3			7.510 MeV
		Helium-3			6.323 MeV

B^{11} (P, 2α,) α: Q: 4.509 MeV (α) ……………………………..………………….. (v)
7.510 MeV (α)
6.323 MeV (α)

Proton beam track information;

Number of Particles = 1

Particle = proton, Track ID = 1, Parent ID = 0

```
*****************************************************************
Step Process   X      Y      Z     KineE   dEStep  StepLeng TrakLeng   Volume
*****************************************************************
  0         50 m    34 m  -36.2 m  10 MeV   0 eV   0 fm    0 fm     boron  initStep
  1       -46.7 m   34 m  -36.2 m   0 eV    0 eV  3.33 m  3.33 m   boron  protonInelastic
*****************************************************************
```

Proton-boron fusion reaction of 1 proton beam has a cross-section of 0.0030068 cm^{-1} and cross-section per atom of 549.68 mbarn with total cross-section of 195.37 mbarn, generated 3 alpha particles (He^3) with an average energy output gain of 8.6829 MeV, each of the generated alpha particles has a mean energy of 4.509 MeV, 7.510 MeV and 6.323 MeV all generated in 76.59 Nano seconds as shown in table 5. This fusion reaction only occurs when proton beam was projected to boron-11 isotope with an input ignition energy of 10 MeV which is relatively a large amount of energy that is difficult to achieve with present day technology.

Simulation for 100 Protons of 10 MeV

Table 6: PB^{11} reaction result for 100 Proton beam.

Fusion Reactant	Input Energy	Particles Generated	Cross section (mbarn)	Output Energy Gain (Q)	Mean Energy of Particles Generated
p	10 MeV	Boron-11	195.37	8.6829 MeV	998.84 KeV
B^{11}		Carbon-11			1.2695 MeV
		Helium-4			6.2276 MeV
		Gamma			5.3176 MeV
		Neutron			1.5729 MeV
		Proton			2.7875 MeV

Proton beam track information; Number of Particles = 100

Particle = proton, Track ID = 1, Parent ID = 0

```
*****************************************************************
Step Process    X      Y      Z     KineE   dEStep  StepLeng TrakLeng   Volume
*****************************************************************
  0        -50 m    14.2 m   23.7 m   10 MeV   0 eV   0 fm    0 fm     boron   initStep
  1       -39.7 m   14.2 m   23.7 m   0 eV     0 eV   11 m    11 m   boron   protonInelastic
.................................................................
*****************************************************************
```

When 100 isotopes of protons at high energy of 10 MeV, cross-section of 0.00099787 cm^{-1} and cross-section per atom of 182.42 mbarn with total cross-section of 195.37 mbarn is projected to boron-11 target, the number of generated particles increases as shown in table 6. Alpha particles with mean energy of 6.2276 MeV, boron-11 with mean energy of 998.84 KeV, carbon-11 (radioactive) with mean energy of 1.2695 MeV and proton with mean energy of 2.7875 MeV. All generated in 254.4 Nano seconds.

4.5 Simulation of Deuteron – Lithium-6 Fusion Reaction

After running Monte Carlo simulation of DLi^{6} fusion reaction on Geant4 Hadr03 GUI process the following results were obtained.

Table 7: DLi^{6} reaction result for 1 Deuteron beam.

Fusion Reactant	Input Energy	Particles Generated	Cross section(mbarn)	Output Energy Gain (Q)	Mean Energy of Particles Generated
D	200 KeV	Alpha	19.409	22.373 MeV	10.63 MeV
^{6}Li		Alpha			11.95 MeV

Number of Particle = 1

Li^{6} (D, α) α: Q: 10.63 MeV (α) ………………………………………………………. (v)

11.95 MeV (α)

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Table 8: DLi^6 reaction result for 100000 Deuteron beam.

Fusion Reactant	Input Energy	Particles Generated	Cross section (mbarn)	Output Energy Gain (Q)	Mean Energy of Particles Generated
D	1 MeV	Beryllium-7	164.62	22.373 MeV	10.63 MeV
^{6}Li		Lithium-7			435.61 KeV
		Alpha			11.684 MeV
		Deuteron			614.93 KeV
		Gamma			1.8407 MeV
		Neutron			250.14 MeV
		Proton			959.5 KeV
		Triton			1.5261 MeV

Deuteron beam track information;

Number of particles = 100000

Particle = deuteron, Track ID = 1, Parent ID = 0

```
*******************************************************************
Step Process   X     Y     Z     KineE   dEStep  StepLeng TrakLeng  Volume
*******************************************************************
  0      0    -50 m  26.1 m  22.3 m  200 keV  0 eV   0 fm   0 fm  lithium  initStep
  1     37 m  26.1 m  22.3 m  0 eV   0 eV   87 m   87 m  lithium  dInelastic
*******************************************************************
```

From the Monte Carlo simulation results in table 7 of the fusion reaction of D + ^{6}Li, this reaction has a cross-section of 0.00011493 cm^{-1} and cross-section per atom of 11.479 mbarn with total cross-section of 19.409 mbarn, it does not produce neutrons in the whole process of decay and all energy is released through charged particles. With minimum low kinetic input ignition energy of 200 KeV enough to overcome Coulomb force binding the nucleus of lithium for the fusion reaction to occur, it also generated high output energy gain of 22.373 MeV considerably enough to power a typical ICF reactor. The simulation results shows the mean energy of the two alpha particles generated in the fusion process as 10.63 MeV and 11.95 MeV all in 19.8 Micro seconds respectively. Table 8 shows the simulation results of 100000 deuterons projected to lithium-6 targets with increased number of particles generated, this result shows the other pathways of deuteron – lithium fusion reaction, however this fusion reaction only occurs when the input ignition was increased to 1 MeV. In consideration of the input ignition energy and target gain, this work mainly focused on the reaction results of table 7.

4.6 Summary of Simulation Results

Table 9: Summary of fusion reactions with their respective input and output energy.

S/N	Fusion Reaction	Input Energy	Output Energy Gain (Q)
i.	T(D,n)α	400 KeV	17.59 MeV
ii.a	D(D,n)^{3}He	10 MeV	3.2696 MeV
ii.b	D(D,t)p	10 MeV	4.033 MeV
iii	^{3}He(D,p)α	1 MeV	18.353 MeV
iv	^{11}B (p,2^{3}He)^{3}He	10 MeV	8.6829 MeV
v	^{6}Li(D,α)α	200 KeV	22.373 MeV

Table 10: Summary of fusion reactions with their respective cross-sections.

S/N	Fusion Reaction	Cross-section (cm^{-1})	Cross-section per atom (mbarn)	Total Cross-section (mbarn)
i.	T(D,n)α	0.0100510	503.46	851.26
ii.a	D(D,n)^{3}He	0.0050927	170.33	157.57
ii.b	D(D,t)p	0.0050927	170.33	157.57
iii	^{3}He(D,p)α	0.0077969	390.60	256.44
iv	^{11}B (p,2^{3}He)^{3}He	0.0030068	549.68	195.37
v	^{6}Li(D,α)α	0.00011493	11.479	19.409

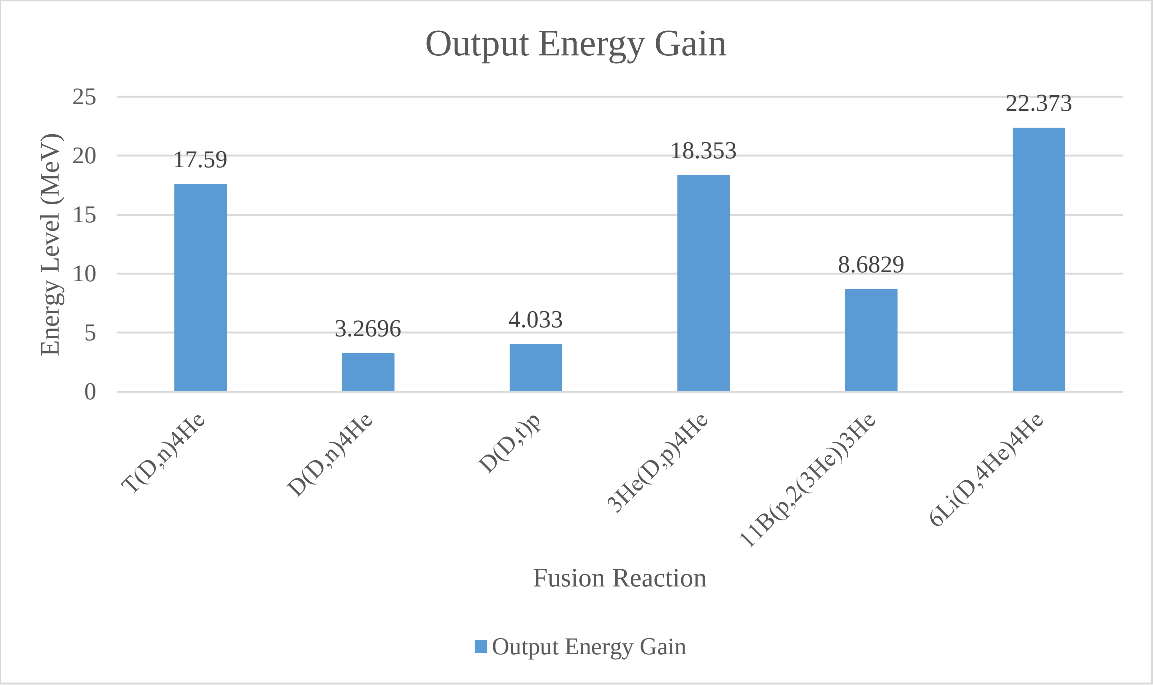

Figure 3: Chart of output energy gain by each fusion reaction in Mega-electronvolts.

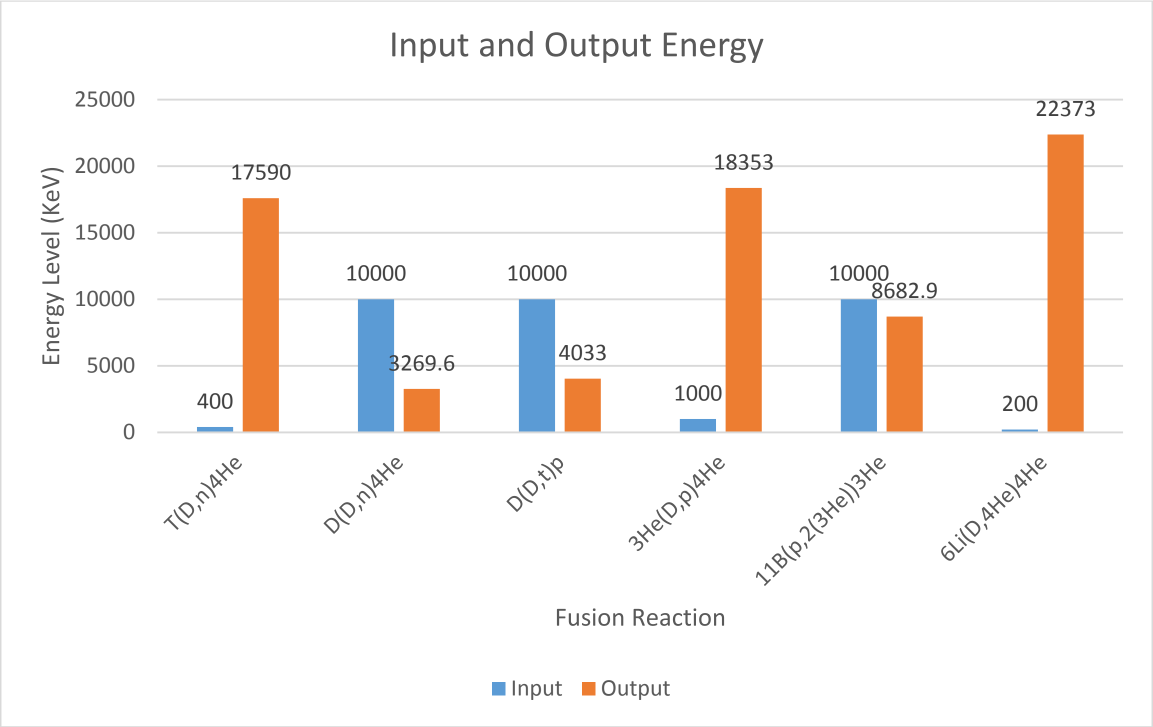

Figure 4: Chart of input and output energy of each fusion reaction in kilo-electronvolts.

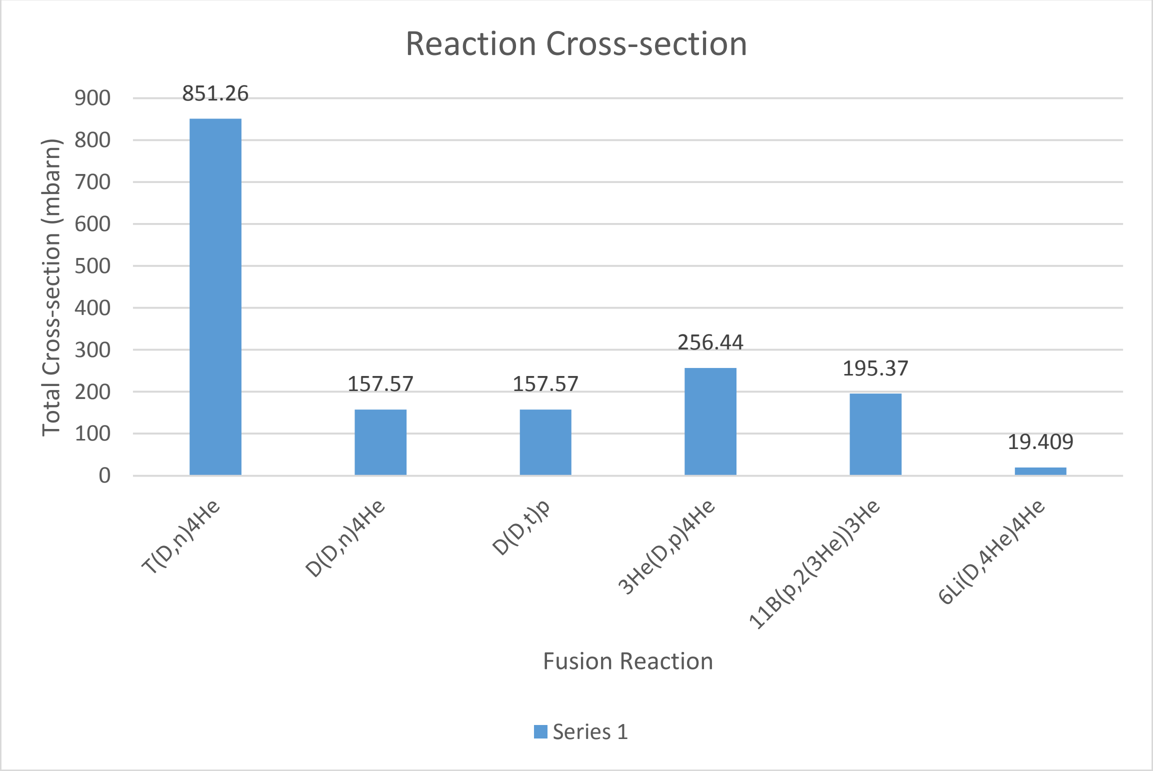

Figure 5: Chart of fusion reaction cross-section.

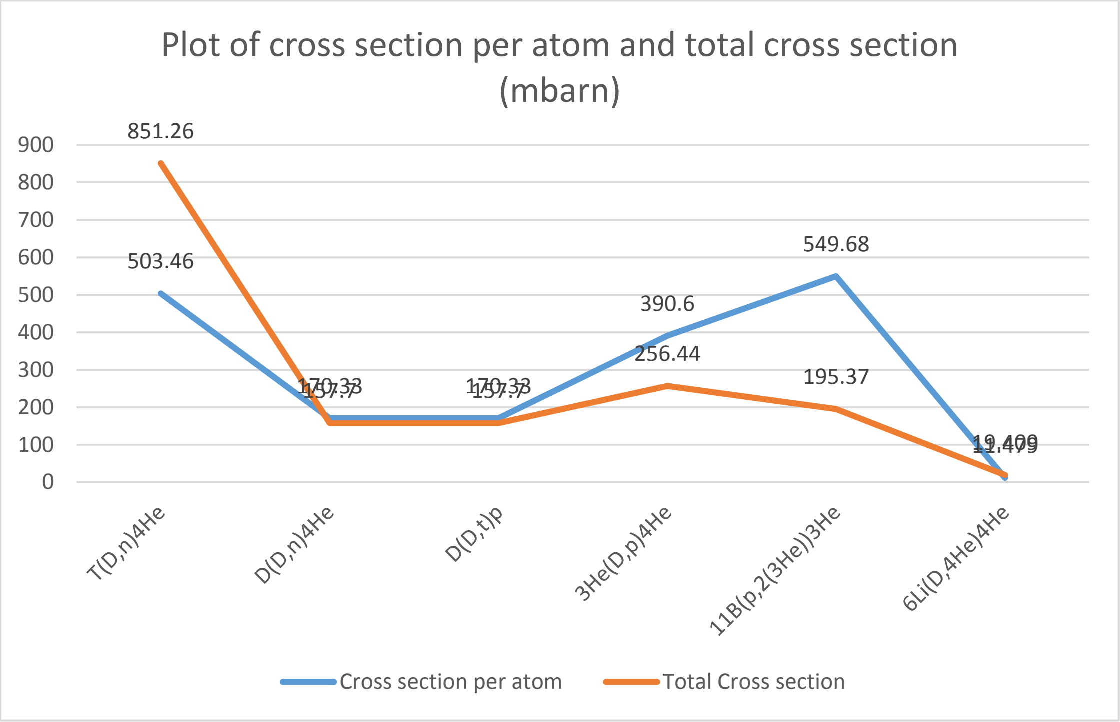

Figure 6: Line chart of the plot of the fusion reaction cross section per atom and total cross section.

Table 11: Comparison with other authors work.

S/N	Fusion Reaction	Author	Gain	Cross section(mbarn)	Input Energy
1	$T(D,n)^4He$	Tahir & Hoffman(1994)	17.60 MeV	-	-
		This work	17.59 MeV	851.26	400 KeV
2	$^6Li(D,^4He)^4He$	Bahmani(2021)	22.3 MeV	-	-
		This work	22.373 MeV	19.409	200 KeV

From table 11, the authors investigations fails to record the minimum input energy for the projection of deuteron isotope to achieve fast ignition of the various fusion reactions and their respective cross sections.

This work made a detailed analysis of fusion reaction equations [i, ii, iii, and iv] in comparison with fusion reaction equation [v] between their input energy, output energy gain, cross sections and types of particles generated after fusion reaction occurs with their respective energy mean, all represented from table (1- 8), with summary of results in table 8 and 9 and charts in figure 3, 4, 5 and 6. The investigation shows the variations in the input ignition energy is due to Coulomb

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force binding the isotopes, which is the dominant mechanism in the slowing down of the projected ion beam. D + T reaction with considerable low ignition energy input of 400 KeV and high total cross section of 851.26 mbarn and output energy gain of 17.59 MeV suitable to be used as thermonuclear fuel in ICF, however it requires large tritium inventory, Tritium is radioactive, decaying with the emission of a soft beta particle, and with a half-life of slightly more than 12 years. It does not occur naturally and therefore must be bred, that is, created artificially and the evacuation of unburnt tritium from the reactor chamber is a difficult task for the operators. The use of intense ion beam is important as a possible way for desirable thermonuclear ignition, we have seen from, D + ^{6}Li reaction simulation results shows a very large energy output gain of 22.373 MeV per event with low input energy of about 200 KeV although with a much smaller total cross section of 19.409 mbarn, it is to be noted that the fusion reaction probability increases by increasing electron temperature. The stopping power of electrons and ions decrease with the increase of temperature. When the energy of deuteron beam is achieved at a few hundred eV, stopping power of the electrons would be more than ions. Nuclear stopping power is considerable at very low deuterons energies. This fusion reaction fast ignition initiated by laser-driven deuteron beam is a promising concept for ICF proposed in this work. This idea can be used to reduce the input energy of the driver as much as possible, which minimizes the required total input beam energy.

5. CONCLUSION

In reducing the cost of electric power and energy efficiency is necessary for the development of a fusion reactor with low neutron production and low radioactive inventory. From the simulation results, with a minimum of about two hundred kilo-electronvolts deuteron beam kinetic energy can be projected to Lithium-6 isotope target enough to overcome the coulomb barrier binding the lithium isotope, then obtain output of 22.373 MeV energy gain as the fusion energy efficiency depends on the electron temperature and deuteron beam initial energy, it can also be established that the D + Li^{6} fusion reaction is pure and safe as it does not generate high number of neutron and tritium, therefore eliminate the need for tritium and is also important for the safety, high efficiency of ICF reactors and operators. The NIF setup of giant lasers is not suitable for power plant reactors, its lasers can only fire about once a day, while a power plant reactor would need to vaporize several fuel pellets every second, therefore efforts are being made to modify the process so that it can be used commercially and achieving lower-powered laser system that could fire much more rapidly. This findings contribute to the core mission of NIF in achieving fast ignition with low ignition energy input to achieve Lawson break-even or "ignition" point of the fusion fuel pellet, where it gives off 100% or more energy than it absorbs.

6. RECOMMENDATION

This findings contribute to the core mission of NIF in achieving fast ignition with low ignition energy input to achieve Lawson break-even or "ignition" point of the fusion fuel pellet, where it gives off 100% or more energy than it absorbs. However the simulation results were based on programmed model of Geant4 Hadr03. This results can be validated with the appropriate experimental design of the Hadr03 process.

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