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Calculation of neutron flux for the intense neutron source (μCF-INS) in optimum conditions

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ABSTRACT

In this study, the neutron spectrum of a high intense neutron source (μCF-INS) based on muon catalyzed fusion was investigated in new conditions. In order to determine optimum conditions for the production of high neutron flux with 14.1 MeV energy our study was grouped into three steps: the first includes the moderation μ^- before entering into fuel mixture, the second is the calculation of neutron intensity produced by μCF cycle in D/T target and the third is simulation of output neutron flux from the device. The muon catalyzed fusion cycles were analyzed according to kinetic equations solved by Rung-Kutta method of the fourth order. Finally, transport of neutrons in DT mixture and its container was simulated by the MCNP4C code to calculate the output neutron intensity. The results show that the intensity of neutron produced by μCF-INS generator is in order of 10^{17} n/s. When this result is compared with those from other neutron generators, μCF-INS generator operating at optimum conditions has a high neutron production yield.

Keywords: neutron generator, muon catalyzed fusion, moderation, neutron flux, μCF-INS

1. Introduction

The reaction between deuterium and tritium is one of the most important nuclear fusion reactions, because it has the lowest Coulomb barrier and the highest cross section:

$$D + T \rightarrow {}^{4}_{2}He + {}^{1}_{0}n + 17.6\ MeV \qquad (1)$$

Besides energy production reasons, it is important as a source of high energy neutrons as well. In this paper, a neutron generator (μCF-INS)[1] [1] based on the muon catalyzed fusion cycle [2-4] was investigated and optimum conditions for producing high neutron flux were determined. For this purpose, all processes during the slowing of muons up to neutron extraction of the generator were considered. Therefore, μCF-INS neutron generator is introduced in Section 2, then moderation of muon is calculated in Section 3; after that, fusion cycle is solved and the extracted neutron flux is simulated in Section 4. Finally, Section 5 presents the conclusions.

2. Neutron generator (μCF-INS)

Neutron generator based on μCF (μCF-INS) has been presented by MUCATEX[2] center [5]. Deuterium beam is produced by an accelerator. This beam with 7.5×10^{16} d/s intensity and the energy of about 2 GeV enters into a liquid lithium target in the generator. This process produces protons, neutrons and pions. Negative pions at 171 MeV and 10^{16} π^-/s current are directed to a D/T fuel mixture located in a spherical titanium container. This spherical container has a radius of 10 cm. Negative pions are surrounded by magnet mirrors located in two ends of generator in the spiral direct [1,5]. Pions decay to negative muons, and muons are directed toward the fuel by the magnet mirrors. In these directions, muons have 40 MeV mean energy with about 10^{15} μ/s intensity. For capturing muon with fuel atoms, it is necessary to stop muons with energies up to 2 keV. Production of muonic atoms starts the muon catalyzed fusion cycle. Many neutrons produced in μCF cycles can be used as high intensity neutron source. To optimize neutron

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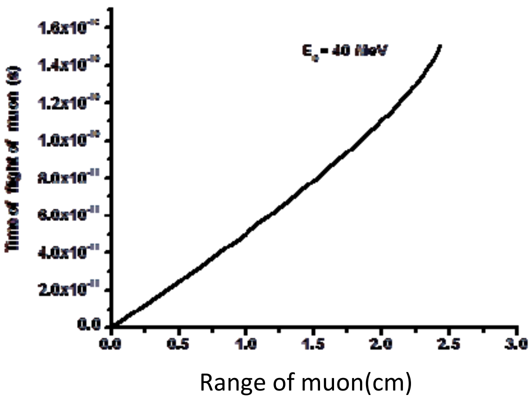

Fig.1 Time of flight with respect to range.

production in the generator, we focused on two main processes: moderation of muons before feeding them in fusion cycle (Section 3) and calculation of the neutron flux in D/T mixture and determination of the output neutron flux of the generator (Section 4).

3. Moderation of negative muon

In this paper, at first, we have obtained the optimum conditions for the moderator in order to reduce muon energy before being captured by the fuel atoms. For this purpose, energy loss of muon per unit length was investigated by ionization and excitation processes. In high energy (E >132 keV), the stopping power of a charged particle is calculated by relativistic Bethe-Bloch equation [6, 7],

$$-\frac{dE}{dx}=\frac{4\pi z^2 e^4 nZ}{m_e v^2}\cdot\left[ln\left(\frac{2m_e c^2\beta^2}{I}\right)-ln(1-\beta^2)-\beta^2-\frac{\delta}{2}-\frac{C(\beta,Z)}{Z}\right], \qquad (2)$$

where I is the excitation potential, n is atomic density, Z is the target atomic number, β= v/c , m_e is the electron mass, $C(\beta,Z)$ and $\frac{\delta}{2}$ are the atomic shell correction and environmental effective density respectively. As there is the lack of a theoretical model in low kinetic energies, experimental curves are used for stopping power of muons [6]. Eq. (2) is employed to calculate the range of muon, which is the distance that muon travels from the initial kinetic energy (E_0) to the final value (E_{tr}). Furthermore, time of flight for muon during this moderation of kinetic energy was calculated.

It should be noted that muons may decay before passing through the moderator. Our calculations show that the time of flight of muon is much lower than muon life time (Fig.1). So the probability of passing through the moderator before the decay of muon is about unity. Thus, almost all muons could arrive into the fuel container ($N_{\mu 0}\approx 10^{15}$ μ^-/s).

Then, the range of muon was calculated in titanium to achieve atomic capture energy by deuterium and tritium. This range was calculated in two steps; first, the required distance (R_1) to reach the final energy (132 keV) starting from the primary energy (40 MeV) was calculated by Bethe-Bloch stopping power (Eq. 2), and then the required distance to achieve energy from 132 keV to 2 keV (R_2) was found. For the last step, we used the experimental stopping power of muons in titanium at low energies [8]. The results of calculations as a function of the muon output energy for the two initial kinetic energies of muon, namely 40 MeV and 132 keV, are presented in Figs 2 and 3.

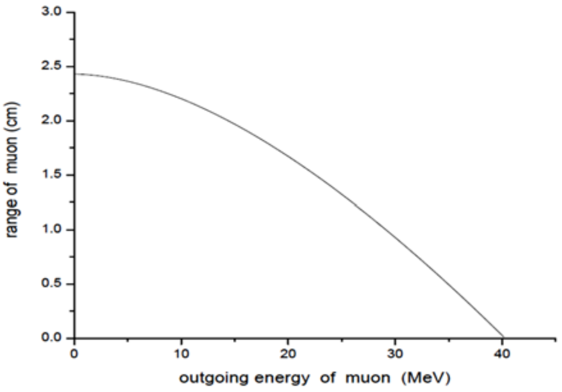

Fig. 2 Muon range in titanium with respect to muon output energy used for decreasing energy from 40 MeV to 132 keV (R_1 = 2.42 cm).

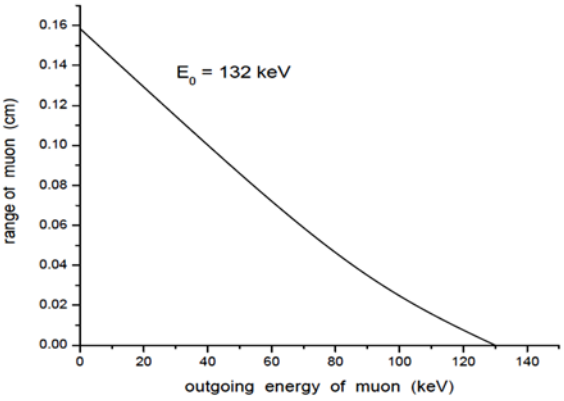

Fig.3 Muon range in titanium with respect to muon output energy used for decreasing energy from 132 keV to 2 keV (R_2 = 0.155 cm).

It can be seen that for stopping muon from 40 MeV to 132 keV energy, R_1= 2.42 cm of titanium thickness is needed. Also, reaching capture muon energy (~ 2 keV) from 132 keV energy, R_2= 0.155 cm is required for the thickness of titanium. Then the lowest thickness of titanium container for fuel D/T was R= 2.575 cm.

4. Calculation of neutron flux

To simulate the neutron production rate in fuel, against reference [1] that used calculations at T=25K temperature, we have re-calculated it at the temperature of 1000 K and at the liquid hydrogen density (LHD). In this temperature, we have the highest fusion rate of μdt molecule [9].

For the chain processes in muon catalyzed fusion, kinematic differential equations are presented, which are solved using the fourth order Runge-Kutta method [10]. The calculations were carried out for different concentrations of deuterium and tritium. It was shown that the maximum fusion yield was 128 per muon, which was achieved at C_t=0.64. Intensity of neutrons was computed according to the following kinematic equation,

$$-\frac{dN_n}{dt} = \lambda_{fdt}N_{\mu dt} + (0.52)\lambda_{fdd}N_{\mu dd}2\lambda_{ftt}N_{\mu tt} \qquad (3)$$

where λ_{fdt}, λ_{fdd} and λ_{ftt}, are nuclear fusion rates in muonic molecules of μdt, μdd and μtt, respectively. $N_{\mu dt}$, $N_{\mu dd}$ and $N_{\mu tt}$ are also number density of the represented molecules. Fig. 4 shows the variation of the neutron intensity versus tritium concentration (C_t). It can be seen that the maximum intensity of neutrons is $I_0 = 9.4 \times 10^{16}$ n/s at $C_t = 0.64$.

The effects of container shape, thickness, material and the kind of fuel on absorption and elastic, inelastic and other processes of neutrons were also investigated to calculate the output flux and the intensity of neutrons from the container. For this purpose MCNP4C Software was used and neutron flux was calculated according to the muon entering location to the fuel. In this simulation, the target was divided in two cells. The first cell was considered as a spherical D/T mixture with the radius of 10 cm and the second cell was regarded as a titanium spherical container with internal and external radii of 10 cm and 12.57 cm, respectively. The neutrons are produced by μCF fusion cycle, because muons entering into the fuel container after crossing the titanium reach to the D/T fuel with low energies, they could start the fusion cycle at the colliding point of the fuel. Thus, the neutron source was considered as a point source with nearly the internal layer of the first cell. Neutrons in the direction of reaching the wall of the container crossed from D/T fuel; accordingly they moved in random paths. So, we did the simulation with use of MCNP4C Software for many different collisions and reactions of the neutrons. The most effective process in the first cell was scattering [11]. As for titanium, we can point to (n,2n), (n,p) and (n,γ) interactions. Among them, particularly (n,2n) interaction produced a brief increase in output neutron flux. Results of neutron flux and neutron intensity in different places of the target are presented in Table 1.

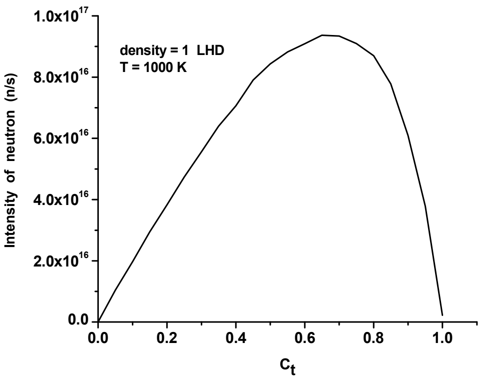

Fig.4 Intensity of neutron versus tritium concentration.

Table 1. Outgoing neutron intensity and flux in different layers of the container.

	Container layers as radius	
	For 10 cm	**For 12.57 cm**
neutron intensity (n/s)	1.25×10^{17}	1.003×10^{17}
neutron flux (n/s/cm^2)	9.9×10^{13}	4.97×10^{13}

Fig. 5 shows the output neutron spectrum from titanium spherical container of the D/T fuel with the radius of 10 cm and the thickness of 2.57 cm.

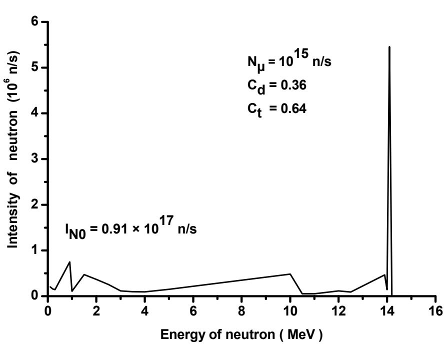

Fig.5 Spectrum of the outgoing neutron intensity from fuel container.

5. Conclusion

The calculations for the μCF-INS neutron generator show that the maximum value of the neutron spectrum is seen at E_n = 14.1 MeV as shown in Fig. 5. The spherical titanium container of D/T fuel with 2.57 cm thickness made a small deviation from the 14.1 MeV single energy of fusion neutrons.

When compared the simulated neutron intensity of μCF-INS in the new condition of D/T fuel at 1000 K with the experimental values of other neutron generators in Table 2, the μCF-INS generator has the highest neutron intensity. Furthermore, the relative efficiency of neutron production, defined as the number of produced neutrons per input ion (I_{out}/I_{in}), is also greater than the other generators.

The other parameter is related to the consumed energy per produced neutron. In μCF-INS generator, deuterium ion with 2 GeV energy is needed to produce muon. However, making such a neutron generators is more difficult than the other generators, though they have better energy efficiency. In other words, for the production of each neutron, lower energy is used than the others. In Table 2, the amount of energy is needed for any produced neutron E_{in}/I_{out} is presented. It is calculated to be 1.5×10^6 keV for μCF-INS which is lower than those the other neutron generators.

The more efficient μCF-INS, comparing with the other neutron generators can be obtained by increasing the fusion yield of 128 neutron per muon in D/T μCF at T= 1000 K. In other words, by producing any D or T ion with 2GeV energy, approximately 128 neutrons were generated based on muon catalyzed fusion.

Table 2. The comparison of different neutron generators in research centers and the present study.

Research centers	**Neutron generator**	**Fusion reaction**	**Ion beam**	**Beam energy (keV)**	**Beam ion intensity (n/s)**	**Neutron intensity (n/s)**	**Energy consumption per produced neutron (keV) (E_{in}/I_{out})**	**The relative efficiency of neutron production (I_{out}/I_{in})**
MUCATEX [5]	μCF-INS (present work)	D + T	D^+	2×10^6	7.5×10^{16}	10^{17}	1.5×10^6	1.33
LBNL [12]	Axial extraction neutron generator	D + D	D^+	100	3.7×10^{17}	10^9	3.7×10^{10}	$2.7 \times 10^{--9}$
		D + T	D^+	100	3.7×10^{17}	10^{11}	3.7×10^8	2.7×10^{-7}
	The coaxial type of neutron generator	D+ D	D^+	100	3.7×10^{17}	10^{10} - 10^{11}	3.7×10^9 3.7×10^8	2.7×10^{-8} 2.7×10^{-7}
	Neutron generator with a point neutron source	D + T	D^+	120	6.0×10^{17}	10^{12}	7.2×10^7	1.6×10^{-6}
		T + T	T^+	120	6.0×10^{17}	10^{10}	7.2×10^9	1.6×10^{-8}
IEA[1] [13]	SNEG-13	D+ T	D^+	300	6.2×10^{18}	10^{13}	1.8×10^8	1.6×10^{-6}
SNL and TEC[2] [14]	API-120[3]	D + T	D^+	95	3.7×10^{13}	5.0×10^7	7.03×10^7	1.3×10^{-6}

[1] Research Institute of Electrophysical Apparatus, Russia.
[2] Sandia National Laboratories and Thermo Electron Corporation, USA.
[3] Associated Particle Imaging, USA.

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