Nuclear Energy Conversion with Stacks of Graphene Nano-capacitors

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Abstract

The efficiency of conventional techniques used to harvest energy in nuclear reactors lies around 35 percent. This limit exists because the nuclear energy is converted to electrical energy via heat engines. We study an alternative approach where the kinetic energy of nuclear reaction products is directly converted into electric energy in a stack of charged capacitors with a gap size of 500 nm and graphene electrodes. Graphene is expected to be chemically and mechanically stable in high radiation environments because it’s tensile strength of 130 GPa is very large, about 100 times larger than most metals. The dielectric strength of such nano-capacitors exceeds 1 GV/m, because avalanching is suppressed at small gap sizes. In a 1 GV/m electric field charged nuclear reaction products, such as 5.6 MeV alpha particles, come to rest in of a stack with 5000 nano capacitors. We show that during the deceleration process more than 90 percent of kinetic energy of charged nuclear reaction products is converted to electric energy and stored as electric energy in the stack. Each stack is 2.5mm thick and produces a high-voltage DC current. A device with a 1 Ci - ²⁴¹Am source is expected to generate 22 mW of electric power.
When the uranium atoms fission, daughter nuclei, typically barium and krypton, are released at a total kinetic energy of 168 MeV [1]. This energy is usually converted into heat as the fission products scatter within the uranium fuel lump and the moderator. The heat is used to drive a steam engine which powers electrical generators. Even under ideal conditions the efficiency of the power plant is limited by the Carnot efficiency of the steam engine and averages around 35% [2, 3], which is much less than the Carnot efficiency for the overall process, because the temperature of the steam is much less than the initial kinetic energy of the nuclear reaction products. The efficiency of nuclear batteries is less than 10%.

In order to increase the efficiency of nuclear-electric energy conversion, the proposed design will capture the kinetic energy of nuclear reaction products before it is dispersed and thermalized. Recently it has been found that the dielectric strength of nano capacitors is in the GV/m - range [4]. Since nuclear reaction products are partially or fully ionized after a nuclear reaction, they can be decelerated in an electric field and increase the charge on a capacitor. The additional charge on the capacitor can be used as an electric power source like alpha-photonic batteries [5].

In this paper we estimate what fraction of the kinetic energy of the charged nuclear reaction products can be directly converted into electrostatic energy. The electric field is created by a stack of nano capacitors. We use a stack of nano capacitors because they have a much larger dielectric strength than conventional capacitors[4], most likely because avalanching is suppressed. The nano capacitor electrodes are proposed to be made of graphene mono layers, because they are electrically conducting, very thin, have an extremely large tensile strength and can withstand large temperatures. Therefore the likelihood that a nuclear reaction product collides with a nucleus in the electrode is small, and if so the radiation damage is small because of the strong carbon bonds. The top and bottom electrodes are graphene multi layers with about 10 layers or a combination of a water moderator and metal neutron reflector, to absorb the charged nuclear reaction products, and to moderate and reflect the neutrons. Graphene multi layers are good thermal conductors and could be used to cool the device.

We assume that the fuel is a thin sheet of thickness \( f \). In the following our numerical calculations we consider a \( f = 1000 \text{nm} \) americium 241 sheet. We assume that the initial kinetic energy \( K \) of each reaction product is above 1\( \text{MeV} \) and its charge is \( Z > 0 \). \(^{241}\text{Am}\) produces 5.6\( \text{MeV} \) alpha particles. For the energy conversion it makes no difference if the
FIG. 1: Sketch of the energy converter. A fuel layer ($^{241}$Am) is sandwiched between two stacks of nano capacitors with graphene electrodes. In the nano capacitors the kinetic energy of charged nuclear reaction products is converted to a high voltage electric current. A power management system maintains a constant voltage between the fuel and the top- and bottom graphene layers.

A nucleus is fully or partially ionized and if it originates from a fission or other nuclear reactions. The average energy loss of the charged nuclear reaction products within the fuel is proportional to the thickness of the thin sheet, i.e.

$$\Delta K_f = \frac{dE}{dx} \cdot \frac{f}{2} \quad (1)$$

where $\frac{dE}{dx}$ is the stopping power. For instance for $K = 5.6 MeV$ alpha particles the stopping power of americium is $\frac{dE}{dx} \approx 240 eV/nm[6]$. In a $f = 1000 nm$ fuel layer, the energy loss for alpha particles with an a kinetic energy of $K = 5.6 MeV$ is $\Delta K_f = 120 keV$, i.e. the particles lose about 2 percent of their energy within the fuel. The heat created by a nuclear reaction product within a fuel sheet of area $A$ is

$$H_f = \Delta K_f \cdot A \cdot f = \frac{dE}{dx} \cdot \frac{f^2}{2} \cdot A \quad (2)$$

Because the heat created in the fuel $H_f$ scales with the square of the thickness of the fuel, it is advantageous to use thin sheets of fuel. The fuel sheet is sandwiched by two stacks of $N$ sheets of graphene mono-layers. The top and bottom sheet are graphene multi layers of width...
a or a more complex conducting layered structure (see Fig. 1). A power management system maintains a constant potential difference between the fuel sheet and the outside layers. The top and bottom layers have three functions: (i) They are the anodes of the device; (ii) stop and absorb the charged nuclear reaction products; and (iii) connect the device to a cooling system. Slightly doped silicon spacers or other radiation hard semiconductor spacers keep the graphene layers apart and maintain a constant the voltage difference $\Delta V$ between adjacent graphene mono layers constant. The gaps between the graphene layers are are evacuated or filled with a low-density, non-reactive gas. The resistance of the spacers $R$ is assumed to be large compared to the resistance of the battery load. The distance between the graphene layers is $d = 500\, nm$. The graphene layers form a stack of nano capacitors. The potential difference between the outside layers and the fuel is $V = N \cdot \Delta V$. Because the layers of graphene divide the space between the fuel and outside electrodes into small compartments, avalanching is supressed and the electric field in the vacuum gaps and the silicon spacers can be as large as $E = \frac{V}{Nd} = 1V/nm$ [4]. The charged nuclei are decelerated in the electric field between the graphene sheets and finally thermalized and neutralized in the top and bottom graphene sheets. When the nuclei pass through the capacitors, collisions with the carbon atoms in the graphene sheets convert some of their kinetic energy to heat

$$\Delta K_g = \frac{dE}{dx} \cdot g$$

where $\frac{dE}{dx}$ is the stopping power of graphene and $g = 0.34nm$ [8] is the thickness of single sheets of graphene. The stopping power depends on the kinetic energy of the particle. For example, the stopping power of graphite for high-energy alpha particles (5.6$MeV$) and low-energy alpha particles (20$keV$) is $\frac{dE}{dx} = 150eV/nm$, whereas the stopping power of graphite of medium-energy alpha particles (600$keV$) is about $\frac{dE}{dx} = 440eV/nm$ [6]. If we use a medium value of $\frac{dE}{dx} = 300eV/nm$ to estimate the energy loss in graphene mono layers, we find $\Delta K_g \approx 100eV$ at 5.6$MeV$. The amount of electrostatic energy converted to heat in each capacitor is

$$\Delta K_e = d \cdot E \cdot Z = 1keV$$

for alpha particles. The fraction of energy which is stored as electrostatic energy is

$$\epsilon = \frac{\Delta K_e}{\Delta K_e + \Delta K_g} = \frac{d \cdot E \cdot Z}{d \cdot E \cdot Z + \frac{dE}{dx} \cdot g} > 90\%$$

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for alpha particles. Therefore we expect the average value for $\epsilon$ above 90%. A charged nuclear reaction product loses its kinetic energy after passing through $N$ nano capacitors, where

$$N = \frac{K}{\Delta K_e + \Delta K_g}$$

(6)

For $K = 5.6MeV$ alpha particles the value is $N \approx 5000$. This suggests a design with a stack $N = 5000$ nano capacitors on each side of the fuel layer. The potential difference between the fuel sheet and the top layer is

$$V = N \cdot E \cdot d$$

(7)

$5.6MeV$ alpha particles would create a $2.5MV$ DC current. The magnitude of current created by the ions is

$$I = S \cdot e \cdot f \cdot A \cdot Z$$

(8)

where $A$ is the area of the fuel layer and $S$ is the specific activity of the fuel, i.e. the number of decays within a volume $v$ and a time span $\Delta t$. For a 1 Curie $^{241}Am$ source the current is $I = 12nA$ and the electric power is $P = 30mW$.

Different designs might have a much larger $\epsilon$-value. For instance, it might be possible to increase the gap size $d$ without decreasing the dielectric strength $E$ significantly. Then the number of graphene sheets $N$ can be reduced and the conversion efficiency $\epsilon$ would increase. A cylindrical geometry where the anode is a carbon nano tube could sustain much larger electric fields, because anode work functions are much larger than cathode work functions.

A device with a $^{242m}Am$ could have a much larger specific activity and therefore a much larger power rating. Because of the high neutron cross section $^{242m}Am$ and because of low neutron self-absorption in thin foils a chain reaction seems possible in micrometer-thick americium foils and other fissable materials [9]. The critical mass for $^{242m}Am$ is speculated to be only 20 grams [10]. The graphene multilayer electrodes could function as radiation-hard neutron moderators and reflectors.

The kinetic energy of the neutrons could be harvested with a 2-step process. (1) A layer of paraffin or proton-rich plastic outside the top and bottom layers is used to transfer kinetic energy from neutrons to protons with a neutron recoil reaction [11]. This transfer is efficient because neutrons and protons have roughly the same mass. (2) Protons are decelerated in a second stack of nano-capacitors similar to the other charged nuclear reaction products.


