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Simulation of Fusion Evaporation of Compound Nuclei Created in Ultra Intense Laser Interaction with Carbon Targets

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Abstract:- *Compound nucleus creation in Ultra Intense Laser UIL interaction with materials could be possible through Fusion-of the target nuclei with the accelerated charged ions in the laser field. The residual radioactive nuclei in the remaining target material could well be due to evaporation of protons, neutrons, deuterons etc. from the created compound nucleus.*
We here report simulation of compound nucleus formation followed by particle evaporation applying Monte Carlo code PACE-4 to estimate the possible Fusion cross-section for carbon nuclei C^{12}+ C^{12} forming excited Mg^{24} compound nucleus. The results indicated the highest cross section of 48.0± 0.5 mb of such possibility, peaking at carbon ions projectile energy = 30± 10 MeV (2.50± 0.83 MeV/ A).
The cross sections for production of neutron deficient nuclei resulting from the Fusion-Evaporation process of C^{12} + C^{12} are also estimated. The estimated cross-section for Na^{22} ($\tau = 2.6\ y$) and O^{15} ($\tau = 2.034\ min$) positron emitters provided values of 100±1.5 and 76± 1.3 mb at carbon ion energies of 60.0±5.0 MeV (5.0±0.41 MeV/A) and 86± 20 MeV (7.17± 1.7 MeV/ A) respectively. The reactions leading to these positron emitters are C^{12}(C^{12}+ d) Na^{22} and C^{12} (C^{12}+2 α + n) O^{15}
The simulation results help greatly in choosing the UIL as well as the design of the experimental set up to be applied in verifying the Fusion-Evaporation Phenomena.

Keywords:– *Simulation by PACE-4, Ultra Intense Laser, fusion- evaporation, positron emitters***.**

I. INTRODUCTION

In the process of the interaction of Ultra Intense Laser UIL beams with carbon targets, it was proved to efficiently bunch accelerated carbon ions [1,2]. The efficient Radiation Pressure Acceleration (RPA) mechanism [3, 4, 5,6] for laser-based ion acceleration, could explain theproduction of bunches of solid state density through the hole-boring mode [7]. Allowing such dense bunches of carbon ions to impinge on a second thicker carbon target would easily result in fusion of the carbon nuclei, resulting in highly excited fused nuclei. Such fused species would soon disintegrate by evaporating light particles or by fission into relatively heavy fragments. In this scenario the first target could well be carbon rich polyethylene foil of thickness less than 500 μm and would be considered the source of the accelerated carbon ions. The second thick carbon target could be considered as both the fusion and the fission evaporant target. This second target would be expected to contain neutron deficient lighter isotopes.

In the following we propose to estimate the possibility of producing important positron emitters such as Na^{22} and O^{15} in the second carbon target. Simulation of fusion, followed by particle evaporation, is elaborated applying Mont Carlo code PACE-4 [8]. In this Contest a planned experiment will be briefly introduced, where the production of such nuclei and the experiment to measure their properties will be elaborated.

II. RADIATION PRESSURE ACCELERATION (RPA)

In the following a new reaction process will be introduced, we shall try to apply the recently reported Radiation Pressure Acceleration RPA mechanism for ion acceleration. It was first theoretically reported in the year 2008 [9, 10] followed by experimental verification [11, 12, 13] during 2009.
It has been shown that RPA operates in two ways:

1) Hole-Boring HB mode: in which the laser beam interact with targets thick enough to allow the front target material to be driven ahead of it without interacting with the rear surface of the target. [6]
2) Light Sail LS mode: which happens if the target is thin enough allowing the laser pulsed beam to punch through the target and accelerate part of the plasma as a single object [14, 15]

In the RPA mechanism in general one can expect to attain quasi-monoenergetic ion beams. The electrons are compressed to a dens sheet in front of the laser pulse, which then through the initiated Coulomb field attracts and accelerates the target ions. This mechanism allows to produce ion bunches with solid-state density(10^{22}- 10^{23} / cm^3), which are much more dense than ion beams produced in accelerators. The areal densities of laser produced ion bunches are approximately 10^7timeslarger than in conventional accelerator beams.
It is possible to estimate the required laser intensitiesper cm^2 using the 1-D RPA model given in reference [7]. The total number of target ions $\mathbf{N_i}$, that can be accelerated could be calculated from the equation

$$\mathbf{Ni} = \chi W_L / \mathbf{E_i}$$

Where $W_L$is the energy of the laser beam pulse

χ is the conversion efficiency of the laser energy to ion energy

And is equal to $2\sqrt{\mathbf{I_L}/m_i\, n_i\, c^3}/(1 + 2\sqrt{\mathbf{I_L}/m_i\, n_i\, c^3})$

In the non-relativistic limit the achievable ion energy

$$\mathbf{E_i} = 2m_ic^2\,(\mathbf{I_L}/m_i\, n_i\, c^3)$$

where $n_i$being the the ion density
m_i being the ion mass
$\mathbf{I_L}$being the the laser intensity
c is the vacuum speed of light

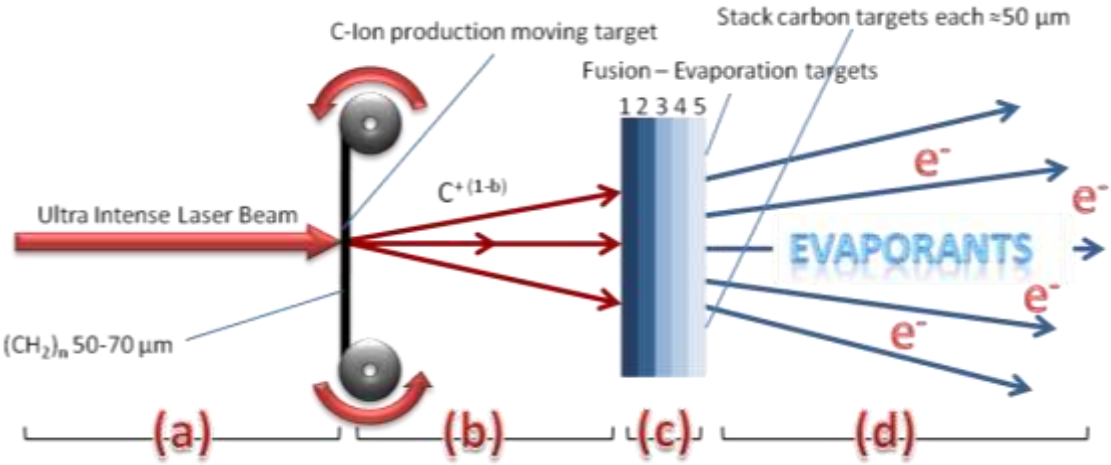
This mechanism requires thin target and ultra- high contrast laser pulses to avoid the preheating and expansion of the target before the interaction with the main UIL beam.
Efficient Carbon ion generation were reported [16] when using diamond like carbon targets of thickness app. 200 nm using UIL of 80 J and 550 fs pulse duration at wavelength 1054 nm providing up to 5x $10^{11}C^{+6}$ions with peak energies between 33 and 700 MeV.

III. PROPOSEDGEOMETRICAL TARGET ARRANGMENT

The experimental set upshould enable the possibility of achieving laser produced carbon ions followed by the fusion of such ions with the C^{12} nuclei in the solid carbon films as well as gaurantee the recognition of the expected evaporation process. In all these expected three processes the targets should be choosen of such thickness to allow the production of :

1- Laser induced Carbon ions from the moving polyethylen or diamond like Carbon target.
2- Permitting the Carbon ions only to proceed towards stacked Carbon foils
3- Stacked carbon targets to recognize where does Fusion Occure and the following Evaporation starts providing the final nuetron defficient isotopes
4- Let go the evaporants as well as the electron sheath

Fig.1 schematically represents the proposed suitable arrangement. The 10 Hz Ultra Intense Laser beam is allowed to be focused on the moving polyethylene target in region (a) under vacuum. The $(CH_2)_n$ moving sheet of thickness between 5 – 7μm is moved by two rollers and at the same time does not allowthe laser beam to pass to region (b).



(Fig. 1) Schematic representation of the target arrangement for fusion – evaporation reaction process representing the following: (a) Focused UIL Pulse 10 Hz Laser Beam. (b) C^{n+} ion production moving poly ethylene targets of thickness ≈ 5-7 µm. (c) Five layers carbon stack targets each≈5µm(d) Evaporants from (C^{12}+C^{12}) fusion reaction the arrows represent the evaporants and the fast e^- leaving the targets.

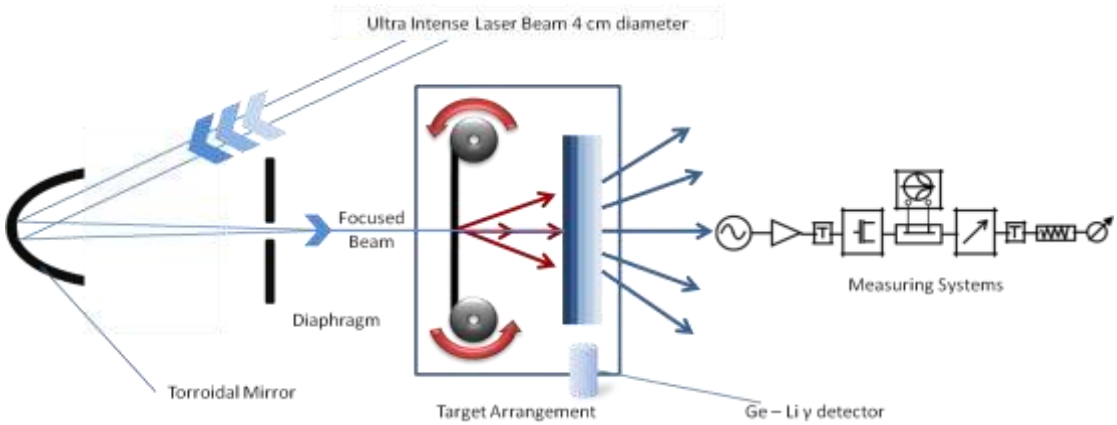
The formed carbon ions accelerated by the RPA process in region (b), interact with the stacked carbon foils forming the Fusion Process as well as the Evaporation following processes into each of the stacked layers in regions (c). It is expected thatthe resultant neutron deficient final nuclei remain in each of the stacked target layers, while the evaporant particles and electrons would proceed behind.

Most important is to choose the experimental measuring equipments to recognize the reaction products either in region (c) or the region (d).

Since the Fusion- Evaporation nuclei implanted in the different solid film stacked carbon targets are expected to be positron emitters of lifetime more than 2 minutes, one may characterize them by high resolution well shielded germanium-lithium gamma spectrometer [17, 18], that could be placed in region (c) as clear in fig.2 by looking for the 0.51 MeV β^+ gamma annihilation line. The stacked targets could be transferred to an outer region with shielded detectors, where each target from the stack can be characterized separately.

Fig. 2 schematically represents the traditional different methods that could be utilized in region (a) to focus the Ultra Intense Laser beam using torroidal gold mirror. The vacuum target Chamber comprising both the regions (b), and (c) is shown in fig.1. that represents the carbon ion formation target and the Fusion- Evaporation reaction region. However the evaporants in region (d) from the different reactions varying in mass and in velocities require different separation schemes.The measuring equipments conventionally used are summarized in recoil separators, and coarse magnetic dipole pre-separators or coarse magnetic dipole pre-separator like the multi-reflection time of flight mass spectrometer [19].

We suggest in our experiment to stick to investigate the regions (a), (b) and (c) and to concentrate on the further possible methods to separate the formed positron emitters from each of the stacked carbon targets.



(Fig. 2) Schematic arrangement of the experimental set up. During the experiment the stacked carbon target should be diagnosed for 0.51 γ ray produced by the annihilation of the B^{+}emitted from the formed isotopes in each layer. The measuring system will record the evaporant particles and determine their properties, electron detectors could be added.

IV. RESULTS

Recently the demand for positron emitting short- lived isotopes has increased significantly as a result of the growing use of the medical imaging technology, Positron Emission Tomography-Computerized Tomography PET-CT [20],at hospitals worldwide for cancer diagnostics as well as in neurology, cardiology and physiology. They are of course also important in controlled nuclear reactions, fusion processes as well as new communication technologies**.**We therefore speculated the possibility of producing radioactive β^{+} emitters by UIL interaction with thin films of carbon.Simulation of Fusion- Evaporation reaction was adopted using the statistical model formalism of nuclear reactions, in which the cross-section of formation of the residual nucleus could be estimated as a function of projectile energy irrespective of how the incident projectile was produced. This was applied to the reaction of the UIL produced accelerated C^{12} ions with theC^{12}nuclei ofthe stacked carbon targets using the above proposed experimental set up. The Projection Angular-momentum Coupled Evaporation PACE4 program [8] was used to numerically estimate the cross section of fusion to form Mg ^{24} as well as for Fusion-Evaporation reactions producing the residual positron emitting nuclei, Na^{22} and O^{15}.

The cross section for the formation of the compound nucleus $Mg^{24}$was found to reach a maximum value of 48.0± 0.5 mb, peaking at carbon ions projectile energy = 30± 10 MeV (2.50± 0.83 MeV/ A) as clear from fig.3

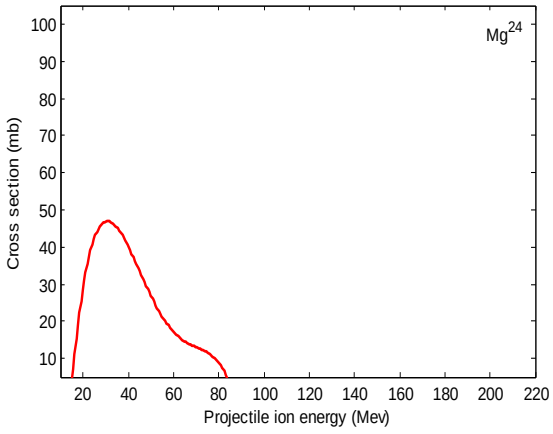


Fig.3: Cross section for the production of Mg24 calculated by PACE-4 evaporation code.

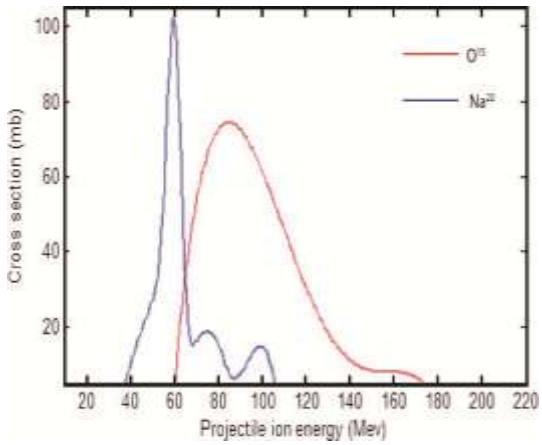


Fig.4: Cross section for the production of Na^{22} & O^{15} calculated by PACE-4 evaporation code.

The formation cross sections for the β^{+}radioactive nuclei, resulting from the Fusion-Evaporation processof C^{12} + C^{12} are shown in fig.4. The estimated cross-section for Na^{22} ($\tau = 2.6$ y) and O^{15} ($\tau = 2.034$ min) positron emitters show max.values of 100± 1.5 mb and 76± 1.3 mb at carbon ion energies of 60.0±5.0 MeV (5.0± 0.41 MeV/A) and 86± 20 MeV (7.17± 1.7 MeV/ A) respectively. The Evaporation of deuterons by the Fusion nucleus Mg ^{24} leads to the positron emitter Na^{22}through the reaction C^{12}(C^{12}+ d) Na^{22}. The Evaporation of Alpha particles and neutrons through the reactionC^{12} (C^{12}+2 α + n) O^{15} immediately after fusion produce the positron emitter O^{15} is naturally expected at higher incident energy of the projectile C ^{12} ion as verified in fig.4.

V. CONCLUSION

Theβ^{+} radioisotopesare nowadays produced by bombarding suitable targets with fast ions from particle accelerators usually cyclotrons with their huge known highly demanding technologies. In our present experimental proposal using UIL to produce positron radioisotopes one would achieve a new technology to prepare such nuclei. Our results ofthe simulation of the Fusion-Evaporation process in the present work points to promising way of the preparation process. It could be easily established as reasonable compact laboratory at hospitals instead of the huge cyclotrons already

existing at the university hospitals eg.7 cyclotronsin Denmark.One may conclude that it is worthy to verify the proposed experiment using Ultra Intense Laser interaction with C^{12} to prepare $Na^{22}(\tau = 2.6\ y)$, $F^{18}(\tau = 110\ min.)$ and $O^{15}(\tau = 2\ min.)$positron emitting radioisotopes, having important scientific and medical applications especially in PET-CT medical imaging technology.

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