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Physics

Fusion and Fission of Rare Radioactive Isotopes by Laser Driven Ions

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(Presented by Academy Member Nodar Tsintsadze)

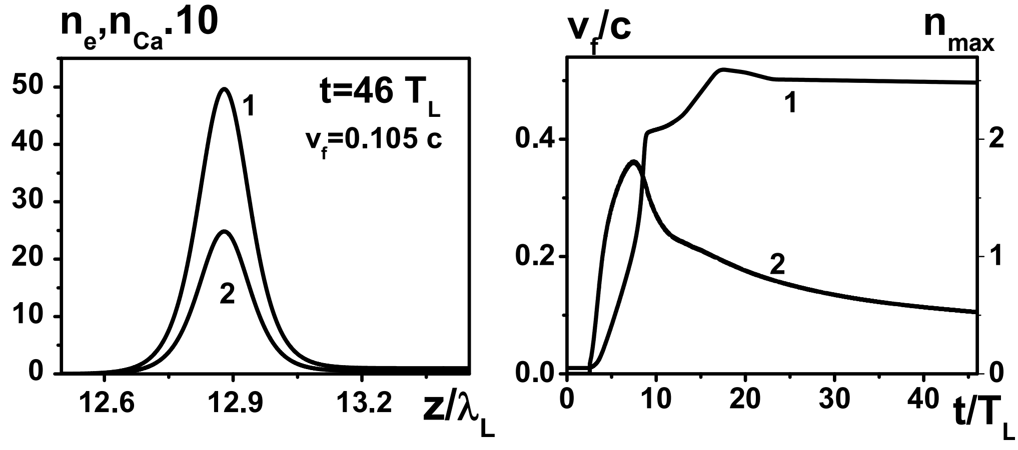
ABSTRACT. The dynamics of overdense ion bunches created by ultra-intense femtosecond laser pulses is studied in order to use them for the fusion of rare isotopes. It is possible to use them for creation of superheavy elements as well as for fission of radioactive nuclei. *© 2012 Bull. Georg. Natl. Acad. Sci.*

Key words: *ion acceleration, laser-driven, nuclear fusion.*

Development of compact laser systems in recent years enabled generation of femtosecond pulses of $10^{22}\div10^{23}$ W/cm^2 intensities. Acceleration of ions up to relativistic velocities by the pressure of such pulses is considered as one of the most important use of these lasers [1-4]. Bunches of light ions obtained in this way can be accelerated up to very high (v~0.4÷0.8c) velocities. As opposed to the traditional accelerators, the time (t~10÷20 T_L where T_L is the period of the laser irradiation and is of femtosecond scale) and distance (l~10÷15λ_L, where T_L is the wavelength of the laser radiation and is of micron scale) for the acceleration in this case are very short. In addition, concentrations of bunches obtained in such way are much more than that in the ion fluxes generated in traditional accelerators. The incidence of ultraintense circularly polarized pulses on a thin solid foil compressed in advance at cryogenic temperatures ($n_{i0}\sim0.2\div4\cdot10^{23}$ cm^{-3}), leads to its further compression to very high concentrations ($n_i\sim10^{25}$ cm^{-3}). The dimensions of these few GeV ion bunches are very small ($a_\perp\sim20\div50\,\lambda_L$, $a_\parallel\sim\lambda_L$). The field of use of such bunches can be quite wide including creation of femtosecond sources of energetic neutrons, generation of fast ignition in laser confined fusion, proton imaging and oncology, formatting “flying” mirrors for generation monochromatic terahertz and x-rays generation, rare isotopes production and heavy ion collider [5-12].

In this work, the accelerating of bunches of different nuclei to the optimal energies for the fusion of expensive isotopes and decay of radioactive nuclei are considered. Possible application of laser-driven relativistic ion bunches for such purposes was mentioned in one of the pioneering works dedicated to acceleration of ions in this way [1].

The advantage of ion acceleration using pressure of laser radiation is well seen at obtaining superheavy



a) b)

Fig. 1. Acceleration and contraction of Ca^{48} plasma foil (thickness – $10\lambda_L$, n_e=$18.6^2 n_{cr}$) by ultraintensive supergaussian (m=4) laser radiation (amplitude – 300, pulse duration – $4T_L$).

a) Concentrations of Ca^{48} isotope electrons (1) and ions (2) at t=$46T_L$;

b) Time dependences of Ca^{48} ions concentration maximum – $n_{\max}$(1) and its velocity – v_f/c (2).

(Z>100) unstable elements. For fusion of such nuclei, thin foils of Pu^{242}, Pu^{244}, Am^{248}, Cm^{245}, Cm^{248}, Cf^{249}, Bk^{249} were radiated for 70 days by $7\cdot 10^{12}$ s^{-1} flux of Ca^{48} [13-14]. The results of these experiments show that the number of generated superheavy nuclei is too small (for instance, only five Z=117 nuclei were observed after Bk^{249}+Ca^{48} reactions). This was caused by both low cross-section of the reactions (σ~1.3 ÷1.5 pb), and low concentration of the accelerated calcium ions. We have shown that better results can be expected at irradiation of thin foils (l_{Bk}~20μm) made of Ca^{48} with n_{i0}=$1.9 \cdot 10^{22}$ cm^{-3} concentration by ultraintense (e/mc^2, A_0=300) Nd (λ_L=1.06 μm) short (t_L~10 T_L) circularly polarized narrow ($a_\perp$~$40\lambda_L$) pulses. In this case, formation of 252 MeV overdense n_i=$0.95 \cdot 10^{25}$ cm^{-3} bunch will take place (Fig.1) and the number of events of generation of superheavy nuclei at its interaction with thin ($10\,\lambda_L$) Bk^{249} foil exceeds one.

$$N_R = n_R a_\perp^2 l_{Bk} = n_{Bk} a_\perp^2 l_{Bk} \int n_i \sigma v_i dt > 1 .$$

Obtaining of heavy nuclei in this way is not only much quicker, but also requires much less energy as well.

At the above evaluations, we used the experimental values of the nuclear reaction cross sections, which were obtained at colliding of charged nuclei of much less densities in traditional colliders. Our opinion is that it should be increased at collision of high concentration electrically neutral bunches, where the ions are enveloped by electronic coatings. Importance of such experiments is even greater as there is no information about the probability of many nuclear reactions due to the duration and expensiveness of the experiments needed for obtaining such information. Compact, fast and inexpensive mechanism of obtaining dense energetic ions accelerated by laser irradiation allows one to provide numerous experiments for establishing the cross sections of quite a wide spectrum of nuclear reactions. First of all, the probabilities of obtaining expensive and rare elements need to be defined and in some cases adjusted. The method of fusion is not in fact used currently for obtaining rare isotopes. Usually they are obtained in centrifuges by separation from the isotopes with similar atomic numbers. Often this is a rather time and energy consuming way, especially in the cases of heavy elements, which conditions their high prices. On the other hand, this was still more cost-effective than in nuclear fusion in traditional accelerators. Nuclear fusion by laser-operated relativistic ion bunches might be more convenient as well as more cost-effective. By the same token, in many cases, there is a possibility of chemical separation of heavy

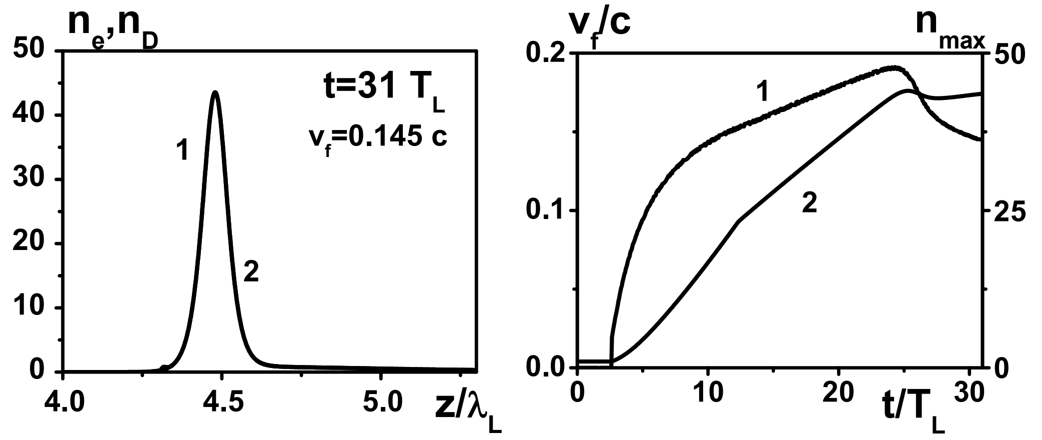


Fig. 2. Acceleration and contraction of deuterium plasma foil (thickness – $5\lambda_L$, n_e=18^2n$_{cr}$) by ultraintensive supergaussian (m=20) laser radiation (amplitude – 60, pulse duration – $10T_L$).

a) Concentrations of deuterium electrons (1) and ions (2) at t=$31T_L$;

b) Time dependences of deuterium ions concentration maximum – n_{max} (1) and its velocity – v_f/c (2).

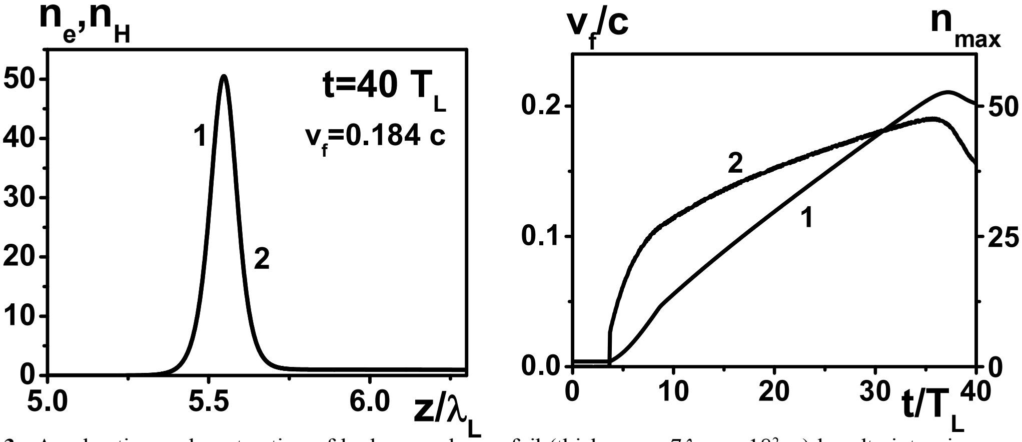


Fig. 3. Acceleration and contraction of hydrogen plasma foil (thickness – $7\lambda_L$, n_e=18^2n$_{cr}$) by ultraintensive supergaussian (m=20) laser radiation (amplitude – 30, pulse duration – $30T_L$).

a) Concentrations of hydrogen electrons (1) and ions (2) at t=$40T_L$;

b) Time dependences of hydrogen ions concentration maximum – n_{max} (1) and its velocity – v_f/c (2).

nuclei obtained in such way from the others. As an example, we can consider the fusion of Os^{187} the most expensive isotope. If we bomb a thin (l_{Re}~20 μm) foil of Re^{187} by overdense (n_i=1.8 ·10^{25} cm^{-3}) bunch of deuterium that was accelerated to v_i~0.145c velocities by irradiation of 0.5 ·10^{22} W/cm^2 intensity (Fig.2) and t_L~$14T_L$ duration (at these energies, the local maximum of the cross section is ~0.25b (Interpreted ENDF file “RE-187(D,2N)OS-187,SIG MAT=7531 MF=3 MT=16 Library: TENDL-2009), about 1% of it will be transferred in Os^{187}. If the width of the pulses is $40\lambda_1$, then the fusion of 1g Os^{187} would require about ten million pulses. The cost of Os^{187} produced in this way, will be much less than its current market price.

Similarly, at collision of deuterium and hydrogen nuclei with Np^{237}, there occur Pu^{238} and Pu^{236} fusion reactions. The cross sections are relatively high and reach 275 mb and 200 mb respectively, when the deuterium energy is 16.5 MeV, and that of hydrogen is 12.5 MeV (Fig.3) [15]. By adjusting the parameters of the pulses and foils, it is possible to create bunches which, after interaction with 10 μm Np^{237} target, will lead to transformation of about 2% of its nuclei to

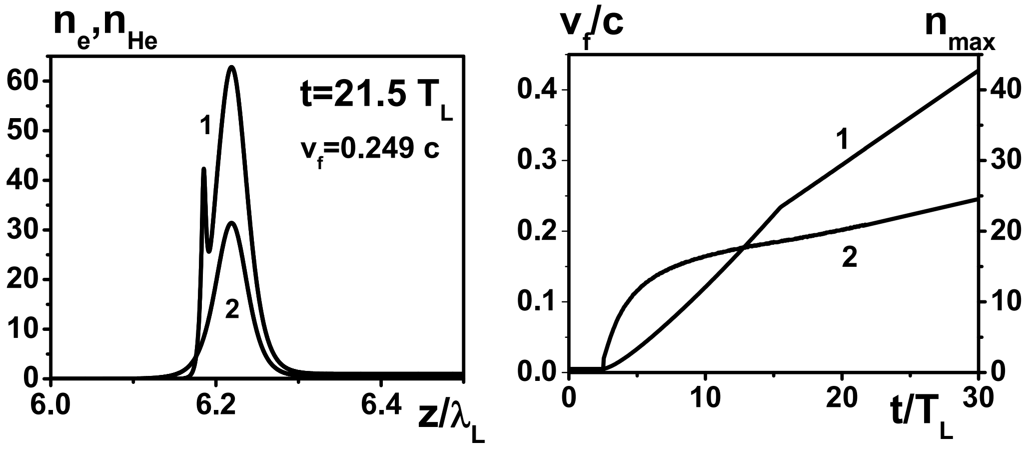


Fig. 4. Acceleration and contraction of He^4 plasma foil (thickness – $5\lambda_L$, $n_e=18^2n_{cr}$) by ultraintensive supergaussian (m=20) laser radiation (amplitude – 85, pulse duration – $22T_L$).

a) Concentrations of He^4 isotope electrons (line 1) and ions (line 2) at t=21.5T_L;

b) Time dependences of He^4 ions concentration maximum – n_{max} (1) and their velocity – v_f/c (2).

plutonium.

Laser-driven ion bunches can be used also for decay of radioactive nuclei to neutralize them. This would allow security against radioactive dust. With this regard, let us first of all discuss the process of U^{235} and U^{238} decay to inactive nuclei. The cross-section of U^{235} decay reactions goes up to 2.7b at their interaction with α particles of 100 MeV energy, and up to 1.2b at their collision with protons of 100÷1000 MeV energy. Effective decay of U^{238} occurs at bombardment with 103 MeV energy α particles (σ=3.2b) [16]. We have found the conditions (Fig.4) when generation of superdense bunches of sufficient energies takes place. One such process leads to decay of 4÷5% of target nuclei.

As was shown in the above studies, at interaction of laser-driven overdense bunches with the target, effective nuclear reactions take place and the colliders based on such process can be used successfully for investigation of nuclear occurrences as well as for production of rare isotopes.

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ფიზიკა

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ი. ჯავახიშვილის სახ. თბილისის სახელმწიფო უნივერსიტეტის ე. ანდრონიკაშვილის ფიზიკის ინსტიტუტი

(წარმოდგენილია აკადემიის წევრის ნ. ცინცაძის მიერ)

შესწავლილია ულტრაინტენსიური ლაზერული გამოსხივების წნევის მოქმედებით ზემკვრივი პლაზმის იონების იშვიათი იზოტოპების მიღებისთვის საჭირო ოპტიმალურ ენერგიებამდე აჩქარების დინამიკა. ამ მეთოდით ზემძიმე ელემენტების სინთეზი მიიღწევა ბევრად უფრო მცირე დროში, ვიდრე ტრადიციულ ამაჩქარებლებში. რელატივისტური ზემკვრივი იონების გამოყენება შეიძლება რადიაქტიური ბირთვების დაშლისთვისაც.

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