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Fission-Fusion: A new reaction mechanism for nuclear astrophysics based on laser-ion acceleration

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Abstract. We propose to produce neutron-rich nuclei in the range of the astrophysical *r*-process around the waiting point $N = 126$ by fissioning a dense laser-accelerated thorium ion bunch in a thorium target (covered by a CH_2 layer), where the light fission fragments of the beam fuse with the light fission fragments of the target. Via the 'hole-boring' mode of laser Radiation Pressure Acceleration using a high-intensity, short pulse laser, very efficiently bunches of ^{232}Th with solid-state density can be generated from a Th target and a deuterated CD_2 foil, both forming the production target assembly. Laser-accelerated Th ions with about 7 MeV/u will pass through a thin CH_2 layer placed in front of a thicker second Th foil (both forming the reaction target) closely behind the production target and disintegrate into light and heavy fission fragments. In addition, light ions (d,C) from the CD_2 layer of the production target will be accelerated as well, inducing the fission process of ^{232}Th also in the second Th layer. The laser-accelerated ion bunches with solid-state density, which are about 10^{14} times more dense than classically accelerated ion bunches, allow for a high probability that generated fission products can fuse again. The high ion beam density may lead to a strong collective modification of the stopping power, leading to significant range and thus yield enhancement. Using a high-intensity laser as envisaged for the ELI-Nuclear Physics project in Bucharest (ELI-NP), order-of-magnitude estimates promise a fusion yield of about 10^3 ions per laser pulse in the mass range of $A = 180 - 190$, thus enabling to approach the *r*-process waiting point at N=126.

Keywords: laser-particle acceleration, high-power lasers, fusion reactions, nuclear astrophysics, r process
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INTRODUCTION

Heavy elements in the universe are produced via the rapid neutron capture process (*r*-process) in an intense neutron flux [1] at astrophysical sites like merging neutron star binaries or supernova explosions. We aim at improving our understanding of these nuclear processes by measuring the properties of heavy nuclei on (or near) the *r*-process path, particularly in the vicinity of the third peak of the elemental abundance distribution around $A = 180 - 200$, corresponding to the waiting point at N=126. The *r*-process path exhibits characteristic vertical regions for constant magic neutron numbers of 50, 82 and 126, where the *r*-process is slowed down due to low neutron capture cross sections when going beyond the magic neutron numbers. These bottlenecks of the *r*-process flow are the 'waiting points' [2]. Since so far nothing is known around the waiting point at N=126 (being up to 15 neutrons apart from the last known nuclide), measurements

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of nuclear properties like nuclear masses or lifetimes may help to clarify the sites of the r-process, which is still under debate. The waiting point at N=126 represents the bottleneck for the nucleosynthesis of heavy elements up to the actinides. It is the last region, where the r-process path gets close to the valley of stability and thus can be studied with the new isotopic production scheme discussed below. If we improve our experimental understanding of waiting point, many new visions open up: (i) For many mass formulas (e.g. [3]), there is a branch of the r-process leading to extremely long-lived superheavy elements beyond Z=110 with lifetimes of about 10^9 years. If these predictions could be made more accurate, a search for these superheavy elements in nature would become more promising. (ii) At present the prediction for the formation of uranium and thorium elements in the r-process is rather difficult, because there are no nearby magic numbers and those nuclei are formed during a fast passage of the nuclidic area between shells. Such predictions could be improved, if the bottleneck of actinide formation would be more reliably known. (iii) Also the question could be clarified if fission fragments are recycled in repeated r-process loops or if only a small fraction is reprocessed.

THE FISSION-FUSION REACTION PROCESS

In our proposal of a new nuclear reaction scenario (described in more detail in [4]), we envisage to exploit the new Radiation Pressure Acceleration (RPA) mechanism for ion acceleration with circular polarized laser light as first proposed theoretically [5, 6, 7, 8], holding promise of quasi-monoenergetic ion beams. We plan to exploit the 'hole-boring' mode of RPA, where the laser pulses interact with targets thick enough to allow to drive target material ahead of it as a piston, but without interacting with the target rear surface [5]. The first experimental observation of RPA in the 'hole-boring' regime was achieved only recently in experiments [9, 10]. The RPA mechanism allows to produce ion bunches with solid-state density (10^{22} - 10^{23}/cm^3), which thus are $\approx 10^{14}$ times more dense than ion bunches from classical accelerators. It is important to note that these ion bunches are accelerated as neutral ensembles together with the accompanying electrons and thus do not Coulomb explode. For our estimates we use the 1-D RPA model as outlined in [5, 6], which holds true for the relativistic 'hole-boring' regime of RPA. For the achievable ion energy E_i it yields the expression $E_i = E_u \cdot A = 2m_ic^2\Xi/\left(1+2\sqrt{\Xi}\right)$, where E_u is the energy per nucleon, A the atomic mass number, m_i the ion mass, c the vacuum speed of light, and Ξ is the dimensionless pistoning parameter given by [5] $\Xi = I_L/(m_in_ic^3)$. I_L denotes the laser intensity and n_i the ion density. In the non-relativistic limit $\Xi << 1$, the expression for the ion energy reduces to $E_i = 2m_ic^2\Xi$. The conversion efficiency of laser energy to ion energy χ follows from [5] as $\chi = 2\sqrt{\Xi}/\left(1+2\sqrt{\Xi}\right)$. The total number of ions, N_i, that can be accelerated results from the energy balance $N_iE_i = \chi W_L$, where W_L denotes the energy of the laser pulse. The target arrangement we want to use is depicted in Fig. 1. It consists of two targets: 'production' target and 'reaction target'. The first is composed of two spatially separated foils, one made from thorium and the other from deuterated polyethylene, CD_2. They serve for the generation of a thorium ion beam and a beam containing carbon ions and deuterons. The

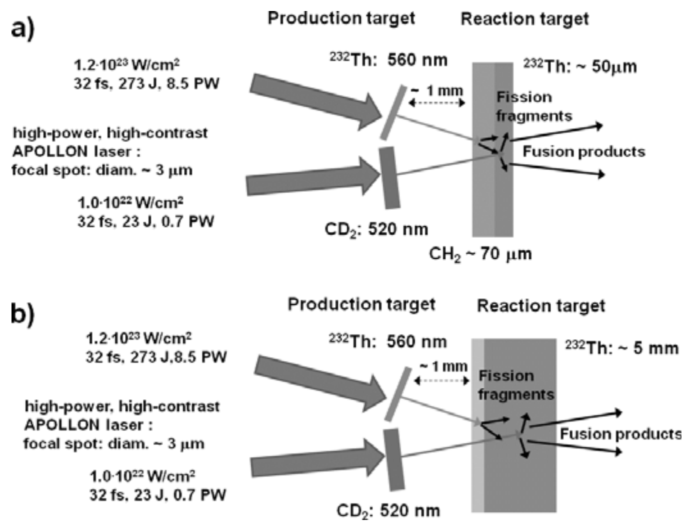

FIGURE 1. Target arrangement envisaged for the fission-fusion reaction process based on laser-ion acceleration. a) illustrates the situation in case no collective effects on the electronic stopping are taken into account. b) depicts an alternative scenario, where we consider collective effects in the reaction target induced by the ultra-dense ion bunches, leading to a reduced electronic stopping and allowing for a larger target thickness (see text).

reaction target has a sandwich structure. The first layer is made from CH_2 and causes fission of the accelerated thorium nuclei. The second layer is a pure thorium film. The accelerated carbon ions and deuterons lead to fission of these thorium nuclei. Fusion of the fragments created in both layers generates neutron-rich nuclei in a mass range towards the waiting point N=126. This reaction scheme works best when the thorium and carbon ions and the deuterons each have an energy of about 7 MeV/u. Accelerating ^{232}Th ions whose density amounts to 11.7 g/cm^3 to E_u=7 MeV/u with laser light of 0.8 μm wavelength needs an intensity of $1.2{\cdot}10^{23}$ W/cm^2. The conversion efficiency χ reaches 11% ($\Xi = 3.8 \cdot 10^{-3}$). Intensities of this level will be achievable with the APOLLON facility, which is under development at the ENSTA/Ecole Polytechnique in Palaiseau within the ILE project [11] and will form the backbone of the ELI Nuclear Physics project[12]. The APOLLON single-beam pulses will provide 150 J in 32 fs. The sum of two of these beams is assumed to be available for the present estimate. Because of $W_L = I_L \cdot A_F \cdot t_L$ these values fix the focal spot area on the thorium production target, A_F, to 3 μm diameter, while the number of accelerated thorium ions N_i is determined by energy balance to $1.2{\cdot}10^{11}$. The thickness of the thorium foil, d_{Th}, follows from $N_i = A_F d_{\mathrm{Th}} n_{\mathrm{Th}}$ and amounts to 560 nm ($n_{\mathrm{Th}} = 3 \cdot 10^{22}/cm^3$). The data for the CD_2 case is obtained similarly. As shown in [13], the carbon ions and deuterons will experience the same energy per nucleon. The pistoning parameter and the conversion efficiency have hence the same values as before. The corresponding focal intensity results as $I_L = 1.0 \cdot 10^{22}$ W/cm^2. Assuming here again a focal spot diameter of 3 μm, the required laser energy, $W_L = I_L A_F t_L$, results in 23 J. The number of accelerated carbon ions and deuterons amounts to $1.4 \cdot 10^{11}$ and $2.8 \cdot 10^{11}$, respectively. The resulting thickness of the polyethylene foil is 520 nm.

For laser-accelerated ions the ion bunch densities reach solid-state density, collective effects become important. According to Ref. [14], the Bethe-Bloch equation describing the atomic stopping of energetic individual ions can be decomposed into a first part describing binary collisions and a second term describing long-range collective contributions according to

$$-dE/dx = 4\pi n_e \frac{Z_{eff}^2 e^4}{m_e v^2}[ln(m_e v^2/e^2 k_D) + ln(k_D v/\omega_p)]. \quad (1)$$

Here k_D is the Debye wave number and ω_p is the plasma frequency of the electrons. We now discuss a strongly reduced atomic stopping power that occurs when sending the solid-state density ion bunch into a solid carbon or thorium target. For this target the plasma wavelength is much smaller than the ion bunch length and only the binary collisions contribute to the stopping power. In this case the first layers of the ion bunch will attract and remove the electrons from the target like a snow-plough. Hence the predominant part of the ion bunch is screened from electrons and we expect a drastic reduction of the stopping power. The usable effective thickness of the thorium target, where the remaining projectile energy for e.g. 7 MeV/u deuterons is still sufficient to induce fission, amounts to about 50 μm. A reduction of the atomic stopping is essential to avoid a strong slowing down of the ions below the Coulomb barrier energies, where nuclear reactions are no longer possible. Taking collective effects into account by assuming a range enhancement by a factor of 100, we expect a usable thickness of several mm for a thorium target.

The Fission-Fusion Process. For our discussion we choose ^{232}Th as fissile target material, primarily because of its long halflife of $1.4{\cdot}10^{10}$ years, which avoids extensive radioprotection precautions during handling and operation. In general, the fission process of the two heavy Th nuclei from beam and target will be preceded by the deep inelastic transfer of neutrons between the inducing and the fissioning nuclei. Here the magic neutron number in the superdeformed fissile nucleus with N=146 [15] may drive the process towards more neutron-rich fissioning nuclei, because the second potential minimum acts like a doorway state towards fission. Since in the subsequent fission process the heavy fission fragments keep their A and N values [16], these additional neutrons will show up in the light fission fragments and assist to reach more neutron-rich nuclei. This process will be of particular importance for the case of collectively reduced stopping in the reaction target. Fig. 1 shows a sketch of the proposed fission-fusion reaction scenario for two different situations, a) for the case of normal electronic stopping as described by the Bethe-Bloch equation and b) for the case of reduced stopping due to collective effects in the target induced by the ultra-dense ion beam discussed earlier. As mentioned before, in case a) the accelerated thorium ions are fissioned in the 50 μm thick Ch_2 layer of the reaction target, whereas the carbon ions and deuterons generate thorium fragments in the thick thorium layer of the reaction target. Using a distance of 2.8 between atoms in solid layers of CH_2, the accelerated light ion bunch ($1.4{\cdot}10^{11}$ ions) corresponds to 1860 atomic layers in case of a 520 nm thick CD_2 target. In order to allow for an optimized fission of the accelerated Th beam, the thicker Th layer of the reaction target, which is positioned behind the production target, is covered by about 70 μm of polyethylene. This layer serves a twofold purpose: Primarily it is used to induce fission of the impinging Th ion beam, generating the beam-like fission fragments. Here polyethylene is advantageous compared to a pure carbon layer because of the increased number of atoms able to induce fission on the impinging Th ions. In addition, the thickness of this CH_2 layer has been chosen such that the produced fission fragments will be decelerated to a kinetic energy which is suitable for cold fusion with the target-like fission fragments generated by the light accelerated ions in the Th layer of the reaction target. After each laser shot, a new double-target has to be rotated into position.

In order to estimate the fission cross sections both of beam and target nuclei, we apply geometrical considerations based on the involved nuclear radii. The resulting fission cross section of the ^{232}Th beam in the CH_2 layer of the reaction target amounts to $\sigma_{\mathrm{fis}} = \pi(R_1 + R_2)^2 = 3.5 \cdot 10^{-28}\ m^2$ (3.5 b). Correspondingly, the deuteron-induced fission in the Th reaction target occurs with a cross section of about $2.47 \cdot 10^{-28}\mathrm{m}^2$ (2.47 b). If we use the atomic distance of 3.2 Å for thorium, we conclude a fission probability of about $4.1{\cdot}10^{-9}$ per atomic layer.

The required thickness of the CH_2 front layer of the reaction target can be estimated as 70 μm ($\sim 2.5{\cdot}10^5$ atomic layers), suitable to decelerate fission fragments from 7 MeV/u Th ions to about 3 MeV/u, thus allowing for subsequent cold fusion with target-like light fragments accoring to PACE4 calculations [17]. This finally results in a fission probability for the Th ion beam of about $3.1{\cdot}10^{-3}$ in the 70 μm CH_2 layer, thus generating about $3.7{\cdot}10^8$ beam-like fission fragments per laser pulse.

In general, the fission process proceeds asymmetric [16]. The heavy fission fragment for ^{232}Th is centred at A=139.5 (approximately at Z=54.5 and N=84) close to the magic numbers Z=50 and N=82. Accordingly, the light fission fragment mass is adjusted to the mass of the fixed heavy fission fragment, thus resulting for ^{232}Th in A_L=91 with $Z_L \approx 37.5$. The width (FWHM) of the light fission fragment peak is typically $\Delta A_L = 14$ mass units, the $1/10$ maximum width about 22 mass units [16].

So far we have considered the fission process of beam-like Th nuclei in the CH_2 layer of the reaction target. Similar arguments can be invoked for the deuteron- (and carbon) induced generation of (target-like) fission products in the subsequent thicker thorium layer of the reaction target. Since we can consider the $2.8{\cdot}10^{11}$ laser-accelerated deuterons (plus $1.4{\cdot}10^{11}$ carbon ions) impinging on the second target per laser pulse as 1860 consecutive atomic layers, we conclude a corresponding fission probability in the Th layer of the reaction target of about $2.3{\cdot}10^{-5}$, corresponding to $3.2{\cdot}10^6$ target-like fission fragments per laser pulse.

In a second step of the fission-fusion scenario, we consider the fusion between the light fission fragments of beam and target to a compound nucleus with a central value of $A \approx 182$ and $Z \approx 75$. Again we employ geometrical arguments for an order-of-magnitude estimate of the corresponding fusion cross section. For a typical light fission fragment with $A = 90$, the nuclear radius can be estimated as 5.4 fm. Considering a thickness of 50 μm for the Th layer of the reaction target that will be converted to fission fragments, equivalent to $1.6{\cdot}10^5$ atomic layers, this results in a fusion probability of about $1.8{\cdot}10^{-4}$. With this estimate for the fusion cross section, we can finally derive an order-of-magnitude for the final yield of fusion products generated via the presented fission-fusion process of about 1-2 fusion products per laser shot (so far neglecting any collective effects in the target that may lead to increased fission rates and fusion yields).

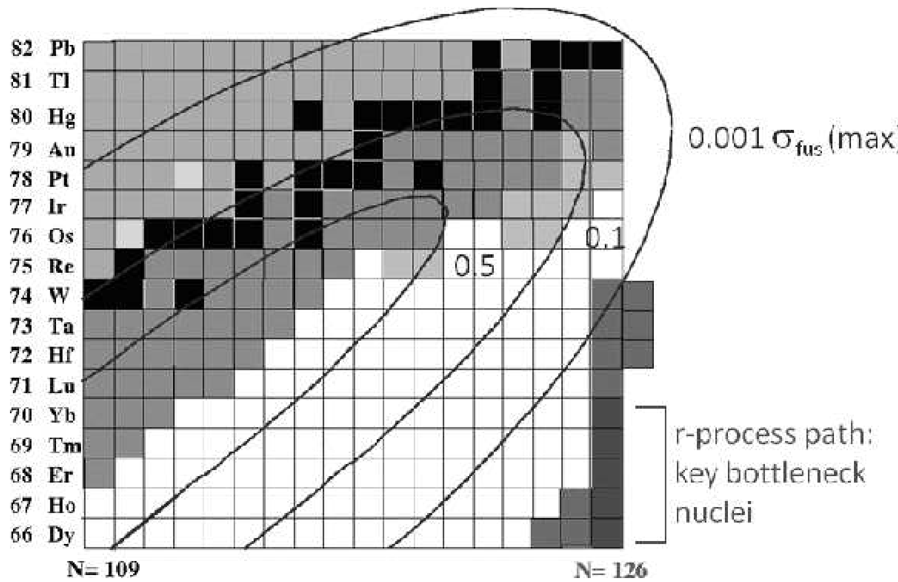

FIGURE 2. Chart of nuclides around the N=126 waiting point of the *r*-process path. The ellipses denote the expected range of isotopes expected to be accessible via the fission-fusion process. The indicated lines represent 0.5, 0.1 and 0.001 of the maximum fusion cross section after neutron evaporation. The N=126 nuclides relevant for the *r*-process are marked, with the dark colour indicating the key bottleneck nuclei for the astrophysical *r*-process.

Fig. 2 displays a closer view into the region of nuclides around the N=126 waiting point of the *r*-process, with dark colour highlighting the key bottleneck *r*-process isotopes at N=126. The elliptical contour lines indicate the range of nuclei expected to be accessible with our new fission-fusion scenario on a level of 50%, 10% and 10^{-3} of the maximum fusion cross section between two neutron-rich light fission fragments. If we now include collective effects in the reaction targets that may reduce the electronic stopping as discussed earlier, this would allow to extend the thickness of the Th production target to probably a few mm (situation 'b)' in Fig. 1). We now propose to abandon the front CH_2 layer of the reaction target and use only a homogeneous, 5 mm thick Th target as indicated in Fig. 1b). We now use the first part of the target (marked by the lighter colour in Fig. 1b) primarily as stopping medium for the incoming Th ions in order to decelerate them to about 3 MeV/u for subsequent cold fusion with target-like fragments. The drastic increase of the reaction target thickness now results in a full conversion of the Th beam into fission fragments. Consequently the deuteron-induced fission yield in the reaction target would also rise to a target fission probability of $2.3 \cdot 10^{-3}$. So we finally conclude that the expected collective stopping range enhancement will lead to a drastic increase of the fusion yield to about $4 \cdot 10^4$ exotic nuclides per pulse. As an average between these two extreme scenarios we quote an estimate of about 10^3 fusion products generated per laser pulse. The following table finally gives a quantitative overview of the two discussed experimental scenarios. All numbers refer to yields expected for one laser pulse. Presently the high-intensity APOLLON laser envisaged to be used for laser ion acceleration is designed to operate at a repetition rate of one laser pulse per minute. However, laser technology is progressing rapidly with large efforts presently devoted

TABLE 1. Compilation of relevant parameters determining the expected yield (per laser pulse) of the fission-fusion reaction process proposed in this work.

	production target ^{232}Th	CD$_2$	Th ions	accelerated deuterons	C ions	reaction target CH$_2$	^{232}Th
norm. stopping	560 nm	520 nm	$1.2 \cdot 10^{11}$	$2.8 \cdot 10^{11}$	$1.4 \cdot 10^{11}$	70 μm	50 μm
red. stopping	560 nm	520 nm	$1.2 \cdot 10^{11}$	$2.8 \cdot 10^{11}$	$1.4 \cdot 10^{11}$	–	5 mm
	beam-like light frag.	fiss. prob. (target)	light frag. (target)	fusion prob.	fusion yield		
norm. stopping	$3.7 \cdot 10^{8}$	$2.3 \cdot 10^{-5}$	$3.2 \cdot 10^{6}$	$1.8 \cdot 10^{-4}$	1.5		
red. stopping	$1.2 \cdot 10^{11}$	$2.3 \cdot 10^{-3}$	$1.2 \cdot 10^{11}$	$1.8 \cdot 10^{-4}$	$4 \cdot 10^{4}$		

to the development of higher repetition rates, aiming of up to 10 Hz together with an increase of the laser pulse energy beyond 1 kJ.

EXPERIMENTAL ASPECTS

Exploring this 'terra incognita' of yet unknown isotopes towards the *r*-process waiting point at N= 126 certainly calls for a staged experimental approach. First studies should focus on the range and electronic stopping powers of dense laser-accelerated ion beams as discussed previously, followed by systematic optimizations of target properties in order to optimize the yield of fission fragments. Subsequently the A, Z and N distributions of the light thorium fission fragments should be characterized. Moreover, it is unclear in how far neutron transfer preceding fission will additionally broaden all these distributions. Also the yields for the fusion products should be measured in exploratory experiments, where it will be crucial to optimize the kinetic energy of the beam-like fission products. The probably most essential and also most demanding experimental task will be the separation of the fusion products with about 2-3 MeV/u from faster beam-like fission fragments with about 7 MeV/u, or target-like fragments with about 1 MeV/u, which could be achieved with a (gas-filled) recoil separator. In first studies, a tape station could be used to transport the reaction products to a remote, well-shielded detector system, where the characterization of the implanted fusion products could be performed e.g. via β-decay studies. Since most of the fusion products have typical lifetimes of $\approx$ 100 ms, they will survive the transport to a secondary target and/or detector station. In a later stage, the fusion products may be stopped in a buffer gas stopping cell [18], cooled and bunched in, e.g., a radiofrequency quadrupole ion guide before then being transferred to a Penning trap system for high-accuracy mass measurements.

CONCLUSION

The exploration of nuclei far away from the valley of stability is a long-term endeavour with strong relevance for astrophysical applications. In our present experimental proposal of a new nuclear reaction scheme, we address the heavy nuclei of the *r*-process nucleosynthesis path towards the waiting point at N=126, where our new production scheme holds promise to bring these extremely neutron-rich isotopes into reach of direct experimental studies with significantly higher yields than accessible with classical radioactive ion beam accelerator technology. With compact high-power, short-pulse laser systems we intend to develop an optimized production scheme for extremely neutron-rich fusion products following induced fission from laser-accelerated ion beams at solid-state density. A two-step production scheme of neutron-rich nuclides ('fission-fusion') is proposed, where asymmetric fission preceded by a deep inelastic transfer reaction will be followed by fusion of the light fission fragments. Moreover, collective effects reducing the electronic stopping power in the target are expected for such ultra-dense ion bunches, allowing to use much thicker targets and thus increasing the fission yield significantly. The fusion of short-lived, neutron-rich fission fragment beams with short-lived, neutron-rich fission fragments in the target will result in very attractive production rates of extremely neutron-rich nuclides towards $N=126$ and $Z>70$. Order-of-magnitude estimates promise fusion rates of several 10^3 fusion products per laser pulse, based on the laser parameters envisaged for the ELI-Nuclear Physics project in Bucharest. In this way, high-power lasers used for laser ion acceleration can significantly contribute to access terra incognita in nuclear physics and astrophysical nucleosynthesis of heavy elements.

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