Eur. Phys. J. D (2009)
DOI: 10.1140/epjd/e2009-00170-1

THE EUROPEAN
PHYSICAL JOURNAL D

Regular Article

dt nuclear fusion within a single Coulomb exploding composite nanodroplet

I. Last[1], J. Jortner[1,a], F. Peano[2], and L.O. Silva[2]

[1] School of Chemistry, Tel Aviv University, Ramat Aviv, 69978 Tel Aviv, Israel
[2] GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, 1049-0001 Lisboa, Portugal

Received 15 December 2008 / Received in final form 7 April 2009

Abstract. We present a computational study of dt fusion driven by Coulomb explosion within a single, large, heteronuclear two-component D_2/T_2 nanodroplet, originating from kinematic overrun effects between deuterons and tritons. Scaled electron and ion dynamics simulations have been used to explore the size dependence and the isotopic composition dependence of the intra-nanodroplet (INTRA) dt fusion yield in a composite $D_{2n-2k}T_{2k}$ nanodroplet, initially consisting of an inner sphere of D_2 molecules surrounded by an outer sphere of T_2 molecules ($n = 1.4\times10^8$–2.0×10^9, $k/n = 0.10$–0.60, and initial radii $R_0 = 1100$–2700 Å) driven by a single, ultraintense, near-infrared, Gaussian laser pulse (peak intensity 10^{20} W cm^{-2}, pulse length 25 fs). INTRA dt fusion in $D_{2n-2k}T_{2k}$ nanodroplets with neutron yields of 30–90 (per nanodroplet, per laser pulse) were attained in the size domain $R_0 = 2000$–2700 Å with the optimal composition in the range of $k/n = 0.2$–0.4. INTRA yields in $D_{2n-2k}T_{2k}$ nanodroplets are similar (within 20–40%) to those in initially homogeneous $(DT)_n$ nanodroplets of the same size. These INTRA yields are sufficiently large to warrant experimental observation in a single nanodroplet. The INTRA dt fusion can be distinguished from the inter-nanodroplet dt fusion reaction, which occurs inside and outside the macroscopic plasma filament, by the nanodroplet size dependence of the yield and by the different energies of the neutrons produced in these two channels.

PACS. 36.40.Qv Stability and fragmentation of clusters – 25.60.Pj Fusion reactions – 34.10.+x General theories and models of atomic and molecular collisions and interactions

1 Introduction

The quest for tabletop dd and dt fusion was recently realized by nuclear fusion driven by Coulomb explosion of deuterium and tritium containing molecular clusters and nanodroplets (CaNs) [1–14]. Coulomb explosion of such molecular CaNs, e.g., $(D_2)_n$ [1,2,4,6–8,10–12], $(CD_4)_n$ [2,3,9,12], $(D_2O)_n$ [5–7], $(DI)_n$ [13,14], $(DT)_n$ [7], and $(DTO)_n$ [7], was induced by their extreme multielectron ionization by ultraintense (peak intensity I_M = 10^{15}–10^{20} W cm^{-2}), ultrafast (pulse length τ = 10–100 fs) near-infrared laser pulses. Extensive experimental [1–5] and theoretical [4,6–10,13–17] studies of nuclear fusion driven by Coulomb explosion of CaNs focused on inter-CaN (INTER) reactions, which occur between nuclei originating from different CaNs inside or outside the macroscopic plasma filament produced by Coulomb explosion of an assembly of CaNs [1,2,6–10,13,17]. Recent theoretical-computational studies predicted that tabletop dd and dt fusion [11,12,18–21], as well as nucleosynthesis of heavier nuclei [19], can be generated by intra-CaN (INTRA) collisions between nuclei (and ions) within a single exploding CaN. INTRA collisions and fusion in spherically symmetric Coulomb explosion are induced by kinematic overrun effects, which trigger nonuniform Coulomb explosion [11,12,19]. Kinematic overrun effects are realized in exploding homonuclear CaNs with an initial [18] or transient [11,12,20,21] inhomogeneous density profile, or in exploding heteronuclear CaNs with an initial homogeneous density profile [19], which can be induced by the following mechanisms:

(A) Kinematic overrun effects in exploding homonuclear CaNs: (A1) inhomogeneity of the initial surface profile. This effect is manifested by deviations of the energy distributions under the conditions of complete outer ionization of the energy distribution for vertical ionization, which was exhibited in relatively small $(D_2)_n$ clusters [22]; (A2) two-pulse excitation of an initially homogeneous $(D_2)_n$ CaN [11,12,20,21]. This scheme is based on the attainment (by the first weaker pulse) of a transient inhomogeneous density profile that serves as a target for the

---

[a] e-mail: jortner@chemsg1.tau.ac.il

second, ultraintense pulse (with $I_M = 10^{18}$–10^{20} W cm^{-2}), which drives extreme outer ionization and nonuniform Coulomb explosion [11,12,20,21]. Two-pulse irradiation results in the formation of "shock shells" in the vicinity of the boundary of the exploding cluster [11,12,17], which serve as a transient medium for overrun and dd fusion generation [11,12,18,20,21].

(B) Kinematic overrun effects in exploding heteronuclear CaNs: (B1) the formation of transient thin shells of deuterons by Coulomb explosion of light-heavy heteroclusters, i.e., $(\mathrm{D}^+\mathrm{I}^{25+})_n$ [13,14,23]. These thin shells provide a medium for (very low-yield) dd fusion [14,23]; (B2) kinematic overrun effects in Coulomb explosion of initially homogeneous heteronuclear nanodroplets , e.g., $(\mathrm{D}^+\mathrm{T}^+)_n$, when inner, light D^+ nuclei with a higher velocity overrun and react with heavy nuclei (ions) in the periphery, which are characterized by a lower velocity. This mechanism drives $^3\mathrm{T}(d,n)^4\mathrm{He}$ and $^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}$ nuclear reactions within the entire volume of the exploding CaN [19,21].

The contributions to the dd yield from the INTRA reaction mechanisms (A1) and (B1) are expected to be minor [14,22]. The dominating mechanisms, explored up to date, for the attainment of INTRA nuclear reactions with a sufficiently high yield to warrant experimental observation, involves mechanism (A2) for dd fusion [11,12,20,21], and mechanism (B2) for dt fusion [19,21] and for $p+^{12}\mathrm{C}$ nucleosynthesis [19]. All the effective mechanisms previously considered for INTRA nuclear reactions focus on Coulomb explosion within initially microscopically homogeneous (homonuclear or heteronuclear) CaN structures, which are driven by a one-pulse irradiation (i.e., mechanism (B2)) or by a two-pulse irradiation (mechanism (A2)). In this paper we will extend the landscape of INTRA fusion mechanisms in heteroclusters. We shall consider Coulomb explosion of a composite, two-component CaN, which initially consists of an inner sphere of lighter deuterium molecules surrounded by a peripheral sphere of heavier tritium molecules, and is driven by a one-laser pulse. The high cross sections for the $\mathrm{T}(d,n)^3$ He reaction [24] favor the use of the dt nuclear reaction both for INTER [7,19] and for INTRA [19,21] fusion. Kinetic overrun effects in the exploding composite nanodroplet will drive INTRA nuclear reactions between the low-mass, higher-velocity, and the high-mass, lower-velocity nuclei. We shall provide a theoretical-computational study of the dt, $^3\mathrm{T}(\mathrm{D},n)^4\mathrm{He}$ INTRA fusion reaction within a composite, two-component $\mathrm{D}_{2n-2k}\mathrm{T}_{2k}$ nanodroplet consisting of an inner core of $(\mathrm{D}_2)_{n-k}$ surrounded by a periphery shell of $(\mathrm{T}_2)_k$ (with $n = 1.4\times10^8$–2×10^9 and $k/n = 0.1$–0.6). The choice of the dt fusion is favorable in view of the high cross sections for this nuclear reaction [24]. The use of Coulomb explosion of nanodroplets (with an initial radius of $R_0 \approx 1000$ Å) is required for the attainment of high kinetic energies (in the MeV range) of the d and t nuclei, which in turn are required for the accomplishment of effective INTRA collisions and fusion [19]. We shall explore the control of the dt fusion yield by changing the isotopic composition of the two-component nanodroplet and compare the results for INTRA fusion yields in the composite, two-component $\mathrm{D}_{2n-2k}\mathrm{T}_{2k}$ nanodroplet with those for the one-component $(\mathrm{DT})_n$ heteronuclear nanodroplet [19,21]. We shall establish the experimental prospects for the selective observation of the INTRA reaction mode, which are based on the nanodroplet size dependence of the fusion yield, on the specific neutron energies and on the distinct time scale for neutron emission.

2 Intra dt fusion in $\mathrm{D}_2/\mathrm{T}_2$ nanodroplets

We consider $\mathrm{D}_{2n-2k}\mathrm{T}_{2k}$ composite nanodroplets with initial radii R_0 for the entire nanodroplet and R_D for the central core of deuterons. Neglecting isotope effects on the density, the triton/deuteron ratio $\kappa = k/(n-k)$ is $\kappa = (R_0/R_\mathrm{D})^3$–1, while the width $R_\mathrm{T} = R_0$–R_D of the tritium peripheral core is $R_\mathrm{T} = R_0[1$–$(1+\kappa)^{-1/3}]$. Typical values of size and composition were $R_0 = 1000$–3000 Å and $\kappa = 0.15$–1.5. We used the scaled electron and ion dynamics simulation method [25], which is applicable for nanodroplets containing up to 10^9 D and T atoms [17,19], for simulations of INTRA dt fusion yields in exploding composite $\mathrm{D}_{2n-2k}\mathrm{T}_{2k}$ nanodroplets and also in an initially uniform $(\mathrm{DT})_n$ nanodroplet [19,21].

The expressions for the INTRA fusion yield previously obtained for exploding homonuclear nanodroplets [21] were modified to the heteronuclear case. The total yield of INTRA dt fusion (per laser pulse) driven by Coulomb explosion of a single $\mathrm{D}_{2n-2k}\mathrm{T}_{2k}$ or $(\mathrm{DT})_n$ nanodroplet is

$$Y = \int_0^\infty y(t)dt \tag{1}$$

where $y(t)$ is the differential fusion yield (per unit time), which is given by

$$y(t) = 2\pi \int_0^{R_\mathrm{T}(t)} r^2 \rho_\mathrm{T}(r,t)dr \int_0^\pi \rho_\mathrm{D}(\alpha;r,t)\zeta(\alpha,r,t)\sin(\alpha)d\alpha \tag{2}$$

where $R_\mathrm{T}(t)$ is the maximal radius of the tritium ion location at time t. $\rho_\mathrm{D}(\alpha;r,t)$ is the local nuclei density of deuterons at distance r and angle α between the radius vector r and the laser field polarization axis. $\rho_\mathrm{T}(r,t)$ is the nuclei density of tritons averaged over α, and $\zeta(\alpha,r,t) = \langle\sigma v\rangle$ is the averaged product of the reaction cross section σ [24] and the center of mass collision velocity v. The averaging is taken over the center of mass energy E' distribution $P(E';\alpha,r,t)$, so that

$$\zeta(\alpha,r,t) = \int_0^\infty P(E';\alpha,r,t)\sigma(E')v(E')dE'. \tag{3}$$

The center of mass energy E' and the velocity v for a deuteron-triton pair are:

$$E' = (3/5)m_{\mathrm{D}}\left[(E_D/m_{\mathrm{D}})^{1/2} - (E_{\mathrm{T}}/m_{\mathrm{T}})^{1/2}\right]^2 \quad (4)$$

$$v = 2\,(E_{\mathrm{D}}/m_{\mathrm{D}})^{1/2} - (2E_{\mathrm{T}}/m_{\mathrm{T}})^{1/2} \quad (5)$$

where E_{D} and E_{T} are the deuteron and the triton laboratory frame energies.

Data for the time-dependent local density $\rho(\alpha, r, t)$, the energy distribution $P(E'; r, \alpha, t)$ and the velocities $v(E')$, which determine the INTRA reaction yields (equations (1)–(5)), were obtained from scaled electron and ion dynamics simulations [25], which self-consistently incorporated both electron and ion dynamics. The present approach is more general than previous simulations of INTRA dynamics [19], which were based on complete outer ionization of the nanodroplet and were performed in the framework of the cluster vertical ionization (CVI) model that considers solely dynamics of nuclei. The initial radii of the $\mathrm{D}_{2n-2k}\mathrm{T}_{2k}$ nanodroplets were taken in the range R_0 = 1100–2700 Å. The scaled electron and ion dynamics simulations were performed with the scaling parameters $s = 4\times10^4$, 10^5, 1.6×10^5 and 4×10^5 for R_0 = 1100 Å ($n = 1.36\times10^8$), 1500 Å ($n = 3.45\times10^8$), 2000 Å ($n = 8.2\times10^8$) and 2700 Å ($n = 2.0\times10^9$), respectively. These s values were found to be sufficiently small to ensure the convergence of the simulation results and to provide reliable estimates of the INTRA dt fusion yields. The parameters of the Gaussian, near-infrared laser pulse were taken as follows: peak intensity $I_M = 10^{20}$ W cm^{-2}, pulse width $\tau = 25$ fs and frequency $\nu = 0.35$ fs^{-1} (wavelength 860 nm).

The ultrahigh laser intensities of $I = 10^{20}$ W cm^{-2} for the driving of INTRA dt reactions may also be relevant in the context of light absorption within a single nanodroplet [19,26]. A basic assumption underlying our treatment of INTRA collisions and reactions is that the laser field inside a nanodroplet is spatially homogeneous, and there is no attenuation (due to absorption) along the propagation path inside the nanodroplet. Following a previous treatment [19], the attenuation within the nanodroplet will be unimportant if [17,26]

$$E_{fl} > 2E_{tot} \quad (6)$$

where E_{fl} is the energy flow through the nanodroplet and E_{tot} is the total energy absorbed by the nanodroplet particles (electrons and ions), which is determined by the energy of the ions [16,17,26]. Previous simulations for $(\mathrm{DT})_n$ nanodroplets driven by a Gaussian pulse ($\tau = 25$ fs) with $I = 10^{20}$ W cm^{-2} [19] established that the validity condition, equation (6), is well satisfied in the initial size domain of R_0 = 1000–2000 Å. We can therefore assert that for the composite $\mathrm{D}_2/\mathrm{T}_2$ nanodroplets with R_0 = 1100–2700 Å, driven by an ultraintense pulse, the condition for small attenuation is valid. The largest nanodroplet sizes used in our simulations, with R_0 = 1100–2700 Å for the initial structure driven by the near-infrared laser pulse with a wavelength of $\lambda = 860$ nm, correspond to R_0/λ = 0.13–0.35. The treatment of Coulomb explosion driven by ultraintense laser excitations of larger nanodroplets will require the extension of laser-nanodroplet interaction models.

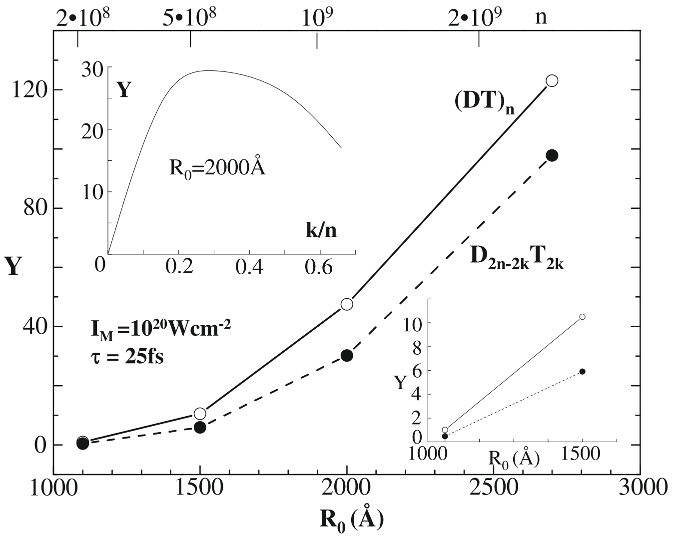

Fig. 1. The nanodroplet size dependence of the INTRA dt fusion yield in composite $\mathrm{D}_{2n-2k}\mathrm{T}_{2k}$ nanodroplets (- - ● - -) and in neat $(\mathrm{DT})_n$ nanodroplets (–○–), with $n = 2\times10^8 - 2\times10^9$ and R_0 = 1100–2700 Å. The parameters of the single Gaussian laser pulse are $I_M = 10^{20}$ W cm^{-2} and $\tau = 25$ fs. The upper inset on the left hand side shows the composition dependence of the INTRA dt fusion yield in a $\mathrm{D}_{2n-2k}\mathrm{T}_{2k}$ nanodroplet in the range k/n = 0.1–0.6. The data for the INTRA yields in the composite nanodroplet (figure and lower right hand side inset) were obtained for the optimal value of k/n for each value of R_0.

3 Composition and size dependence of intra dt fusion yields

For the two-component composite nanodroplets , the total dt fusion yield, equation (1), depends on the nanodroplet size and on the composition k/n, while for initially homogeneous $(\mathrm{DT})_n$ heteronuclear nanodroplets of fixed composition, Y exhibits a nanodroplet size dependence only [19]. The dependence of the total yield Y for INTRA dt fusion on the compositional parameter k/n in a $\mathrm{D}_{2n-2k}\mathrm{T}_{2k}$ nanodroplet (R_0 = 2000 Å, $n = 8.2\times10^8$) is presented in the upper inset to Figure 1. For other cluster sizes in the range R_0 = 1100–2700 Å, Y manifests a similar dependence on k/n as that for R_0 = 2000 Å. The INTRA fusion yield within a nanodroplet with a fixed size exhibits a broad maximum in the compositional range of k/n = 0.15–0.4, which corresponds to a relatively low triton abundance. Accordingly, the optimal composition of the $\mathrm{D}_{2n-2k}\mathrm{T}_{2k}$ nanodroplet (for the attainment of maximal fusion yield at a fixed size) contains a relatively thin periphery tritium shell within the range of $R_T/R_0 \approx 0.07$–0.16.

Figure 1 portrays the size dependence of the INTRA total yield in a composite $\mathrm{D}_{2n-2k}\mathrm{T}_{2k}$ nanodroplet, where for each size R_0 the Y value is given for the optimal ratio of k/n. These INTRA yield data for the composite two-component nanodroplets are compared with the nanodroplet size dependence of the INTRA fusion yields in an initially homogeneous, one-component $(\mathrm{DT})_n$ nanodroplet (Fig. 1 and lower inset to this figure). The increase of the INTRA fusion yields in $\mathrm{D}_{2n-2k}\mathrm{T}_{2k}$ nanodroplets , with increasing their size, is steeper than the increase of the number of atoms. In the size domains of $R_0 = 1100$–1500 Å, $R_0 = 1500$–2000 Å and $R_0 = 2000$–2700 Å, Y increases by numerical factors of 12, 3.8 and 3.3, respectively (right inset to Fig. 1 and Fig. 1). Accordingly, at the high end of the nanodroplet size domain, i.e., $R_0 = 2000$–2700 Å, the increase of Y is only slightly steeper than that of n, and a further increase of the nanodroplet size will not be advantageous, at least not for the laser parameters used herein.

In Figure 1 we compare the INTRA dt fusion yields in the two-component $\mathrm{D}_2/\mathrm{T}_2$ composite $\mathrm{D}_{2n-2k}\mathrm{T}_{2k}$ nanodroplet and in the initially homogeneous $(\mathrm{DT})_n$ nanodroplet. The neutron yields for the INTRA fusion from a $\mathrm{D}_{2n-2k}\mathrm{T}_{2k}$ nanodroplet are lower by only 20–40% than those of the INTRA yields from the $(\mathrm{DT})_n$ nanodroplet of the same size. We conclude that efficient dt INTRA fusion can be achieved both in composite $\mathrm{D}_{2n-2k}\mathrm{T}_{2k}$ and in homogeneous $(\mathrm{DT})_n$ nanodroplets .

From the point of view of methodology of scaled electron and ion dynamics simulations, the INTRA dt fusion yields in $(\mathrm{DT})_n$ nanodroplets reported herein (Fig. 1) are lower by about a numerical factor of 2 than those previously reported for this size domain [19]. This numerical difference originates from the incorporation of electron outer ionization dynamics in the present 'full' scaled electron and ion dynamics simulations, while previous simulations [19] were based on the CVI approximation. The present simulation results are more reliable and were used in our analysis.

4 Experimental perspectives

The simulation results for INTRA dt fusion yields (per nanodroplet, per pulse) from large composite $\mathrm{D}_{2n-2k}\mathrm{T}_{2k}$ nanodroplets ($R_0 = 2000$–2700 Å, $n = 8.2\times10^8$–2.0×10^9) driven by a single ultraintense laser pulse are high, i.e., $Y = 30$ for $R_0 = 2000$ Å and $Y = 90$ for $R_0 = 2700$ Å (Fig. 1). Similar yields are exhibited for INTRA dt fusion in $(\mathrm{DT})_n$ nanodroplets (Fig. 1). These high values for INTRA dt fusion originate from the large cross sections for this reaction [24], and the prevalence of kinematic overrun effects [19]. The values of Y are sufficiently large to warrant experimental observation in a single nanodroplet. Under common experimental conditions, an ensemble of nanodroplets must be considered. The total INTRA dt fusion yield is $Y_{INTRA}^{total} = N_{nd}Y$, where N_{nd} is the number of nanodroplets . Using previous estimates [19] for N_{nd} we obtained (Fig. 2) for INTRA dt fusion both in $\mathrm{D}_{2n-2k}\mathrm{T}_{2k}$ and in $(\mathrm{DT})_n$ nanodroplets $Y_{INTRA}^{total} = 2\times10^3$–$1.5\times10^4$ in the size domain of $R_0 = 1100$–2700 Å. Y_{INTRA}^{total} for both the composite $\mathrm{D}_{2n-2n}\mathrm{T}_{2k}$ and for the initially homogeneous $(\mathrm{DT})_n$ exhibits an increase with increasing the nanodroplet size (Fig. 2). The high yield of the INTRA $\mathrm{T}(d,n)^4$ He reaction has to be compared with the Y_{INTER}^{total} yield for the corresponding inter-CaN (INTER) reaction, which occurs between nuclei produced from different CaNs. We used the procedure previously advanced [18,19] for the estimates of the yield Y_{INTER}^{total} for the INTER channel in an assembly of nanodroplets (Fig. 2). The total yields for INTER dt fusion in assemblies of composite $\mathrm{D}_{2n-2k}\mathrm{T}_{2k}$ and initially homogeneous $(\mathrm{DT})_n$ nanodroplets of the same size are similar. Y_{INTER}^{total} is higher by 10–30% for an assembly of $(\mathrm{DT})_n$, relative to an assembly of $\mathrm{D}_{2n-2k}\mathrm{T}_{2k}$ nanodroplets in the size domain $R_0 = 1100$–1500 Å, while in the range $R_0 = 2000$–2700 Å, Y_{INTER}^{total} values are practically identical for the two types of nanodroplets (Fig. 2). The INTER total yields Y_{INTER}^{total} decrease with increasing the nanodroplet size, exhibiting a qualitatively different size dependence than the INTRA yields Y_{INTRA}^{total}, which increase with increasing R_0 (Fig. 2). The decrease of Y_{INTER}^{total} with increasing the nanodroplet size is due to a very high energy (E) of the colliding $d + t$ nuclei. The energy of the nuclei produced within the exploding nanodroplet lies in the range of 1–10 MeV, where the $d+t$ reaction cross section $\sigma(E)$ decreases with increasing E [24]. Consequently, the increase of the nanodroplet size with the corresponding increase of the nuclei energy contributed to the decrease of Y_{INTER}^{total}. On the other hand, the increase and saturation of Y_{INTRA}^{total} with increasing R_0 (Fig. 2) is due to lower values of the relative center of mass energies of the D and T nuclei (∼100–300 keV). This energy domain corresponds to the increase of $\sigma(E)$ with increasing E [24]. For assemblies of very large $\mathrm{D}_{2n-2k}\mathrm{T}_{2k}$ and $(\mathrm{DT})_n$ nanodroplets ($R_0 = 2000$–2700 Å) the dominating fusion mechanism involves the INTRA channel.

The prediction (Fig. 2) for the nanodroplet size dependence of the INTRA yield of the $\mathrm{T}(d,n)^4$ He reaction, which dominates for very large nanodroplets (Fig. 2), can be experimentally verified by measurements of the neutron energies. The two parallel $\mathrm{T}(d,n)^4$ He channels for the INTRA and the INTER reactions produce neutrons in different energy ranges. We estimated the neutron energies by using the analysis of Youssef et al. [27], as applied to "forward" and to "backward" collisions. The laboratory energy E_n of the emitted neutron as a function of the incident ion (deuteron or triton) energy $E_{d/t}$ is given by a modification of the formalism of Youssef et al. [27] for dt fusion in the form

$$E_n^{1/2} = (1/5)\left\{\left[20Q + 12E_{d/t}\right]^{1/2} \pm (2E_d)^{1/2}\right\} \qquad (7)$$

where $Q = 17.58$ MeV is the energy release of the $\mathrm{T}(d,n)$ ^{4}He reaction [24], and +(−) refers to forward (backward) collisions. In the limit of low ion energies $E_{d/t} = 0$, and the neutron energy is $E_n = 14.06$ MeV. According to our simulations for the INTRA reaction mode within an exploding nanodroplet, typical deuteron energies fall in the range of $E_d = 0.1$–0.5 MeV, so that $E_{d/t} << Q$ and a neutron narrow energy distribution

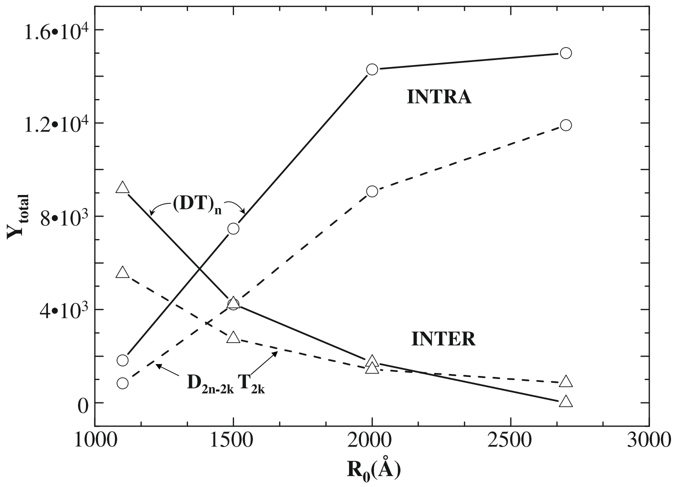

Fig. 2. The size dependence of the total INTRA and INTER dt fusion yields Y_{total} in our assembly of $D_{2n-2k}T_{2k}$ and of $(DT)_n$ nanodroplets (see text). Y_{total} for INTRA dt fusion in Coulomb explosion of $D_{2n-2k}T_{2k}$ (- - ○ - -) and of $(DT)_n$ (–○–) increases with increasing R_0, while Y_{total} for INTER dt fusion in Coulomb explosion of $D_{2n-2k}T_{2k}$ (- - Δ - -) and of $(DT)_n$ (–Δ–) decreases with increasing R_0. A crossover of the yields is manifested at $R_0^C = 1400$–1500 Å, whereas the contribution of the INTRA mode dominates for $R_0 > R_0^C$.

at $E_n = 14.06$ MeV will be exhibited. For the INTER reaction mode inside and outside the macroscopic plasma filament produced by Coulomb explosion of $(DT)_n$ nanodroplets (with $R_0 = 2000$ Å), the maximal value of the energies of the nuclei obtained from our simulations is $(E_{d/t})_{MAX} \simeq 9.5$ MeV (while ion energies in the range of $E_d > 9.5$ MeV contribute less than 15%). Using $E_{d/t} = 9.5$ MeV in equation (6), we estimate the neutron energy domain for the INTER reaction mode in the broad range of 11.8 MeV $< E_n <$ 22.4 MeV. The energy resolution of the neutrons will provide the identification of the INTRA reaction, which will result in a narrow neutron peaking at $E_n = 14.06$ MeV, and which is superimposed on a broad energy distribution $E_n = 11.8$–22.4 MeV due to the INTER reaction mode. An additional diagnostic tool for INTRA and INTER fusion pertains to the distinctive time scales for these two reaction modes. According to our simulations, the time scale for the INTRA reaction is $\tau_{INTRA} \approx 30$–50 fs. On the other hand, the time scale for the INTER reaction, which mainly occurs via collisions of nuclei from the plasma filament with clusters outside it [17], is in the range of $\tau_{INTER} \approx 2$ ps–100 ps [17]. Accordingly, neutrons from the INTRA reaction with a narrow energy distribution at $E_{d/t} = 14.96$ MeV will be emitted in an ultrashort (femtosecond) burst, prior to the appearance of neutrons with the INTER reaction with a broad energy distribution (11.8–22.4 MeV) on the picosecond time scale. We conclude that the selective observation of the INTRA reaction mode, as compared to the INTER channel, will rest on the different nanodroplet size dependence of the dt fusion yields, on the different neutron energies and on the different time scales for neutron emission.

This research was supported by the James-Franck Binational German-Israeli Program on Laser Matter Interaction at Tel Aviv University and by FCT Portugal, through grant PDTC/FIS/66823/2006.

References

1. J. Zweiback, R.A. Smith, T.E. Cowan, G. Hays, K.B. Wharton, V.P. Yanovsky, T. Ditmire, Phys. Rev. Lett. **84**, 2634 (2000)
2. K.W. Madison, P.K. Patel, D. Price, A. Edens, M. Allen, T.E. Cowan, J. Zweiback, T. Ditmire, Phys. Plasmas **1**, 270 (2004)
3. G. Grillon, P. Balcou, J.-P. Chambaret, D. Hulin, J. Martino, S. Moustaizis, L. Notebaert, M. Pittman, T. Pussieux, A. Rousse, J.-Ph. Rousseau, S. Sebban, O. Sublemontier, M. Schmidt, Phys. Rev. Lett. **89**, 065005 (2002)
4. S. Karsch, S. Düsterer, H. Schwoerer, F. Ewald, D. Habs, M. Hegelich, G. Pletzler, A. Pukhov, K. Witte, R. Sauerbrey, Phys. Rev. Lett. **91**, 015001 (2003)
5. S. Ter-Avetisyan, M. Schnürer, D. Hilscher, U. Jahnke, S. Busch, P.V. Nicles, W. Sandner, Phys. Plasmas **12**, 012702 (2005)
6. I. Last, J. Jortner, Phys. Rev. Lett. **87**, 033401 (2001)
7. I. Last, J. Jortner, Phys. Rev. A **64**, 063201 (2001)
8. P.B. Parks, T.E. Cowan, R.B. Stephens, E.M. Campbell, Phys. Rev. A **63**, 063203 (2001)
9. I. Last, J. Jortner, J. Phys. Chem. A **106**, 10877 (2002)
10. J. Davis, G.M. Petrov, A.L. Velikovich, Phys. Plasmas **13**, 064501 (2006)
11. F. Peano, R.A. Fonseca, L.O. Silva, Phys. Rev. Lett. **94**, 033401 (2006)
12. F. Peano, R.A. Fonseca, J.L. Martins, L.O. Silva, Phys. Rev. A **73**, 053202 (2006)
13. A. Heidenreich, I. Last, J. Jortner, Proc. Natl. Acad. Sci. USA **103**, 10589 (2006)
14. H. Li, J. Liu, C. Wang, G. Ni, C.J. Kim, R. Li, Zh. Xu, J. Phys. B **40**, 3941 (2007)
15. V.P. Krainov, M.B. Smirnov, Phys. Rep. **370**, 237 (2002)
16. A. Heidenreich, I. Last, J. Jortner, *Analysis and Control of Ultrafast Photoinduced Processes,* edited by O. Kühn, L. Wöste (Springer Verlag, Heidelberg, 2007), Vol. 87, p. 575
17. I. Last, J. Jortner, Phys. Plasmas **14**, 123102 (2007)
18. A.E. Kaplan, B.Y. Dubetski, P.L. Shkolnikov, Phys. Rev. Lett. **91**, 143401 (2003)
19. I. Last, J. Jortner, Phys. Rev. A **77**, 033201 (2008)
20. F. Peano, J.L. Martins, R.A. Fonesca, F. Peinetti, R. Mulas, G. Coppa, I. Last, J. Jortner, L.O. Silva, Plasma Phys. Contr. Fusion **50**, 124049 (2008)
21. I. Last, F. Peano, J. Jortner, L.O. Silva, unpublished
22. I. Last, J. Jortner, J. Chem. Phys. **121**, 3030 (2004)
23. I. Last, J. Jortner, Phys. Rev. A **71**, 063204 (2005)
24. D.J. Rose, M. Clark, Jr., *Plasmas and Controlled Fusion* (M.I.T. Press, Cambridge, Massachusetts, 1961), p. 13
25. I. Last, J. Jortner, Phys. Rev. A **75**, 042507 (2007)
26. I. Last, J. Jortner, Phys. Rev. A **73**, 063201 (2006)
27. Y. Youssef, R. Kodama, H. Habara, K.A. Tanaka, Y. Sentoku, M. Tampo, T. Toyama, Phys. Plasmas **12**, 110703 (2005)