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Search for low-energy nuclear transitions in laser-produced plasmas

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The first experiments [1] with a low-energy excitation of nuclei in hot dense plasmas were performed using a natural uranium target and a modest-parameter TEA CO_2 laser (1 J, 100 ns). Although the interpretation of the obtained results was later questioned, these experiments initiated a detailed investigation of the basic alternative mechanisms of excitation of low-lying nuclear levels (for a review see [2-5]): direct photo-excitation, inelastic electron scattering, inverse internal electron conversion (IIEC, sometimes called nuclear excitation by electron capture, NEEC), nuclear excitation by electron transition (NEET), and inverse electronic bridge (IEB).

The analysis [5] of above-mentioned processes indicates that in dense plasmas with temperature close to the excitation energy of low-lying nuclear levels, resonance mechanisms (direct photo-absorption, IIEC, and IEB) should dominate the nuclear excitation. From the candidate nuclei [6], ^{181}Ta was selected for our experiments because of a suitable energy of its lowest excited state (6.238 keV) and the relatively long half-life (6.05 μs) of decay as well as the high natural isotopic abundance (99.99 %). At the PALS facility [7], a single 1-kJ laser pulse with the FWHM $\tau \sim 250$ ps was focused on Ta target to generate such a plasma at an irradiance up to 7×10^{16} Wcm^{-2} (see Fig.1). Both considerably higher energy and longer duration of the pulse result in creation of large photon- and particle-emitting plasma volumes, increased number and ionization degree of Ta ions, and enhanced broadening of the energy levels, thus the probability for observation of the nuclear transition increases in comparison with experiments at ultra-short pulses, high-repetition-rate lasers (see for example [8]).

Plasma–nuclear interactions in hot, dense laser plasmas can result in nuclear–photonic and nuclear–electronic excitations. The process of nuclear excitation to a level E^* by absorption of a photon with energy E_γ can be described by the resonant cross section $\sigma_\gamma(E_\gamma)$ [9]. Assuming that the plasma with the electron temperature T_e produced under the action of the high-power laser pulse on the solid target occupies the same volume as the pumped nuclei, then the total number of isomeric nuclei N^* excited during the lifetime τ_p may be approximated by

$$N^* = \frac{dN_\gamma}{dtdE_\gamma dS}\sigma_\gamma n_{i0} Sl \approx N_{i0}\frac{\Gamma_\gamma \tau_p}{\exp(E_\gamma / T_e) - 1}.$$

Here n_{i0} is the ion density, N_{i0} is the number of ions in the whole plasma volume $V=Sl$, S being the plasma area on the target surface (approximately equal to the dimension of the laser focal spot) and l its extension along the target normal. To estimate the x-ray emission resulting from the decay of the excited nuclear states, Γ_γ must be replaced by $\Gamma_T/(1+\alpha)$, where α is the internal conversion coefficient (ICC). The simulations have shown that ICC depends on ion charge [10] and drops fast down (by two orders of magnitudes for Ta) above the ion charge Z=50 (see Fig. 2).

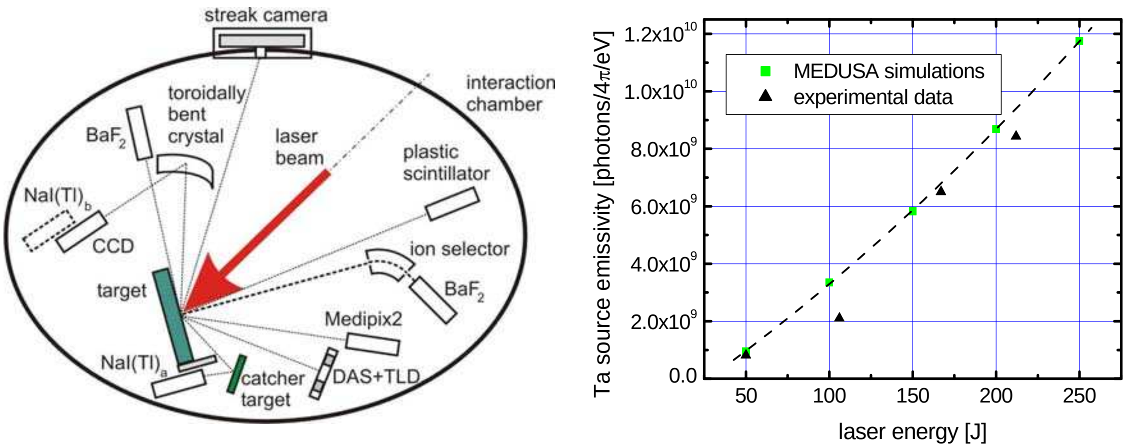

Fig 1. Alternate experimental schemes (left) for observation of laser-plasma-excited nuclear transitions: (i) direct observation of the delayed γ emission, (ii) Ta ions capture at secondary (catcher) target, (iii) selection of ions with Z > 50 motivated by a decrease of internal conversion coefficient α (and consequently, improved signal-to-background ratio). Measurements performed by toroidally bent crystal spectrometer confirm theoretically predicted emissivity of the plasma source around 6.238 keV (right).

For the PALS nominal parameters (1 kJ, 1.315 μm, 250 ps, 7×10^{16} Wcm^{-2} at the focal spot diameter of 80 μm), the characteristics of the plasma created at Ta solid target can be estimated using the well-known analytic formulae [9] and results of 1D MEDUSA modelling [11]; an example of the results obtained is shown in Fig. 2. Approximating the plasma volume by $V = 2.6\times10^{-6}$ cm^{-3}, we obtain $N_{i0} = n_e V/Z \sim 4.2\times10^{13}$. For $T_e = 1$ keV, $\tau_p \sim 1$ ns, and $\Gamma_T \approx 1.8\times10^5$ s^{-1}, we arrive to $N^* = 1.5\times10^7$ excited nuclei. Taking into account the tabulated value $\alpha = 70.5$, the number of activated nuclei decaying via x-rays is about 2×10^5.

It should be emphasized that these estimates of the activated nuclei population in the plasma represent a rough approximation only. To determine a concentration of the isomeric nuclei rigorously, it is generally desired to simulate the 2D plasma evolution and to treat the absorption of the pumping x-ray continuum due to the photo-effect in more detail. However, for our conditions, we can neglect this effect because the photon mean free path is about 10 μm for Ta plasma of density $n_e = 10^{21}$ cm^{-3}. On the other hand, the uncertainties in the broadening of the nuclear levels in the plasma, internal electron conversion coefficient, etc., may introduce large errors. The more precise evaluation of them represents one of the key issues in this field of research.

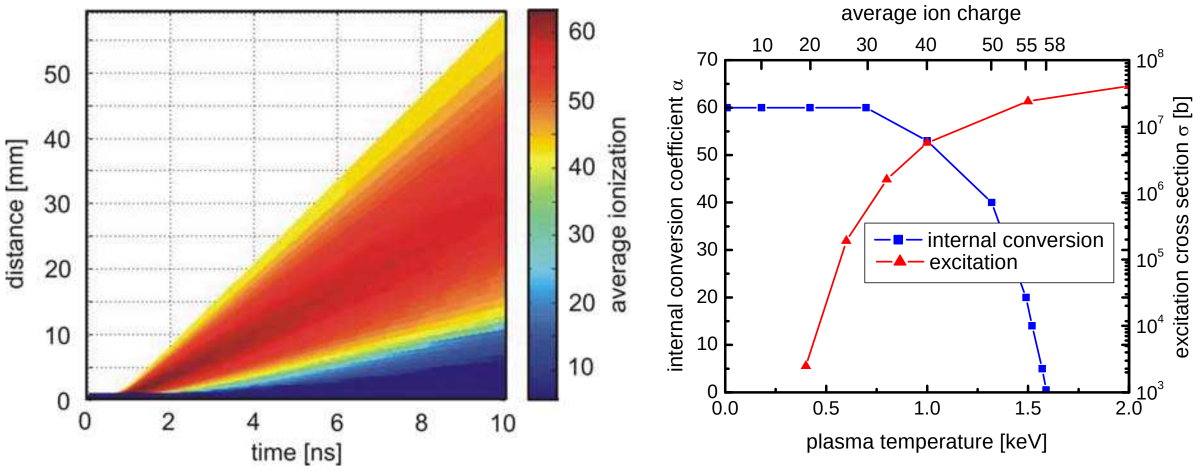

Fig. 2. Temporal and spatial distributions of Ta plasma ionization (left) influence considerably the ^{181}Ta nuclear level excitation and number of activated nuclei decaying via emission of 6.2-keV photons (right).

The estimated number of 6.2-keV photons at the level of 10^5 is sufficient for detection by our detectors (Medipix, scintillators, x-ray spectrometers with back-illuminated CCD, micro-channel plates [9]) but the laser plasma produces a huge amount of x-rays from secondary processes of accelerated particles, which come to detector together with photons from nuclear de-excitation. This results in detection of the relatively strong x-ray signal within tens of microseconds after the laser pulse [9]. Direct observation of x-ray emission around photon energy of 6.2 keV is not fully adequate to separate x-ray quanta produced by decay of excited nuclear states from those originated in collisions of isotropic part of fast ions [12] with chamber walls. The analysis of the delayed photon emission registered by scintillator detectors shows several alternative half-lives for different pulse amplitudes which does not allow the univocal interpretation of the measured signals.

Two alternate experimental schemes shown in Fig. 1 were suggested to suppress these spurious effects. The application of secondary (catcher) targets resulted in capture of Ta ions on polyethylene (PE) slabs (20×30×1 mm^3). Depth profiles of Ta deposited in PE collector were measured by the standard Rutherford back-scattering (RBS) technique employing alpha particles with energies of several MeV [13]. The catchers placed 10 cm from laser-illuminated target contained more than 10^{16} Ta atoms uniformly distributed within 3.5-μm near surface layer. The chosen geometry allows effective detector shielding from directly viewing the plasma. On the other hand, the deposition of ions in molten PE layer results in quick completion of their electron envelopes and the competition between radiative de-excitation and internal electron conversion handicaps x-ray identification of nuclear transitions.

The second method suggested to suppress the parasitic x-ray signals from plasma and ion-wall collisions consists in separation of the emitted highly charged ions ($Z > 50$) by magnetic field in shielded target chamber area. Despite a small fraction of such ions ($\propto$ 10% of a total number) the drop in the ICC value (Fig. 2) may increase the total number of 6.2-keV photons by one order of magnitude compared to the ordinary case and thus provide the possibility to discriminate the sought signal from the radiative background. This layout is very promising not only for demonstration of the excited Ta nuclei formation in laser-produced plasmas but also for investigation of the excitation mechanisms in details. Relevant experiments are currently being prepared.

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