Pions and muons produced via ultra-intense laser interaction with matter

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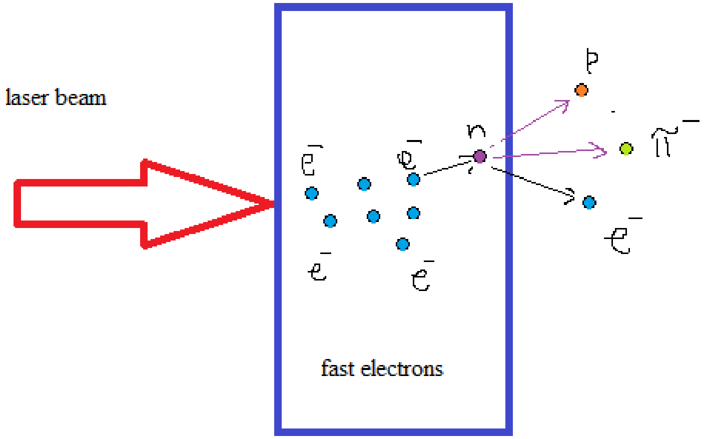
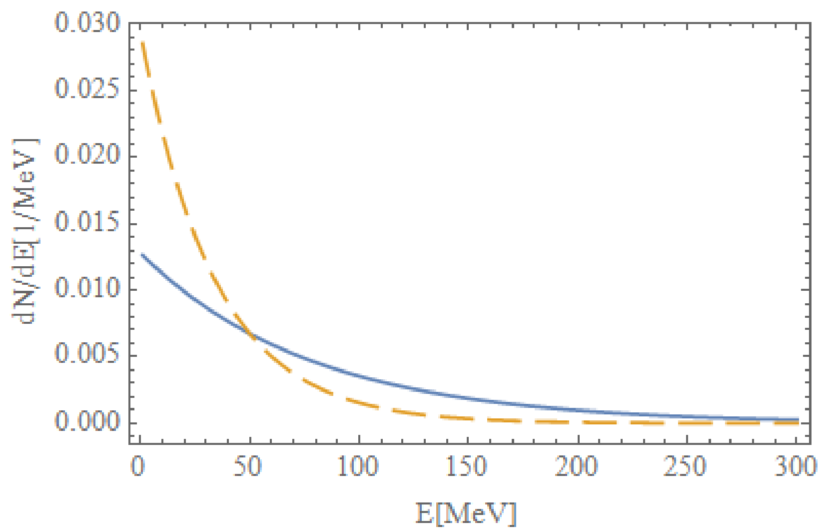
An ultra-intense laser beam incident on a solid target creates a population of fast (suprathermal) electrons, with exponential energy distribution:

$$f(E) \sim \exp(-E/\Theta_s)$$





The „temperature" Θ_s of this distribution scales as (laser intensity)^1/2.

For laser intensities (1-5)$\times10^{22}$ W/cm^2 the parameter Θ_s varies between 34 MeV (solid line on the figure) and 78 MeV (dashed line on the figure).

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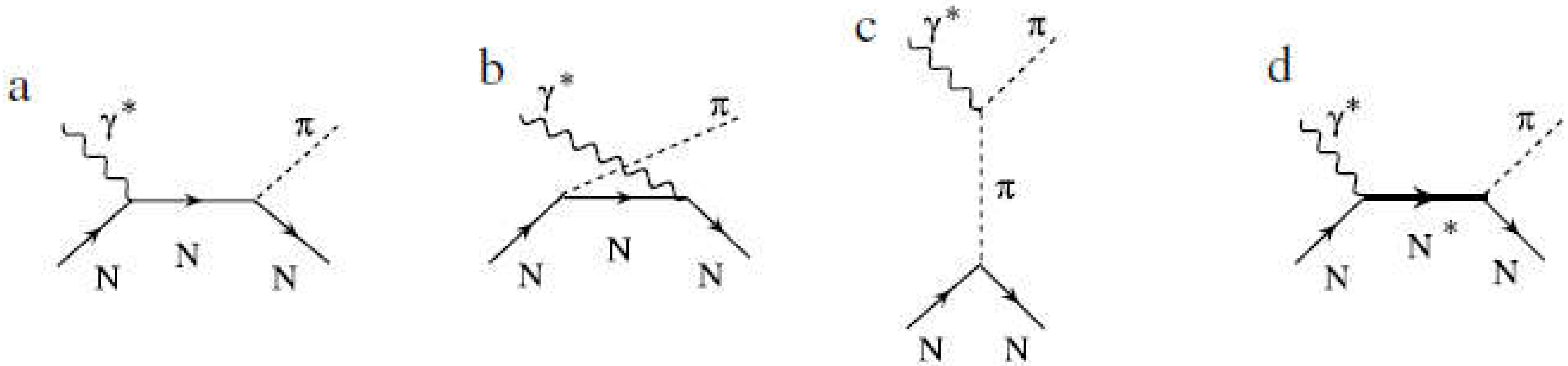
Propagation of fast electrons leads to a prolific e^+e^- pair production.

The next particle production threshold is at 150 MeV – fo single pion production on free nucleons:

$$e + p \rightarrow e' + n + \pi^+ , \quad e + n \rightarrow e' + p + \pi^- , \quad e + N \rightarrow e' + N + \pi^0,$$

which is a result of an effective coupling of virtual gammas to π-N-N system, with the Δ-resonance contribution:



For Θ_s = 78 MeV (solid line on the figure) approximately 15% of all fast electrons have energies above 150 MeV; for Θ_s = 34 MeV (dashed line on the figure) it is 0.1%.

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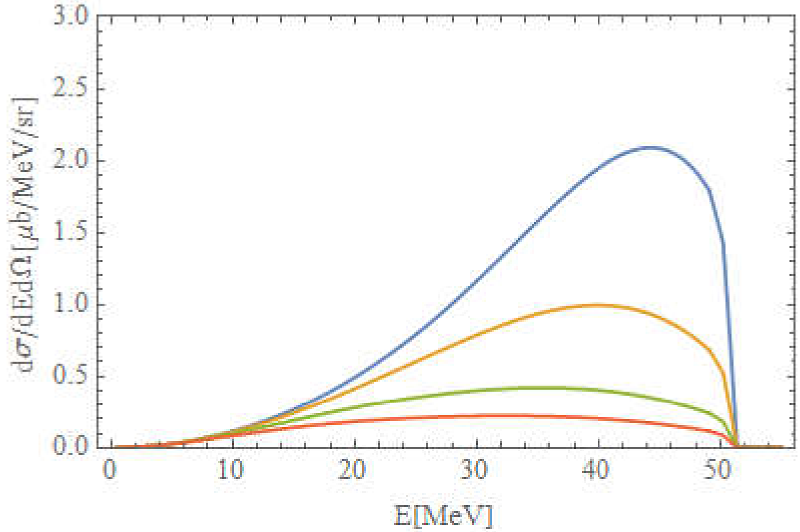
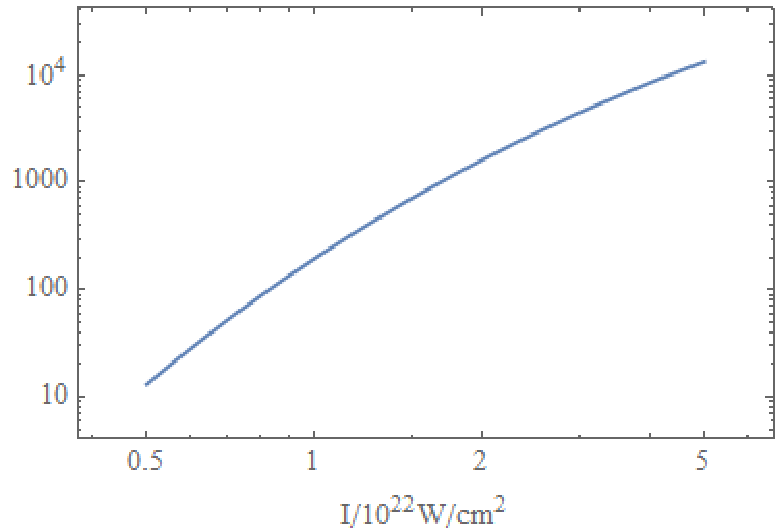
The cross section for pion production, doubly differential in the final electron energy and solid angle, is peaked in the forward direction:



The pion electroproduction cross section for 200 MeV incident electron, as a function of the final electron energy, for several values of the scattering angle of the final electron: 0.0 rad (top curve) , 0.1 rad, 0.2 rad, 0.3 rad (bottom curve), reconstructed from the reaction databases. The maxima of these curves reflect the presence of the Δ resonance.

Assuming laser wavelength 0.8 μm , 20 fs pulse duration, 5 μm diameter of the laser spot, and 30% laser-to-electron energy coversion efficiency, the following estimate is obtained for the number of negative pions produced on a D_2O target with 1mm thickness, as a function of the laser intensity:



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For thick targets the pion production is greatly enhanced due to the generation of high energy real photons and the process of pion photoproduction:

$$\gamma + p \rightarrow \gamma' + n + \pi^+ , \ \gamma + n \rightarrow \gamma' + p + \pi^- , \quad \gamma + N \rightarrow \gamma' + N + \pi^0 .$$

Another process which may lead to pion production is through the laser-accelerated protons:

$$p + p \rightarrow p' + n + \pi^+ , \ p + n \rightarrow p' + p + \pi^- , \quad p + N \rightarrow p' + N + \pi^0 .$$

It is expected that protons with energies of 300 MeV or more – as well as energetic ions with the energy per nucleon of this order - would be generated at ELI-NP through the laser interaction with solid foils of micrometer thickness.

The threshold for pion production of free nucleons is 290 MeV, but it is much smaller for heavier targets - only 140 MeV for p-^{14}N interaction.

It is further reduced if the projectile itself is a heavier ion: it is 23 MeV/nucleon for ^{12}C incident on ^{12}C, which is well within the foreseen capabilities.

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π^0 have lifetime of 0.08 fs and decay mainly to two gammas.

Much more interseting are charged pions: $\pi^{+/-}$ have lifetime of 26 ns, which is long relative to the laser pulse, and they decay mainly to $\mu^{+/-}$ with the lifetime of 2.2 μs.

The advanteges of the laser as a source of pions are the large particle fluxes that may be generated and a short duration of the particle pulse.

Negative pions are of particluar interest, as they may replace electrons on atomic orbits, giving rise to **exotic atoms.**

The Bohr radius in a $\pi^- p$ system is 216 fm, compared to 5.3×10^4 fm for hydrogen. The properties of such exotic atoms are sensitive to strong interactions and offer an opportunity to study these interactions at very low energies.

The reduced dimension of the muonic or pionic hydrogen offer an intersting possiblity of an **enhacement in the DT fusion reactions.**

The muon catalyzed fusion was extensively investigate in cold matter, with ELI lasers we may get the possiblity to investigate this effect and the pion-catalyzed fusion in laser plasma.

F. Negoita et al., *Laser driven nuclear physics at ELI-NP,* Romanian Reports in Physics 68, S37 (2016)