Possibility of measuring the density in the region of compression of a laser thermonuclear target by nuclear-physics methods

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We consider the feasibility of diagnosing the density of a laser thermonuclear target as it becomes compressed, by determining the change of the positron lifetime prior to annihilation with increasing electron density.

Let us estimate the possibility of diagnosing a superdense ($n > 10^{23}$ cm^{-3}) plasma compressed under the action of laser radiation; the diagnosis is based on recording the acts of positron annihilation in the nuclei of the supercompressed target. The difficulty of measuring the density of such a plasma is well known, and the only existing assumption is based on the registration of the line shape in the x-ray region of the emission spectra of the heavy impurities.[1] This is not a direct method and calls for a considerable amount of additional calculated or experimental information.

The cross section for the annihilation of nonrelativistic positrons is given by

$$\sigma = \frac{\pi r^2 c}{v},$$

and their lifetime τ_0 in the medium is

$$\tau_0 = (\sigma v n_e)^{-1} \approx 2{,}3 \cdot 10^{-10} (A/\rho Z), \tag{1}$$

where v is the relative velocity of the electron and positron, $\tau_0 = 2.8 \times 10^{-13}$ cm is the classical radius of the electron, n_e is the electron density (cm^{-3}), ρ is the density of the medium (g/cm^3), and A and Z are the average atomic weight and charge of the target material.

We consider a variant in which only positrons stopped in the targets are used in the measurements. In this case the condition $\tau_{\text{ther}} \ll \tau_0$ should be satisfied (τ_{ther} is the positron thermalization time), and the positron range in the target material should not exceed the target dimensions. These conditions, at a target diameter 200 μ, correspond to a positron energy 50–100 keV, the thermalization time of which to an energy of several keV is $\lesssim 10^{-12}$ sec. The necessary positron flux N_+ is determined by the relation

$$K = N_+ n_e \sigma(v) S t_{\text{eff}} \Delta\tau, \tag{2}$$

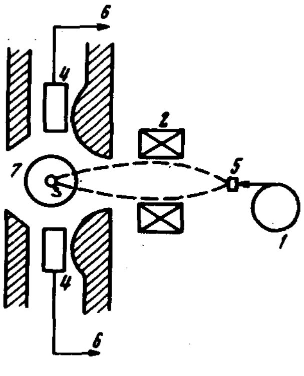
where K is the observed number of annihilation acts, $\Delta\tau$ is the measurement time, t_{eff} and S are the effective thickness and cross-section area of the target.

To ensure sufficient statistical accuracy, we choose $K = 10^4$ at a total measurement time $\Delta\tau \approx 10^{-9}$ sec. The annihilation cross section of positrons thermalized to an energy ~10 keV (expected plasma temperature) is $\sigma(6 \times 10^9 \text{ cm/sec}) = 1.3 \times 10^{-24}$ cm^2, which corresponds, at a 100-fold contraction of a target of 200 μ diameter, to positron fluxes $N_+ \approx 10^{18}$ cm^{-1} sec^{-1}.

Although the production of such positron fluxes is a complicated problem, it is quite feasible. Indeed, from numerical calculations whose results can be found in a number of papers (see e.g., [2,3]) it follows that the yield of positrons of energy $E_+ < 0.5$ MeV from thick converter targets with large Z depends little on the primary electron energy (E_-), on the thickness of the converter target (t), and amounts to 10^{-4} MeV^{-1} sr^{-1} for $E_- = 8$–20 MeV and $t = 1$ rad.un. That is to say, to produce the necessary positron fluxes at short distances from the converter target, the flux of electrons of energy $E_- \leqslant 10$ MeV should be ~10^{23} cm^{-2} sec^{-1}. Such fluxes can be produced, for example, with the aid of an iron-free pulsed betatron[4] with an equilibrium-orbit diameter ≈10 cm and a one-turn beam-dumping system, and correspond to ~10^{12} electrons per orbit in a single acceleration cycle.

One of the possible variants of a setup for measuring the density in the core of a supercompressed target is shown in the figure.

Measurement of a positron lifetime ~10^{-12} sec, corresponding to a compression ~10^2–10^3, while possible in principle, calls for the use of a complicated technique of measuring picosecond pulses (see, e.g., [5]). There exists, however, a simpler and more effective method, based on the fact that if the positron concentration in the target is maintained constant for a time exceeding the compression time (~10^{-9} sec), then a sharp increase of the density in the compression region will cause rapid annihilation of almost all the positrons thermalized in the target, and the ratio of the number of annihilation



Schematic diagram of measurements: 1- batteries, 2- focusing system, 3- laser-heated spherical target, 4- γ-ray detectors, 5- converter target, 6- to coincidence circuit, 7- thermonuclear chamber.

acts in the compressed and normal states of the target yields directly the degree of compression ρ/ρ_0.

The following should be noted in conclusion: 1. Measurement of the total number of annihilation events during the lifetime of a dense core of the nucleus, as seen from (2), makes it possible to determine the mass of the compression region, but it is necessary in this case to know the absolute value of the incident flux of the positrons and their energy spectrum. 2. It is possible to use for diagnostics the region of high compression photonuclear reactions, for example photospallation of the deuteron. Photonuclear reactions, especially the reaction (γ, n), can be particularly effective in the investigation of targets of heavy elements, or of targets with heavy shells.

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