Registration of 14.4 keV ^{57}Fe conversional decay after nuclei excitation induced with the help of plasma created by the powerful femtosecond laser pulse

G. Golovin, D. Uryupina, R.Volkov, and A. Savel'ev

Faculty of Physics and International Laser Center of Lomonosov Moscow State University, 119991, Moscow, Russia

Abstract. Plasma created by the femtosecond laser pulse with intensity 10^{17} W/cm^2 was used as a source of protons with mean energy of 26 keV. Conversional deexcitation of 14.4 keV nuclear state of ^{57}Fe, excited by impact of these protons, was observed. Abnormally high energy transfer (up to 70%) from protons to knocked out electrons was also registered.

Keywords: laser-driven plasma, conversional decay, low-energy nuclear excitation.
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Plasma created by high-power femtosecond laser pulse is well-known source of energetic electrons, ions and x-rays [1, 2, 3]. Even at moderate intensities energy of these products is high enough to excite low-energy nuclear levels [4, 5]. In this paper we report on first experimental prove of internal conversion decay of 14.4 keV isomeric level of ^{57}Fe excited by plasma corpuscular emission.

Experimental setup is shown in Fig. 1. The radiation of a Ti:Sapphire laser (with a pulse duration of 50 fs and an energy of 2 mJ) was focused at an angle of 45° to the surface of a thick steel plate by an aberration-free objective ($F/D \sim 6$) into a spot with a diameter of about 4 μm (target no. 1, an intensity at the focus of up to 10^{17} W/cm^2). The radiation contrast at the nanosecond scale was at least 2×10^{-7} and was determined by a short prepulse from a regenerative amplifier and, in the picosecond scale, by a short prepulse with a relative amplitude of 3×10^{-5} and a lead of 23 ps.

The mean energy of hot electrons in the generated plasma was measured in each pulse by the two-detector filter method [6, 7] from its X-radiation by means of two photoelectric multipliers with 5-mm-thick NaI scintillators and was found to be 13±2 keV on average. After each laser pulse, the target was shifted so that the radiation interacted with a smooth surface rather than with the crater remaining after the previous shot. Ions accelerated in the plasma perpendicularly to the surface of the target no. 1 bombarded a steel plate (target no. 2) situated at the distance of 27 cm from the first target in a separate vacuum chamber. The angle of incidence of ions onto the second target was about 45°.

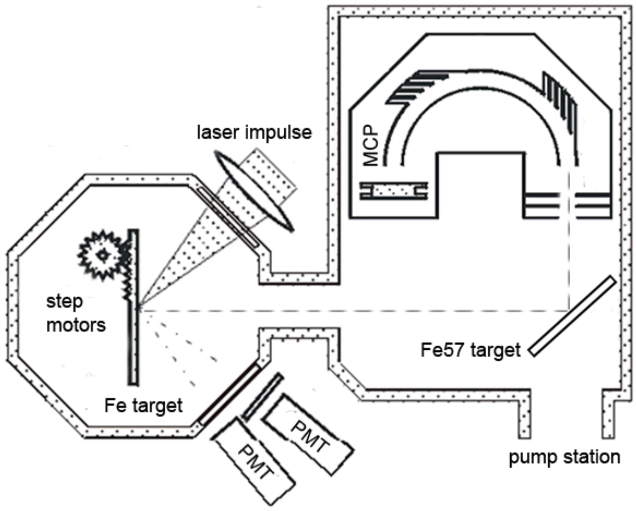

FIGURE 1. Experimental setup.

Electrons knocked out from this target passed through deflecting plates of an electrostatic semi cylindrical spectrometer [7], whose entrance window (2 × 0.5 cm) was situated at a distance of 4 cm from the second target, approximately along the perpendicular to its surface. These electrons were detected by a chevron microchannel plate. Varying the voltage on the plates of the spectrometer, we varied the energy of the detected particles from 6 to 16 keV, and the polarity of the applied voltage determined the sign of the detected particles.

The energy resolution of the spectrometer specified mainly by its geometry was 10%. In the chambers where both targets and the spectrometer were placed vacuum of 10^{-5} Torr was maintained. The electron current from micro channel plate was detected by the digital oscilloscope with a digitization frequency of 2 GHz and a bandwidth of 500 MHz.

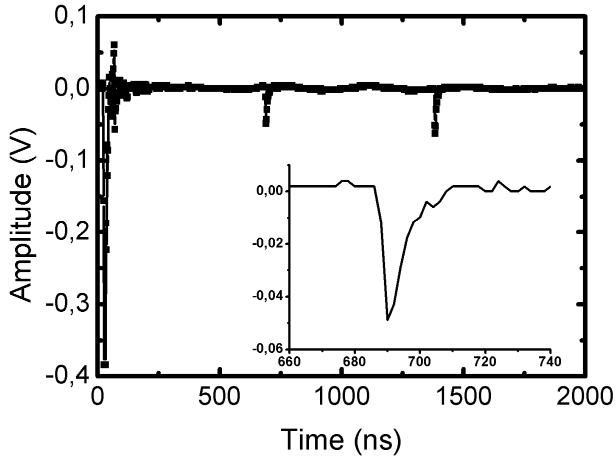

FIGURE 2. Typical signal from micro channel plate.

The typical signal obtained from micro channel plate when detecting negative particles is shown in Fig. 2. According to the preliminary experiments, the detector reacts to the arrival of a single electron by a small typical peak (a sharp front and a smooth drop) with amplitude of more than 10 mV (see the inset in Fig. 2). Such peaks are seen in Fig. 2 at times of about 170 and 690 ns. The sharp minimum near zero time corresponds to a parasitic signal, which was detected by the microchannel plate and was caused by the scattering of X rays and electrons from the plasma by the second target. Indeed, if the distance between the first target (plasma source) and micro channel plate is 50 cm (including the detection path in the spectrometer), 10-keV electrons reach the detector in less than 5 ns. Thus, the front of the given signal corresponds to the plasma production time within the time resolution of the employed detection circuit. In the following overoscillation, the useful signal is indistinguishable, so we could detect electrons only 100 ns after the plasma formation.

Observation of electrons with energy from several to tens of keV appearing with a long delay from the plasma formation instant indicates the presence of some additional mechanism of the production of such electrons. Indeed, an electron produced in the plasma would fly tens of meters before being detected by our spectrometer with delay of about 100 ns and more.

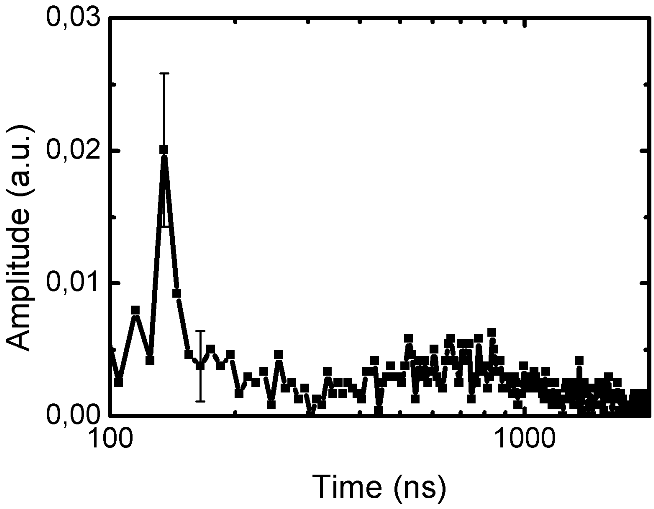

FIGURE 3. Dynamics of the electron current for 6.08-keV detected electrons.

For a number of energies of detected electrons 10000 traces each corresponding to one laser pulse were obtained. A special program automatically identified peaks; as a result, the dynamics of the electron current for each energy was obtained as the number of events (detections of single electrons) versus the time of such detection. In order to estimate the error, the confidence intervals for a confidence level of 0.95 were calculated under the assumption that the probability density of single electron detection has a Poisson distribution. Fig. 3 shows the dynamics of the electron current for 6.08-keV detected electrons.

As seen in Fig. 3, we reliably detected two maxima in the electron current, which have delays of 120–200 and 500–800 ns from the plasma formation instant. Moreover, these typical times are independent of the energy of detected electrons (at least within 10 ns). The most pronounced maximum lies in an interval of 120–200 ns and has an amplitude substantially exceeding the noise level.

In our experiments, the delays corresponding to the observed maxima of the electron current are in good agreement with the arrival times of fast ions (protons and iron ions) from the plasma to the second target. In order to test this assumption, the spectrometer was placed to the position of the second target and the voltage polarity on it was inverted.

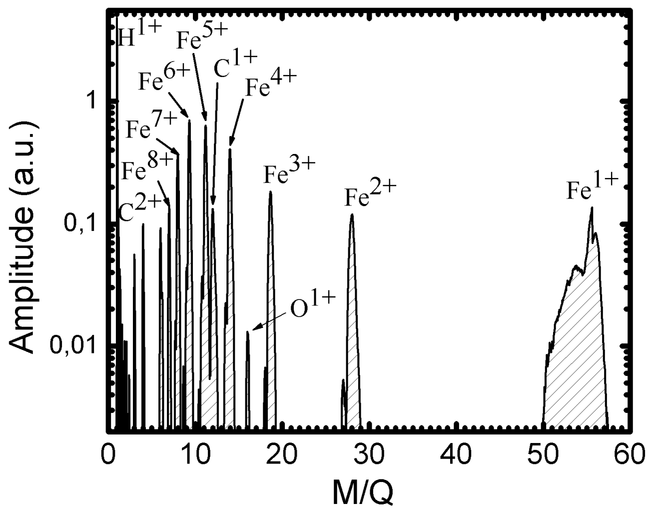

FIGURE 4. Mass spectrum of the ion current from plasma.

Thus, we measured the mass spectrum of the ion current (see Fig. 4), which indicates the presence of asignificant number of protons, as well as carbon and iron ions in this current. Since the time of flight of ions to the detector in this geometry was small, we could not directly measure the energy spectrum of fast ions. At the same time, our previous measurements [8] have shown that the mean energy of fast ions per unit charge is twice as high as the mean energy of hot electrons, i.e., is about 26 keV in this case. The time of flight of 26-keV protons from the first target to the second one is 120 ns, which corresponds to the front of the detected electron-current pulse. The times of flight of 26-keV Fe^{1+}, Fe^{2+}, and Fe^{3+} ions per unit charge are 850, 615, and 500 ns, respectively. Thus, the time positions of the maxima observed in the electron current fully correspond to the times of arrival of fast particles of certain kinds from the plasma.

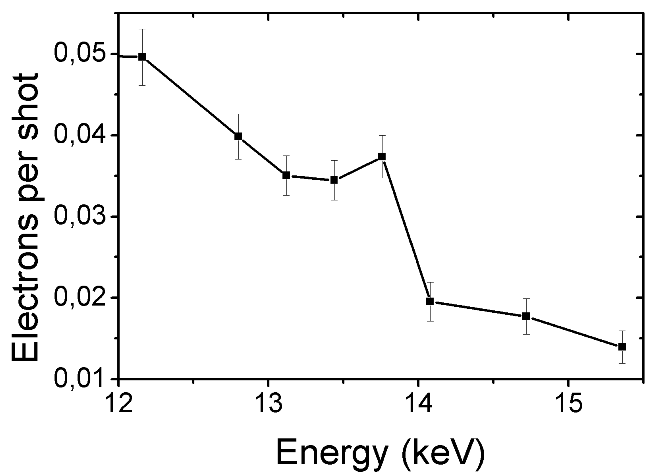

FIGURE 5. Spectrum of electrons from the ^{57}Fe target, knocked out in the interval of 120–170 ns after the plasma creation.

The time dependences of electron currents for different energies of detected particles enable one to construct the electron spectra (or, which is the same, the electron-energy dependences of the double differential ionization cross section) in an arbitrary interval of delays.

The spectrum in the interval of 120–170 ns is of most interest, because the electron signal is maximal at these times and only protons with an energy of 22±2 keV reach the target. Such a spectrum is shown in Fig. 5, where each point represents the number (averaged over 10000 signals) of electrons detected by micro channel plate in an interval of 120–170 ns after the plasma formation per laser pulse. The detected spectrum has 2 components: the smooth background and the peak.

The first component is the result of near to full energy transfer from protons to electrons due to impact ionization. Usually, the incident ion transfers only a small fraction of its energy to an ionized electron. In the limiting case of a free electron, this part is on the order of the electron-to-ion mass ratio. For a bound electron, this part may be significantly greater, because the nucleus increases its effective mass in this case [9]. Actually, we detected electrons with energy 12 – 16 keV, knocked out by protons with energy less than 24 keV, so energy transfer was up to 70%.

There is no interpretation of the second component of detected spectrum (the sharp peak) in the context of purely atomic processes. Indeed, this component is a result of a resonant process, but the maximum bounding energy of electrons in Fe atom is 7,2 keV (K-shell) so the atomic structure is not involved to production of such energetic electrons. We suppose that the excitation of ^{57}Fe ground nuclear level to 14.41 keV isomeric state and its subsequent conversional decay is the key for understanding of this puzzle.

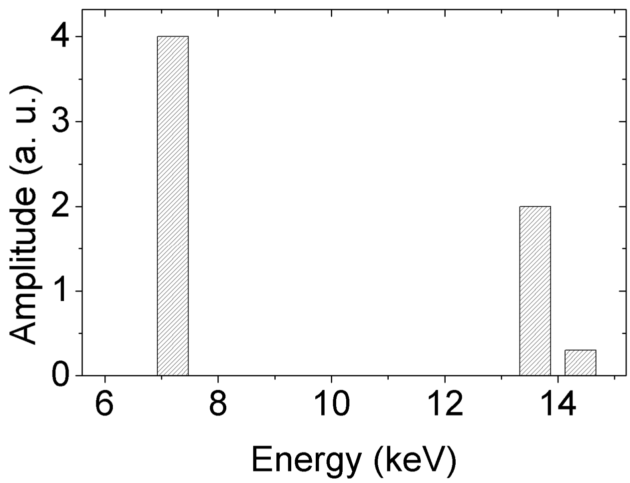

FIGURE 6. The predicted spectra of conversional electrons.

Nuclei of ^{57}Fe, which is the main part of the 2nd target (98%), has the low-energy nuclear state at 14,4 keV. The main mechanism of its relaxation is the internal conversional decay, when excitation energy is transferred to the inner-shell electrons. The products of this type of relaxation are electrons with energies equal to difference between nuclear excitation energy and bound energy of electrons. Quantum mechanics calculation [10] showed that conversion deexcitation would bring to ionization of K-shell with the biggest probability, L1-shell with less probability and so on (see Fig. 6). Then as a result of ^{57}Fe deexcitation we shell expect electrons with kinetic energy equal to 14,4-7,2=7,2 keV (K-shell) and 14,4-0,8=13,6 keV (L1-shell). We registered electrons with energy near to last quantity as the clearest evidence of nuclear deexcitation, and position of detected maximum is in brilliant agreement with the prediction. Taking into account the geometry of our experimental setup (actually, we did not register all of deexcitation incidents) we assume few nuclei excitations events per laser shot.

To conclude, irradiating the surface of a target by a proton beam, we have observed electrons with energy corresponding to the transfer of a substantial (up to 70%) part of the energy from a proton to an electron. The proton beam was generated from a iron target irradiated by a femtosecond laser beam with an intensity of up to 10^{17} W/cm^2. The measured energy spectrum of electrons in a range of 5–16 keV had a smooth quasi-exponential droop with sharp maximum. Smooth part is the result of K-shell electrons impact ionization, sharp maximum is due to 14,4 keV level of ^{57}Fe nuclear deexcitation.key.

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