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Exploring new frontiers in the pulsed power laboratory: Recent progress

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ABSTRACT

One of the most fundamental processes in the Universe, nucleosynthesis of elements drives energy production in stars as well as the creation of all atoms heavier than hydrogen. To harness this process and open new ways for energy production, we must recreate some of the extreme conditions in which it occurs. We present results of experiments using a pulsed power facility to induce collective nuclear interactions producing stable nuclei of virtually every element in the periodic table. A high-power electron beam pulse striking a small metallic target is used to create the extreme dynamic environment. Material analysis studies detect an anomalously high presence of new chemical elements in the remnants of the exploded target supporting theoretical conjectures of the experiment. These results provide strong motivation to continue our research looking for additional proofs that heavy element nucleosynthesis is possible in pulsed power laboratory.

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1. Introduction

Nuclear fusion processes that drive energy production in stars as well as the creation of nuclei as heavy as iron and nickel [1,2] are understood well enough to start conceptual designs of new types of power plants to harness some of these processes [3,4]. Fusion reactions in star interiors as well as those in hot plasma generated in the laboratory environment are based on mechanisms of pair-collision of the reacting nuclei, when their kinetic energy is high enough to tunnel through the Coulomb barrier and engage in strong nuclear interactions.

At the same time, even a theoretical concept of processes in the Universe responsible for the production of nuclei heavier than iron and nickel is incomplete [5–7]. Like fusion models, current models of heavy element nucleosynthesis are based on pair-collision mechanisms involving a capture of free neutrons by target nuclei which then undergo β^- decay moving to higher atomic numbers in the periodic table [8]. Relatively slow neutron capture is called the s-process and takes place in the stable interiors of the massive (several solar masses) stars on time scales ranging from ten million to a few billion years.

Yet if we consider the observed isotope composition of the Universe [9] the model of s-process alone can only explain the abundances of about half of heavy isotopes [10]. Creation of the remaining isotopes is currently attributed to other pair-collision-type processes with the largest contribution by the rapid neutron capture or the r-process, which is theorized to occur solely in type II, core collapse supernovae [6–8,10] on much shorter time scales of a few seconds. R-process models of different levels of sophistication have been constructed over the years, yet unanswered questions are by far more numerous than solved problems [10].

Some answers to numerous unresolved issues in heavy element nucleosynthesis may be found in alternative theories and models. One of these models is the concept of collective nuclear interactions that suggests a nucleosynthesis mechanism occurring on a very short time scale. According to this concept, collective nuclear interactions may be triggered by simultaneous acceleration of all particles in the system. If amplitude and coherency of the acceleration are high enough, these factors may significantly increase the transparency of Coulomb barrier [11]. In this case contrary to pair collisions the strong interactions will be engaged not just between two reacting nuclei but throughout large ensembles of nuclei, which will form heavy nuclear clusters as a result of system self-organization [12,13].

In any finite volume such coherent particle acceleration cannot be sustained indefinitely. Once the acceleration starts to drop these heavy nuclear clusters become unstable and decay into various stable isotopes. Unlike pair-collision nuclear reactions that are

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characterized by specific nuclear products, the nuclear transmutation process driven by the collective interactions produces stable isotopes of virtually every element in the periodic table.

Most of the matter in Universe exists in a state of thermal equilibrium or quasi-equilibrium, which is signified by random particle acceleration. Shock waves that restore thermal equilibrium in the media cannot create the conditions required for coherent particle acceleration for the same reason. Coherent acceleration, however, can be achieved by an action of a long range force, which can be either gravitational or electromagnetic force. In the former case a possible site for such process is type II supernova during its core collapse driven by strong gravitational field of the dying star [14]. It is remarkable that this potential site for collective nuclear interaction process is very close in time and location with the site for the r-process.

The electromagnetic force can also create an environment for coherent acceleration of ions. A radiative collapse of z-pinch [15] is one of the mechanisms that could serve this goal. However, in our research we utilize the effect of an electron beam channel collapse induced by electron beam–solid target interaction and beam self-focusing in the dense plasma [16,17] of the resultant virtual electrodes [18].

In this paper we describe a pulsed power laboratory experiment to test the concept of collective nuclear interactions using a high-power, nanosecond-scale electron beam pulse striking a small metallic target. A material analysis study shows anomalously high concentrations of new chemical elements that are present in the remnants of the exploded target. These elements are spread across the board of the periodic table and are detected in the amounts consistent with energy balance estimations, assuming that they were formed from the original target material.

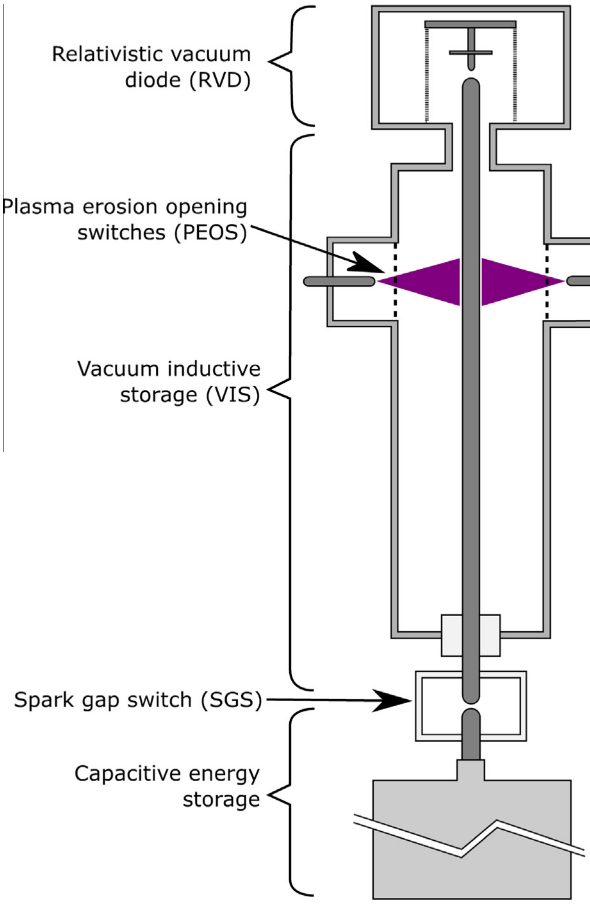

Fig. 1. Schematic of the electron beam pulsed power device.

2. Pulsed power device and the experimental setup

While a manipulation of gravitational field is unattainable in the laboratory, another type of long-range interaction due to the electromagnetic force can be reproducibly generated and controlled in a pulsed power device. Among a variety of pulsed power configurations, an electron beam setup has been selected for its ability to deliver the electromagnetic energy in a single short pulse into a relatively small volume along the central channel of the target producing extremely dense plasma.

We report the results of experiments at our pulsed-power facility IVR-1 in Kiev, Ukraine that uses a 0.5 MV generator producing a 40 kA, 20 ns electron beam pulse to strike a sub-millimeter anode target. The principal scheme of the high voltage pulsed power device and its simplified electric circuit schematic is shown in Figs. 1 and 2A.

The primary features of the pulsed power device are the capacitor energy source, the vacuum inductive storage system, the set of plasma erosion opening switches (PEOS) and the relativistic vacuum diode (RVD). The vacuum systems of the RVD chamber and the inductive storage are combined and maintained at a base pressure of $<5 \times 10^{-5}$ Torr during the shot. The primary function of the pulsed power device is to shape and compress the voltage pulse from the main 3 μF capacitor charged to 50 kV (3.75 kJ stored energy). Pulse compression is performed by an array of twelve plasma opening switches [19–21] axially-arranged around a solid central conductor (cathode) and operated from a separate capacitor bank (see Fig. 2A).

After the main capacitor and PEOS capacitor bank are charged with negative polarity, the spark gap switch for the PEOS is triggered and plasma is generated in the gap between the vacuum inductive storage system and the grounded outer chamber anode, creating a low-resistance short circuit bridge. A few microseconds later, the spark gap for the main capacitor is triggered. The capacitor starts to discharge accelerating current in the vacuum inductive storage system through the short circuit bridge to the ground sustained by plasma in the PEOS region.

An additional microsecond later, the resistance of the plasma bridge in the PEOS region abruptly rises by orders of magnitude on a nanosecond time scale, effectively disconnecting the short circuit plasma bridge. The inductively stored energy is promptly delivered to the RVD inducing a very narrow, $\sim$20 ns, $\sim$0.5 MV voltage spike (see Fig. 2B). The generated electron beam is relativistic with electron velocities $\sim$0.86 c ($\gamma \approx 2$) and estimated peak power up to 12 GW.

The assembly of the RVD [12] is shown in Fig. 3. The anode of the RVD (Fig. 3A) is a cylindrically shaped target with a smooth semi-spherical top, which protrudes through the center of an accumulating screen (Fig. 3B). The electron beam is focused at the tip of the anode target (Fig. 3C) causing the target to explode and "peel open" forming a deep axial channel (Fig. 3D) while ejecting a significant part of the target material on the accumulating screen (Fig. 2E). The cathode plate, the anode target, and the accumulating screen were fabricated from ultra-pure copper (99.9999% metals basis purity, Alfa-Aesar).

3. Material analysis of accumulating screens

According to the concept of the transmutations produced by the collective nuclear interactions, various elements should be generated in detectable amounts from the break-up of the heavy nuclear clusters. We undertook material analysis of the target explosion particles in order to directly examine the products of the

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