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by Ultra-High Magnetic Field Pressure.

II. Results of the Experiment

Post-shot Report

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Isentropic Compression of Condensed Argon by Ultra-High Magnetic Field Pressure. II. Results of the Experiment

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The paper presents the main results of the second experiment on isentropic compression of condensed argon by ultra-high magnetic field pressure, using magnetocumulative generator MC-1. The work has been done within the scope of VNIIEF-LANL 0002P0004-95 contract, task-020. During the experiment the initial magnetic field of MC-1 generator (140 kOe) was measured, the state of electroconductive properties of a compressed sample was registered, a pulsed X-ray image of a compression device was exposed, and all events of the experiment were synchronized at the timescale of compression process. During the joint Russian-American study of the argon isentropically compressed by megabar pressure it was recorded for the first time the argon's conductivity state under compression of ≥ 4 times, according to the estimates based on the experimental X-ray image.

1. Experiment Arrangement

Isentropic compression device arranged vertically includes two-cascade magnetocumulative generator MC-1, which solenoid (the first cascade) is powered by the discharge of a powerful capacitor bank. Under the firing table with a generator a six liters Dewar vessel with liquid nitrogen is located. Above a generator along its axis a cryotube of liquid nitrogen, consisting of two coaxial thin-walled tubes of stainless steel is inserted in such a way that the lower end of a cryotube comes very close to the Dewar's bottom. Also from above a compression tube is inserted into the cryotube. A tube is connected to the capacity with gaseous argon.

After signal cables are connected and measuring diagnostics checked, the volume under the liquid surface in a Dewar vessel is closed, pressure increases as a result of nitrogen evaporation. As a result of that liquid nitrogen goes upward, flows over the compression tube and cools it down to the nitrogen boiling temperature, which is checked by watching boiling nitrogen close to the upper end of a cryotube. Argon is condensed in a lower part of a compression tube, coming sequentially from a liquid state to a solid one. Since the temperature of argon freezing is close to the nitrogen boiling temperature, one can be confident enough that the whole volume of a compression tube is filled first with liquid argon and only then argon freezes, so voids in the frozen argon could be only in the most upper part of a compression tube, going beyond the limits of a compression space. At this stage of the experiment the preliminary radiograph of the compression device, prepared to be fired is exposed. The external view of the device is given in Fig.1. After trigger cables are connected, detonation takes place.

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Figure 1. A picture of the isentropic argon compression device ready to be fired.

The design of a compression tube is explained by the main goal of the experiment - the recording of the expected argon transition into a conduction state, that is why it must provide the predicted conditions of argon transition into a conduction state and possibility to record this transition. That is why, first of all, the weighting layer of tungsten alloy was added to the compression tube. Second of all, its length is more than compression area length in order to exclude the edge effects. Finally, the copper electrode of the measuring circuit, recording the conductive properties of a compressed sample, goes through the tube axis. Fig. 2 shows a sketch of the compression tube with the main tube and sample dimensions.

To record the expected transition we used a simple and from our perspective reliable method of direct measurement of sample conductivity, that is two electrodes with a sample in between. As it is seen from the sketch the copper electrode is located at the axis of the compression tube. The second electrode is the compression tube itself. Both electrodes above beyond MC-1 generator are closed into a resistor of ~ 1 Ohm, along which during the experiment a current pulse flows with an

Figure 2. A sketch of a compression tube.

amplitude of ~ 200 A and duration more than 100 μsec at a half-max. Voltage drop at a resistor is recorded by an oscilloscope. When conductivity appears in a sample the sample by-passes around the standard resistor, voltage drop at a resistor decreases. It is possible to estimate the value of sample resistance (or its upper boundary, if the voltage on the standard resistor drops to zero) by the value of that decrease, knowing the parameters of a measuring circuit - in the first approximation those are ohmic resistance and inductance of a compression tube.

The operation conditions of a compression facility were checked by the measurement of MC-1 generator initial magnetic field, using two inductive probes located on a surface of the second cascade of a generator. The signals from the probes are also used to determine the beginning of implosion of MC-1 generator liner, i.e. the beginning of a time scale of isentropic compression facility. At some moment sample compression was measured by pulsed radiography of a compression facility. The moment of picture exposure was determined using oscillograms of a signal from X-ray radiation probe.

II. Results of the experiment

Figs. 3, 4 give signal oscillograms from initial magnetic field derivative probes dB_0/dt and a signal oscillogram from a system recording the conducting sample state, recorded on digitized oscilloscopes. The procedure of data processing from analog and digital oscilloscopes aiming to get quantitative information was described earlier^{1,2}. From oscillograms of initial magnetic field probes a value of the initial magnetic field $B_0 = 139^{+2}$ kG has been got and also a moment of the beginning of

¹ M.I. Dolotenko. Isentropic Compression of Materials with MC-1 Generator Magnetic Field Pressure. A.I. Pavlovskii Team Activity Review. Review report, subcontract 4756M0014-9Y, 1994, 133 p.

² A.I. Bykov et al. Condensed Argon Isentropic Compression with Ultrahigh Magnetic Field Pressure: Results of the Experiment. Post-shot report, subcontract 4756M0014-9Y, 1994, 10 p.

MC-1 shell implosion at a time scale of an experiment $T_0 = 87.85^{+0.02}_{-0.02}$ μsec has been found. This moment of time is taken as a beginning of isentropic compression process. A moment of radiograph exposure $T_\gamma = 17.19 \pm 0.02$ μsec is defined at a time scale of that process.

Figure 3. A signal oscillogram of an initial magnetic field derivative probe from a digital oscilloscope.

Figure 4. A signal oscillogram of a circuit recording appearance of conductivity in a compressed argon.

The most interesting and important oscillograms in the experiment are those of a signal from a circuit recording a

conducting sample state, where one can clearly see the transition of a compressed sample into a conduction state and coming back into non-conduction state, evidently, after removing a load. Fig. 5 once again shows the fragment of the oscillogram of this signal. A time scale of a compression process is applied to it, the radiograph exposure moment is marked as well. Conductivity in a compressed argon begins at $\sim 16,9 \mu\text{sec}$ of a compression process and begins to disappear at $\sim 17,5 \mu\text{sec}$. The change of compressed sample resistance between these moments was found by using the equation of a measuring circuit, in which parallel to a standard resistor a contour with constant inductance of a known value and resistance changing in time is connected. The measuring circuit is powered by quasi-constant current. According to the voltage on a standard resistor one determines contour resistance, which, as it is shown in Fig. 5, changes from infinity to $\sim 0,3 \Omega$ and back to infinity.

Figure 5. An oscillogram fragment (solid) and a plot of conduction of a compressed sample (time scale of compression process).

Digital processing of radiographs - preliminary and experimental, which prints are given in Fig. 6, and the resulting densitograms: experimental and computational, given in Fig. 7, showed that in $\sim 0,3 \mu\text{sec}$ after conductivity appears, argon compression is $4,9 \pm 0,2$.

Figure 6. X-ray images of the compression tube and 2nd cascade with sample inside: preliminary (upper) and test (lower). Magnification $1:1 \sim 25$.

Figure 7. Fragments of experimental and computational densitograms of preliminary and test radiographs of a compression tube with solid argon.

III. Discussion of the results

According to one of the latest theoretical works having the most detailed and convincing analysis of argon properties with megabar pressures³ with growth of substance compression value p/p_0 (in our case argon with the temperature close to the temperature of nitrogen boiling, $p_0=1.6449/\text{cm}^3$) the following sequence of phase modifications is expected: under the compression < 4.3066 transition from face-centered cubic (fcc) into hexagonal close-packed (hcp); then under the compression 7.2746 transition into body-centered cubic (bcc) and finally, under the compression 10.4528 back to fcc. It is also shown there that a gap between a valence band and a conduction band, which width under zero pressure in hcp structure is 14.3 eV, disappears under the compression 5.27765 (for fcc and bcc, under the compressions 5.784 and 5.4828, correspondingly). The copy of the publication by LANL physicists, kindly given us by Steve Younger right after the experiment, has different data⁴. According to that article the fcc $\rightarrow$ hcp transition has to occur under the compression 4.094, this is close enough to the data [3], the new fact is the conclusion [4] that hcp is stable up to 20 Mbar pressure. In addition according to their calculation the value of argon compression with which the transition of its hcp-phase into a conduction state is a bit more than in a predicted one in work [3], i.e., 5.578. For fcc and bcc critical compressions differ not so significantly: 5.727 and 4.916, correspondingly.

In the experiment argon compression is measured not at the moment of measuring circuit shorting, but in ~ 0.3 μsec later, however, argon compression measured by a radiograph is significantly less than that predicted by theorists, i.e. at the moment of conductivity appearance the argon compression is, evidently, even less. According to our numerical model argon compression 0.3 μsec before experimentally recorded number 4.9 is approximately equal to 4. From our perspective this important experimental result requires additional verification and analysis. As a matter of fact we do not know specific way of a measuring current along a sample, so we can not estimate the value of sample substance conductivity and precise substance compression at phase transition (because of possible high radial pressure gradients over the sample cross-section). So we consider it reasonable while continuing analysis of compressed argon properties to separate experiments on different directions: in some experiments to study compression behavior; it would be preferable to use in these experiments continuous radiography of a compression tube cross-section. In other experiments to try to measure the value of conductivity of argon con-

³ A.K. McMahan. Structural Transitions and Metallization in Compressed Solid Argon, Phys. Rev. B, B33, 5344, 1986.

⁴ I. Kwon, L.A. Collins, J.D. Kress, and N. Troullier. First-Principle Study of Solid Ar and Kr under High Compression, 1995, 13p.

duction phase in a tube with a known way of measuring current flow.

IV. Conclusions

During the joint VNIIEF-LANL experiment isentropic compression of solid argon by ultra-high magnetic field pressure of MC-1 generator has been conducted. For the first time we reliably recorded the fact that conductivity appears in solid argon, compressed more than by a factor of 4. We estimated the resistance of a compressed conductive sample, which decreases in a compression process from ∞ to ~ 0.3 Ohm and in ~ 0.6 μ sec increases again up to ∞ . We propose to continue analysis in different experiments and study behavior of argon compressibility and measure the value of electrical conductivity of argon conduction phase.