Neutron Production in Linear Deuterium Pinches*

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DURING experiments performed in 1954 we observed neutrons from a linear deuterium pinch, similar to observations described later in the excellent report of Kurchatov.[1]

The simple theory of the dynamic pinch is now rather widely understood[2–9] so that only a brief summary of some of the ideas will be given. If a longitudinal electric field is suddenly applied to a cylinder of ionized low-density gas, a longitudinal current flows in a thin layer at the surface of the plasma and the column collapses radially under the magnetic pressure. A shock wave preceding the current sheath goes through the axis and reverses the direction of the current sheath, causing the column to expand. The plasma may expand and contract several times before instabilities destroy the ordered motion, and the dynamic "bouncing" can be observed by the voltage changes across the circuit. Each bounce can be recognized by the characteristic change in inductance, and consequently the hydrodynamic behavior can be compared quite accurately with theory. This theory[9] is in sufficient agreement with the hydrodynamics observed so that the first bounce time can be predicted to within a few percent from known values of condenser capacity, voltage, inductance, tube diameter, and initial gas density. With this basis for believing the theory, the ion kinetic energy just before first bounce can be predicted accurately, and in the case of these experiments was quite high, 215 ev, and so—perhaps naively—a thermonuclear yield was thought possible.

The circuit used is simply a large capacitor bank, 12 μf, charged to 30 to 50 kv in series with a spark gap switch and a linear, cylindrical pinch discharge tube. A large number of discharge tubes were tried in order to optimize neutron yield. For the results quoted here the pinch tube was quartz 7.5 cm in diameter by 45, or, in some cases, 90 cm long.

Neutrons were identified as soon as deuterium gas was used in the discharge—10^7 to 10^8 neutrons per pulse. The first measurement that created an optimism that the neutrons might be from a thermonuclear origin was the timing of production. This showed that the neutrons were generated at the second or third bounce time when the external voltage across the tube was small—7 to 10 kv compared to the original 40 to 50 kv—and also at a time when the additional irreversible heating of reflecting shocks—bouncing—could be expected to give the maximum temperature.

The following experiments, performed in a few months, no doubt could and should be done more accurately, but the enthusiasm for even a qualitative understanding outweighed consideration of long running-time for better statistics.

(1) The neutrons were observed at the time of the second or third bounce in a pulse 0.2 to 0.3 μsec long.

(2) The yield was observed to be uniform along the length of the tube with a fractional length resolution of 10% and a magnitude resolution of plus or minus 20%. The yield fell to one-half value plus or minus 20% opposite either electrode.

(3) By means of our absorption measurement the neutron yield was observed to originate from the region of the central axis of the tube with a full width at half maximum of 1.5 cm compared to a tube diameter of 7.5 cm. The observed width seemed to be due to fluctuations in the position of the pinch from shot to shot and therefore indicated that the reacting column was less than 1 cm in diameter.

(4) The neutron yield—although erratic from shot to shot—was strongly quenched by the addition of a small percentage of the order of $\frac{1}{2}$% of argon but is reduced only stoichiometrically by addition of He.

(5) The yield was observed to originate simultaneously along the length of the tube within a time difference of 5% of the transit time of a 50-kev deuteron from one electrode to the other, thereby excluding the possible mechanism of a sheath drop at one electrode accelerating a few deuterons through the plasma and causing reactions within the plasma column.

(6) The neutron yield became a maximum with initial deuterium pressure at 200 microns Hg and fell by an order of magnitude at 50 and 500 microns, respectively.

(7) The neutron yield increased rapidly with capacitor voltage from 15 to 30 kv but then leveled off and became a maximum by 40 kv. The yield was actually reduced at 50 kv.

(8) An initial axial magnetic field of 100 gauss reduced the neutron yield by a factor of 10.

These experiments were strongly suggestive of a thermonuclear origin with the possible exception of numbers (6), (7), and (8), but these could be explained away on the basis of possible interference with the process of initial ionization and sheath formation. The yield, however, of 10^7 to 10^8 neutrons per pulse was inconsistently large compared to a calculated thermonuclear yield from the dynamic heating, and so a nuclear emulsion experiment was performed in order to observe any inconsistency in the center-of-mass velocity distribution of the reacting deuterons.

One characteristic of a thermonuclear reaction is that the reacting center-of-mass of any two deuterons should be statistically stationary in the laboratory frame of reference. This is in contrast to the case of an accelerated beam striking a target, in which case the reacting center-of-mass has a directed momentum equal to the incident particle momentum in the beam. The resulting velocity of the reacting system results in a nonisotropic velocity distribution (in the laboratory frame), and so consequently the reaction products will show a nonisotropic energy distribution.

(9) The range and consequently energy of proton recoils due to neutrons from the linear pinch were observed in nuclear emulsion plates exposed at either end of the pinch tube. The calculated neutron energies were then interpreted in terms of the energy required of an incident deuteron colliding with a deuteron at rest to give the observed neutron energy in the direction of observation. The resulting histogram clearly showed a shift corresponding to 50-kev deuterons striking deuterons at rest in the direction corresponding to the acceleration of a deuteron in the applied electric field. This shift was toward higher energy at the negative end of the pinch tube, and correspondingly there was an equal and opposite shift toward lower energy at the positive end of the pinch tube. These distributions interchanged appropriately when the polarity of the supply voltage was changed. The full width at half maximum was about equal to the shift, but the reproducibility with change in supply voltage polarity left no doubt that a thermonuclear origin was clearly excluded and that we were dealing with some kind of accelerating mechanism that in some cases gave deuterons up to 200 kev.

The denial of the optimistic conclusion of a thermonuclear yield despite so many favorable results was indeed a sobering experience. A theory for the acceleration of the deuterons due to the rapid growth of the $m=0$ or sausage instability[10] has been developed that qualitatively accounts for the observed behavior. After a bounce or two this instability has grown far enough so that its later nonlinear growth is very rapid indeed. The voltage across such an instability due to its corresponding large and rapid change in inductance becomes of the order of 50 kv when the radius becomes small, like $\frac{1}{10}$th the pinch radius. Deuterons accelerated across this potential will give approximately the observed yield and, in addition, in agreement with experiment, one would expect a small amount of trapped axial magnetic field to stabilize this instability at the small radius required for the high voltages. In a recent different experiment on a dynamic deuterium pinch partially stabilized by an external axial magnetic field, we have observed a small neutron yield (of the order of 10^5) strongly correlated to the growth of the $m=1$ or corkscrew instability. We can recognize the growth of this corkscrew mode quite uniquely by observing the large, sudden, and rapid change (decrease) in the external axial magnetic field component due to the effect of wrapping the pinch into a helix with its resulting "solenoidal" field. The pitch of this solenoid is always just such as to decrease the external field and so can be recognized as a major change in the symmetry of the pinch. A reacting center-of-mass velocity distribution measurement has not been made because of the small yield; however, it seems highly unlikely that an axially shifted distribution can originate from a deformation in which the electric fields are clearly circular rather than axial. In the event of a symmetric distribution, a thermonuclear origin still cannot be claimed because the likelihood of a small accelerated component seems justifiably high, considering the sobering experience in the case of a straight dynamic pinch. It is therefore tentatively suggested that a thermonuclear yield cannot be proven by simply a large number of corroborating neutron measurements but instead must in addition be in agreement with a basic understanding and with measurements of the plasma physics.

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