Hydrodynamic effect in the passage of fission fragments through condensed matter

V. I. Gol'danskiĭ, E. Ya. Lantsburg, and P. A. Yampol'skiĭ

Institute of Chemical Physics, USSR Academy of Sciences
(Submitted February 3, 1975)
ZhETF Pis. Red. **21**, No. 6, 365–367 (March 20, 1975)

When fission fragments pass through condensed matter, the hydrodynamic mechanism of energy transfer causes a short-duration compression of the matter in the vicinity of the fragment track; this, in turn, can increase the concentration of the active particles that stimulate the course of various chemical processes.

1. When heavy charged particles pass through matter, a very high energy is released over a short path length. Thus, the specific ionization for fission fragments is $\approx 30\,000$ MeV-g^{-1} cm^2, with up to 90% of the particle kinetic energy transferred to the medium that produces the deceleration. Let us estimate the volume energy

released when a fission fragment passes through a condensed substance (say, water). The fission fragment range amounts to $L_f \approx 2.6 \times 10^{-3}$ cm.[1] The fragment track width is determined by the mean free path of the secondary electrons that are produced when the fission fragments interact with the atoms of the medium. According to the data of[2] the track radius is $R_0 = 6 \times 10^{-7}$ cm. Thus, the region in which the fragment kinetic energy is released is a cylinder of length L_f and radius R_0. The volume of this cylinder is $V_f = \pi R_0^2 L_f = 3 \times 10^{-15}$ cm^3. The initial fission-fragment velocity is $(1-1.4)\times 10^9$ cm/sec, the time of flight is $t_f \approx 10^{-12}$ sec. The time of flight of the secondary electrons is less then t_f, about 10^{-15} sec. The time t_f is much less than all the other characteristic energy-dissipation times. It can therefore be assumed that the entire energy of the fission fragment is released inside the track volume instantaneously. Assuming a fragment energy $E = 100$ MeV, then the density of the released energy is $E/V_f \approx 5 \times 10$ erg/cm^3, corresponding to an approximate pressure 50 kbar.

2. The effect of the released fragment kinetic energy on the bremsstrahlung depends on the mechanism whereby this energy is next transferred to the medium. One of the possible mechanism, thermal conductivity, was considered in[3,4]. This process is characterized by a time $t_{tc} \sim L^2/\chi$, where χ is the thermal diffusivity coefficient, on the order of 1.4×10^{-3} cm^2/sec for water, and L is a certain characteristic dimensions (e.g., the length L_f or the radius R_0 of the fragment track). It seems that the energy can be transferred to the medium more effectively by a hydrodynamic (HD) mechanism. Indeed, the characteristic HD time is $t_{hd} \sim L/c_0^2$, where c_0 is the speed of sound in the condensed medium ($c_0 \approx 1.5$ km/sec for water). It is easy to verify that for L on the order of L_f or R_0 we have $t_{hd} \ll t_{tc}$. The validity of using the HD description of the transfer of energy from the source to the medium is determined by the fact that the characteristic linear dimensions of the perturbation region are much larger than the intermolecular distances and the free paths of the particles of the medium.

3. Let us describe the indicated HD transport mechanism for energy first released inside the track, assuming that we deal in essence with propagation of a shock wave whose front is concentrated on the cylindrical surface of the source. Since the transverse dimension of the track is much smaller than its longitudinal dimension, we obtain the estimate for a shock wave from an infinitely long "filamentary" instantaneous source with a specified energy release E_0 per unit "filament" length. Let $D = dR/dt$ be the rate of propagation through the medium, of a shock-wave front (SWF) of radius $R(t)$, let v be the velocity of the medium behind the SWF, let ρ_0 and ρ be the densities of the medium ahead and behind the SWF, and let P be the pressure on the SWF, assumed much larger than the "pressure" ahead of the front. We then obtain from the conservation conditions for the mass, the momentum on the SWF, and the energy in the region enclosed by the front,

$$E_0 = \pi R^2 \rho_0 D^2 F(\delta, n), \quad P = \rho_0 D^2 (1 - 1/\delta), \qquad (1)$$

where $F(\delta, n)$ is the compression function, $\delta = \rho/\rho_0$, which will be regarded here, for estimating purposes, as a certain parameter, and n is the exponent in the "equation of state" of the medium $P \sim \rho^n$ (in this form, the equation of state takes into account only the "cold" part of the pressure, since the "thermal" part of the pressure can be neglected under our conditions). In condensed matter, at a pressure on the order of 10^4-10^5 atm, the compression does not greatly exceed unity; for water, e.g., $\delta \leq 2$, and in addition $n = 7$ for water. For $\delta = 3/2$ and $n = 7$ we have $F \approx 0.3$.[1)] Solving the differential equation (1) under the initial conditions $t = 0$ and $R = R_0$, we get $R(t) = R_0(1 + t/t_0)^{1/2}$, where $t_0 = R_0^2(\pi F \rho_0 / 4E_0)^{1/2}$. For $R_0 \approx 6 \times 10^{-7}$ cm, $F = 0.3$ ($\delta = 3/2$), $\rho_0 \approx 1$ g/cm^{-3} and $E_0 = 10^5$ MeV/cm it follows that $t_0 \approx 10^{-12}$ sec, i.e., on the order of the time of flight of the fragment in the medium. Consequently, the SWF velocity is $D \approx 0.34\sqrt{t}$ cm/sec and the pressure is $P \approx 5.8 \times 10^{-8}/t$ atmospheres (the time t is in seconds). For $t \approx 10^{-12}$ we get from these formulas $R \approx 0.7 \times 10^{-6}$ cm, $D \approx 3.4$ km/sec, and a pressure $P \approx 6 \times 10^4$ atm, which corresponds to the initial conditions. The estimated values of D and P are close in order magnitude (accurate to several units) to the experimental values for water,[6] viz., at $P \approx 56.8$ kbar, $\delta \approx 1.52$, $D = 4.09$ km/sec, and $v = 1.39$ km/sec. Since the pressure developed in the vicinity of the fragment track increases like ρ^3 for media of close elemental composition, where ρ is the density, it follows that the HD effect will be more strongly pronounced in a condensed medium heavier than water.

4. Shock compression of water leads to an abrupt increase of the electron concentration. Thus, according to[7], at an approximate pressure 60 kbar the electron conductivity of water, (and hence the electron concentration) increases by 10^4 times the value at normal pressure.

Thus, when fission fragments pass through condensed matter, particularly biological tissue, the HD mechanism must be taken into account in addition to the other energy-transfer mechanisms. As a result of the short-duration compression of the medium in the vicinity of the fragment track, a shock wave is produced and is accompanied by a jump in the temperature behind the front. This increases the concentration of the active particles (electrons, ions, radicals) capable of stimulating various chemical processes.

1)To simplify the estimates it was assumed in the determination of the function $F(\delta, n)$ that all the parameters are uniformly distributed inside the region enclosed by the wave.

1Spravochnik po yadernoĭ fizike (Nuclear Physics Handbook), ed. by L.A. Artsimovich, GIFML (1963).

2A. Mozumder, Adv. Rad. Chem. **1**, 80 (1969).

3V.I. Goldanskii and Yu.M. Kagan, Intern. J. Appl. Radiat. Isotopes **11**, 1 (1961).

4I.M. Lifshitz, M.I. Kaganov, and L.V. Tanatarov, Atom. Energ. **6**, 391 (1959).

5R.H. Cole, Underwater Explosions, Peter Smith.

6J.M. Walsh and I. Rice, J. Chem. Phys. **26**, 815 (1957).

7H. David and S. Haman, Trans. Farad. Soc. **55**, 72 (1959).