FISSION THEN AND NOW

by
John Archibald Wheeler
PALMER PHYSICAL LABORATORY
PRINCETON UNIVERSITY

Pure and Applied Nuclear Physics

Niels Bohr landed at west 57th Street in New York about 1 p.m. on a cloudy day, Sunday, 16 January 1939. He brought with him the observations of Hahn and Strassmann, the explanation of Frisch and Meitner, and considerations of his own. His arrival marked for many investigators the beginning of a new phase of pure physics.

In September the war began. The demands of defence brought applied nuclear physics into being.

Can the universal of pure science be said to be built out of "conclusions" (CON)? Does the action-oriented of applied science consist of "decision data" (DEDA)? If this distinction makes sense (J. W. Tukey), then rarely have the two activities been so closely intermingled as in the history of fission. To recall briefly a few events of a scientific character out of each enterprise may give a little impression of what happened in the field of fission physics from January 1939 and December 1942, and between December 1942 and now.

DEDA 1. Could Fissility be Concentrated?

Is the fissility of natural uranium under slow neutron irradiation a property of U^{238} and thus not subject to concentration? The answer is no. The fissility derives from the 139-fold less abundant U^{235}. This Bohr convincingly argued as early as the spring of 1939 on the basis of the theory of fission then taking form. No "decision datum" entered as centrally as this into the beginnings of the uranium project. It implied that a divergent chain reaction was achievable in principle. The words "in principle" contained the idea of an isotope separation programme. However, the scale of the necessary enterprise, as Bohr put it at the time, was too fantastic to imagine; to carry it through would demand the efforts of an entire nation. It turned out that he was wrong; the joint efforts of three nations were needed!

Not everyone agreed with conclusions so far-reaching on the basis of evidence so theoretical, especially not one theoretical physicist renowned for the critical clarity of his thinking. George Placzek's doubts - expressed in a 1939 bet of $0.01 against $18.36 - were not stilled until 1940 brought enough separated U^{235} and U^{238} for direct confirmation of theory. A souvenir of his warm heart is a 1940 telegram and telegraphic money order for one cent from Ithaca, New York.

John A. Wheeler (Photo Orren Jack Turner)

DEDA 2. The Fissility of Plutonium

A neutron chain reaction could not help to bring peace unless it developed at an explosive rate and in a small mass. A large slow neutron reactor could at most contribute to this immediate objective by proving ahead of time the concept of a chain reaction.

This assessment had hardly even been clearly sensed by the time when it had to be changed. In March and May 1940 L. A. Turner pointed out consequences of fission theory. (a) The nuclear species Pu^{239} almost certainly had to be fissile. (b) A slow neutron reactor operating on natural uranium would synthesize Pu^{239} at roughly the rate at which it would destroy U^{235}. (c) Chemical separation of this Pu^{239} should be simpler than isotopic separation of U^{235}. Therefore the idea arose to make a production reactor and manufacture a new chemical element. A third horse, a late entry, joined the race with electromagnetic separation and diffusion plant separation of U^{235} to provide a stock of fissile material.

Action started towards the new goal months before there was any direct radiochemical proof of the fissility of Pu^{239}. This proof - when it came (1942) - further strengthened the drive toward element synthesis. So did an inspiring visit in mid-1942 from a British scientific team, concerned that reactor work should pay off in two years, not two decades.

DEDA 3 and 4. Fast Fission and Resonance Absorption

As some features of nuclear structure influenced the broad plan of the plutonium project, so others affected the detailed design of a slow neutron chain reactor. It was clear that fission neutrons have an appreciable chance, while still fast, to collide with U^{238} nuclei. The supplementary fissions brought about in such impacts increase the effective "multiplication factor, k" of the predominantly slow neutron chain reaction. To enhance this "fast neutron effect" it was desirable to concentrate the uranium of the reactor into a lattice of large spheres or cylinders. The same lattice arrangement that enhances this favourable effect had already been advocated by Szilard and Wigner to decrease a competing parasitic effect. Neutrons undergoing moderation have an appreciable chance to take on one or another resonance energy characteristic of the compound nucleus $U^{238} + n = U^{239}$ and undergo absorption. Both this resonance absorption and the fast effect were and still are beyond detailed prediction from first principles. Both have to be characterized by empirical parameters. These and other reactor parameters - "decision data" of a special type - are defined by theory, found through experiment and used to optimize lattice design.

The design of the first "zero energy" reactor was in hand in the fall of 1942. Construction was proceeding without hitch towards success. The next steps ahead occupied the energies of many participants. This one spent 2 December as Chicago representative working with duPont design engineers in Wilmington. Many issues arose in planning a high energy reactor. The physics of fission was central to two of them: control and poisoning.

DEDA 5. Effective Lifetime of One Generation

Control of the total energy and the distribution of energy in a high flux reactor might have been even more difficult than it was. The effective interval from one generation in the neutron chain to another could have turned out to be the time for moderation and capture of the neutron, a period of the order of a millisecond. In this event a slight accidental rise in the multiplication factor k above the steady running level of unity could result within one minute in a catastrophic increase in power. However, the delayed neutrons from certain fission products extended the effective lifetime for one generation from the millisecond level to minutes. Control could be - and was - made safe.

DEDA 6. Xenon Poison

As important to guard against as reactor runaway was reactor stoppage. The products of nuclear fission must themselves absorb neutrons. But how strongly? The stable fission products were investigated thoroughly enough to remove fears that they would poison the reaction. However, the possibility of a radioactive neutron absorber could not be excluded by any evidence from a reactor of low heat output. In such a reactor the abundance of a fission product of limited life is negligible compared to its concentration in a full scale plutonium producer.

Should the Hanford piles be oversized to allow for an unsuspected poison? Experienced chemical engineers know how almost everything that can go wrong will go wrong unless explicitly guarded against. George Graves, a veteran of duPont nylon pioneering, reviewed all the evidence and lack of evidence of fission product poisons. Then he took the courageous decision to spend the extra millions of dollars and the extra days of construction time to build reactors 25 per cent larger than would otherwise be necessary.

The fringe tubes were not loaded with uranium when on 27 September 1944 the control rods were slowly withdrawn from the first Hanford reactor up to the critical point. Cold Columbia River water began to come out hot. Plutonium production continued for some hours without incident. Then the pile began to lose reactivity. The control rods had to be withdrawn step by step to keep the neutron chain reaction self-sustaining. At last the rods were all the way out. No margin of reactivity remained. The reaction came to a halt. The outlet water temperature fell to equality with the inlet temperature.

What had gone wrong? Had the reaction caused some neutron absorbing constituent of river water to deposit out in the tubes? Or had the tubes leaked water into the whole graphite matrix of the reactor? While these and other ideas were being considered, the pile began to gain reactivity. The rods had to be pushed in to keep it under control. The heat output rose to normal and production was resumed. After some hours the multiplication factor again fell off and the pile died.

Anyone concerned for months about fission product poisons, receiving periodic reports about the situation at the laboratory a few miles away, could hardly fail to think of a reasonable explanation. A non-absorbing mother fission product of some hours' half-life decays to a daughter dangerous to neutrons. This poison itself decays with a half-life of some hours into a third nuclear species, non-absorbing and possibly even stable. If this explanation made sense, then an inspection of the chart of the nuclei showed that the mother had to be 6.68 hr I^{135} and the daughter 9.13 hr Xe^{135}. Within an hour Fermi arrived with detailed reactivity data which checked this assignment. Within three hours two additional conclusions were clear. (a) The cross section for absorption of thermal neutrons by Xe^{135} was roughly 150 times that of the most absorptive nucleus previously known, Cd^{113}. (b) Almost every Xe^{135} nucleus formed in a high flux reactor would take a neutron out of circulation. Xenon had thrust itself in as an unexpected and unwanted extra control rod. To override this poison more reactivity was needed.

The reactivity was available. The extra tubes were loaded. Plutonium production was resumed. The level of operation rose week after week. Another pile came into operation, then another.

DEDA 7. Spontaneous Fission

Pu^{239} from the Hanford chemical separation plant and U^{235} from the two kinds of isotope separation operations began to arrive at Los Alamos. However, it would be impossible to assemble a mass of either metal into a super-critical assembly at any then attainable speed if pre-ignition occurred by reason of a substantial natural output of neutrons from the metal. Through the 1939 work of Flerov and Petrjak it was known that natural uranium undergoes spontaneous fission. But was it not reasonable to consider the even-even nucleus U^{238} to be stable compared to U^{235}? Then the observed fission would almost all have to be ascribed to U^{235}. In this case the fission half-life of U^{235} would be as short as 6×10^{13} yrs. The output of neutrons from U^{235} would be so high as to raise the question of pre-ignition. In contrast to this view, direct measurements by Segré and his collaborators on the substantial amounts of separated isotopes by now available gave half-lives with respect to spontaneous fission of 1.8×10^{17} yrs for U^{235} (and 8×10^{15} yrs for U^{238}) and 5.5×10^{15} yrs for Pu^{239} (compared to a later figure of 1.2×10^{11} yrs for Pu^{240}). Whatever the explanation, the fissile nuclei with their odd masses were more stable than expected. Assembly became feasible. 16 July 1945 brought the first test, the era of nuclear weapons, and the beginning of the end of the war in the Pacific.

DEDA 8. Fission Induced by 14 MeV Neutrons

The first full scale thermonuclear device was tested at Elugelab Islet, Eniwetok Atoll, on 1 November 1952. Neutrons of 14 MeV were produced in great numbers. In the new era of thermonuclear devices the effectiveness of such neutrons in producing fission promptly became and has since remained an important "decision datum".

Less than three years later came the first Geneva Conference on the Peaceful Uses of Atomic Energy. Much information previously secret about the fission process was released. Interest was renewed.

A Stark Outline of Fission Physics Today

An account fuller than this would report all the discoveries about fission before and since 1955, and tell in detail who did the work that led to them. However, let the account to follow be stripped of almost all these important details. Let fission as it is understood today stand out in stark outline for comparison with fission as it stood on 16 January 1939. It is difficult to imagine how far one would have come towards the conclusions listed here if there had been no 2 December 1942 and no nuclear technology!

CON 1. Fission by a Neutron with $E_{kin} < 5$ MeV Proceeds Through an Intermediate Stage of Compound Nucleus Formation

When a neutron or other agency of moderate energy bombards a nucleus, it may (a) preserve most of its primary momentum on its way through the nucleus ("direct reaction") or (b) exchange so much energy with the system that a compound nucleus is formed.

The classical analogue of the compound nucleus is a system of particles interacting for so long that they lose all memory of the mechanism by which they came together. The quantum system differs from the semi-classical analogue in that the number of states of a given angular momentum J is not in general proportional to $(2J + 1)$. In consequence, the angular distribution of reaction products is not fully independent of direction. The chance for the compound system to dispose of its energy by neutron re-emission, or radiation, or fission, depends on J-value and parity as well as energy.

Work of recent years has shown that the direct type of reaction occurs with significant probability or even dominates over compound nucleus formation in many situations - but not in fission induced by neutrons with kinetic energy less than 5 MeV. Moreover, whatever the reaction, if it occurs through a well isolated resonance, typical in its properties of levels above and below it, a compound nucleus reaction is said by definition to be involved.

CON 2. The Compound Nucleus Divides by Way of One or Another Fission Channel

One is accustomed in molecular physics to a division of the energy of the molecule between rotation and vibration on the one hand and electronic excitation on the other. That division is defined by a surface which gives the electronic energy as a function of the nuclear co-ordinates. Similarly in nuclear physics a fission channel has to do with a division of the energy of the compound system between collective motion and nucleonic or "intrinsic" excitation. Radiationless transitions occur in polyatomic molecules and in nuclei. The system "slips over" from one such partition of the energy to another. In consequence a fission channel is ordinarily a defined concept only in that limited domain of collective configuration space in which the system is passing over - or under - a potential barrier on the way to fission.

CON 3. Fluctuations in Fission Widths Give Evidence on the Number of Accessible Fission Channels

Compare the compound nucleus to an auditorium and a resonance state to a standing sound wave. Then the probability per second of fission through the k th channel, A_{f_k} - or the partial width $\Gamma_{f_k} = \hbar A_{f_k}$ of the resonance level with respect to fission - is to be compared with the fraction of the sound emerging per second out of a selected small window. This fraction fluctuates from one resonance to another about a certain average value $\langle\Gamma_{f_k}\rangle$, according to how the "window" and the node of the wave are related.

Experimentally one does not know through which channel the fission has occurred in the usual case of slow neutron induced fission (sound emerging through several windows!). The observed total width of the resonance level with respect to fission is the sum $\Gamma_f = \Gamma_{f_1} + \Gamma_{f_2} + \ldots$ of the contributions from all channels. This width fluctuates little percentagewise from level to level when the number of effectively contributing channels is large, and fluctuates much when this number is small. Thus one finds for the best known fissile nuclei a "fluctuation effective number of channels" in the range from one to four. The experimental situation is still too fluid to allow a sharp correlation between this number and the "yield effective number" found from the absolute value of the average width, $\langle\Gamma_f\rangle$.

CON 4. The Height of the Barrier in the Fission Channel Determines the Yield Number of that Channel

Nest into each window of the auditorium a length of air duct, each duct having a different cross section. Then a given duct transmits effectively to the outside only when the frequency of the sound exceeds a certain critical limit. This critical frequency varies from duct to duct. Similarly in fission. Average the partial width associated with a particular channel over several resonances, divide by the average spacing between resonances, and multiply by 2π. The resulting quantity gives the "yield number" of that channel. For an energy significantly above the fission barrier in that channel the yield number was shown already in 1939 to have the value unity. Well below the barrier the yield number falls exponentially with energy (spontaneous fission). The sum of the yield numbers over all fission channels gives the "yield effective number of channels" N_f.

CON 5. Spontaneous Fission Lifetimes are Longer by a Factor of 10^2 to 10^4 for Odd-A Nuclei than for Neighbouring Even-Even Nuclei

The lowest channel available to a nucleus of $K = 7/2$, for example, (odd A) can be seen to have a lower barrier than the lowest channel available to a nucleus with $K = 0$. Pairs of lowest nucleonic orbitals give $K = 0$ for all elongations of the nucleus, whereas $K = 7/2$ cannot be obtained for all elongations out of the lowest lying single particle states.

CON 6. Rises and Falls in the Fission Cross Section in the MeV Region Mark Access to New Fission Channels and to New Channels for Neutron Re-emission, Respectively

In the auditorium analogy, the fraction of the sound going out of ducts through the north wall rises when the frequency is increased enough to let one new duct in that wall transmit. The fraction falls when one new duct in the other walls starts to transmit. A neutron channel - in contrast to a fission channel - is analogous to a duct of infinite length. It does not transmit at all below threshold.

CON 7. The Angular Distribution of Fission Fragments is Fixed by the Total Angular Momentum J of the Compound Nucleus, Its Projection M along a Space-Fixed Axis, and the Angular Momentum K of the Extended Fission - or Saddle Point - Form about the Axis of Approximate Rotational Symmetry

The quantity K does not remain constant for a time long compared to the time of immediate passage over the barrier. For a given resonance level it usually differs from one channel to another, and is most readily determined from the angular distribution itself.

CON 8. The Neck that Connects the Nascent Fission Fragments Extends and Takes up the Work of the Coulomb Forces until it Thins and Breaks

(a) The kinetic energy of the separating fragments is less by tens of MeV than the energy of spheres in contact. (b) This kinetic energy varies widely from one act of fission to another. (c) The following words seem appropriate to describe the observations on the neutron emission of the individual fragments. The work of extension does not go into general nucleonic excitation of nuclear matter (no "heating"). Sometimes the break in the neck occurs much closer to one nascent fragment than the other. The first fragment is left with too little excitation to emit even one neutron. Almost the entire neck falls back on the other fragment which then becomes excited and emits several neutrons.

Physics Beyond the Barrier

Fission physics "beyond the barrier" appears to be a source of new insights into the nuclear analogue of molecular slipover and the mechanism of interchange of collective and nucleonic excitation.