

Elementary Theory of the Chain-reacting Pile

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THE RESULTS AND THE METHODS DISCUSSED in the following outline of the theory of a chain-reacting pile working with natural uranium and graphite have been obtained partly independently and partly in collaboration by many people who participated in the early development work on the chain reaction. Very important contributions to the theoretical ideas were given by Szilard and Wigner. Many physicists contributed experimental results that helped to lead the way, among them, H. L. Anderson and W. H. Zinn, first at Columbia University and later at the Metallurgical Laboratory of the University of Chicago; R. R. Wilson and E. Creutz, at Princeton; and Allison, Whitaker, and V. C. Wilson, at the University of Chicago. The production of the chain reaction was finally achieved in the Metallurgical Laboratory directed by A. H. Compton.

ABSORPTION AND PRODUCTION OF NEUTRONS IN A PILE

We consider a mass, "the pile," containing uranium spread in some suitable arrangement throughout a block of graphite. Whenever a fission takes place in this system, an average number ($\bar{\nu}$) of neutrons is emitted with a continuous distribution of energy of the order of magnitude of 1,000,000 EV. After a neutron is emitted, its energy decreases by elastic collisions with the atoms of carbon and to some extent also by inelastic collisions with the uranium atoms. In the majority of cases the neutrons will be slowed down to thermal energies. This process requires about 100 collisions with carbon atoms. After the energy of the neutron is reduced to thermal value, the neutron keeps on diffusing until it is finally absorbed. In several cases, however, it will happen that the neutron is absorbed before the slowing-down process is completed.

The neutron may be absorbed by either the carbon or the uranium. The absorption cross-section of carbon for neutrons of thermal energy is quite small, its value being approximately $.005 \times 10^{-24}$ cm.² For graphite of density 1.6, this corresponds to a mean free path for absorption of about 25 m. It is believed that the absorption cross-section follows the $1/v$ law, and consequently the absorption cross-section, which is already quite small at thermal energies, becomes practically negligible for neutrons of higher energy. It is therefore a sufficiently

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good approximation to assume that absorption by carbon during the slowing-down process can be neglected.

The absorption of a neutron by uranium may lead either to fission or to absorption by a (n, γ) process. We shall refer to this last possibility as the process of resonance absorption. The relative importance of fission and resonance absorption in the different energy intervals is not the same. In this respect we can consider roughly three intervals:

(1) Neutrons with energy above the fission threshold of U^{235} —We can call these conventionally "fast neutrons." For fast neutrons the most important absorption process is fission, which normally takes place in the abundant isotope U^{238} . Resonance absorption is smaller but not negligible.

(2) Neutrons of energy below the fission threshold of U^{235} and above thermal energy—We shall refer to these neutrons as "epithermal neutrons." For epithermal neutrons the most important absorption process is the resonance capture. The cross-section for this process as a function of energy is quite irregular and presents a large number of resonance maxima that can be fairly well represented by the Breit-Wigner theory. In practical cases the resonance absorption becomes important for neutron energy below about 10,000 EV and increases as the energy of the neutrons decreases.

(3) Neutrons having thermal agitation energy or "thermal neutrons"—For thermal neutrons both the resonance and fission absorption processes are important. In this energy range both cross-sections follow approximately the $1/v$ law, and therefore their relative importance becomes practically independent of the energy. Let σ_f and σ_r be the cross-sections for fission and resonance absorption for neutrons of energy kT , and $\bar{\nu}$ be the average number of neutrons emitted when a thermal neutron is absorbed by uranium. Then $\bar{\nu}$ differs from $\bar{\nu}_f$ since only the fraction $\sigma_r/(\sigma_f + \sigma_r)$ of all the thermal neutrons absorbed by uranium produces a fission. It is, therefore,

$$\bar{\nu} = \bar{\nu}_f / (\sigma_f + \sigma_r). \quad (1)$$

The preceding discussion leads one to conclude that only a fraction of the original fast neutrons produced will end up by producing a fission process. For systems of finite size, further losses of neutrons will be expected by leakage outside the pile.

Limiting ourselves for the present to systems of practically infinite dimensions, we shall call P the probability that a fast neutron ultimately is absorbed by the fission

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 - The Rise of Digital Reading Elementary Pile Theory
 - Advantages of eBooks Over Traditional Books
2. Identifying Elementary Pile Theory
 - Exploring Different Genres
 - Considering Fiction vs. Non-Fiction
 - Determining Your Reading Goals
3. Choosing the Right eBook Platform
 - Popular eBook Platforms
 - Features to Look for in an Elementary Pile Theory
 - User-Friendly Interface
4. Exploring eBook Recommendations from Elementary Pile Theory
 - Personalized Recommendations
 - Elementary Pile Theory User Reviews and Ratings
 - Elementary Pile Theory and Bestseller Lists
5. Accessing Elementary Pile Theory Free and Paid eBooks
 - Elementary Pile Theory Public Domain eBooks
 - Elementary Pile Theory eBook Subscription Services
 - Elementary Pile Theory Budget-Friendly Options
6. Navigating Elementary Pile Theory eBook Formats

- ePub, PDF, MOBI, and More
 - Elementary Pile Theory Compatibility with Devices
 - Elementary Pile Theory Enhanced eBook Features
7. Enhancing Your Reading Experience
- Adjustable Fonts and Text Sizes of Elementary Pile Theory
 - Highlighting and Note-Taking Elementary Pile Theory
 - Interactive Elements Elementary Pile Theory
8. Staying Engaged with Elementary Pile Theory
- Joining Online Reading Communities
 - Participating in Virtual Book Clubs
 - Following Authors and Publishers Elementary Pile Theory
9. Balancing eBooks and Physical Books Elementary Pile Theory
- Benefits of a Digital Library
 - Creating a Diverse Reading Collection Elementary Pile Theory
10. Overcoming Reading Challenges
- Dealing with Digital Eye Strain
 - Minimizing Distractions
 - Managing Screen Time
11. Cultivating a Reading Routine Elementary Pile Theory
- Setting Reading Goals Elementary Pile Theory
 - Carving Out Dedicated Reading Time
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- Fact-Checking eBook Content of Elementary Pile Theory
 - Distinguishing Credible Sources
13. Promoting Lifelong Learning
- Utilizing eBooks for Skill Development
 - Exploring Educational eBooks
14. Embracing eBook Trends
- Integration of Multimedia Elements
 - Interactive and Gamified eBooks

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