Western European Journal of Historical Events and Social Science
Volume 3, Issue 8, August 2025
https://westerneuropeanstudies.com/index.php/4
ISSN (E): 2942-1926 Open Access| Peer Reviewed

APPLICATION OF QUANTUM MECHANICS AND PROBABILITY THEORY IN RADIOACTIVE DECAY

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Abstract: Radioactive decay is a fundamental process of nuclear physics, characterized by the random transformation of unstable nuclei and the release of particles and radiation. This article analyzes in detail the probabilistic nature of radioactive decay from the perspective of probability theory and quantum mechanics. The mathematical derivation of the classical decay law and the exponential distribution of nuclei over time are shown. The quantum mechanical mechanism of alpha decay and the tunneling effect are also analyzed using the Schrödinger equation. Beta and gamma decays are briefly described based on quantum field theories. The article is intended for students and researchers to study the main aspects of nuclear physics.
Keywords: quantum mechanics, radioactive decay, tunneling effect, exponential distribution, alpha decay, beta decay, probabilistic model, Schrödinger equation, decay constant, half-life.

Introduction

Radioactive decay was discovered by Antoine Henri Becquerel and the Curie family at the end of the 19th century, which marked the beginning of a new era in the study of the structure of matter. The random emission of radiation and particle emission from unstable nuclei led to the formation of nuclear physics and the development of quantum theory.

Decay does not obey the classical deterministic laws of motion: the exact time of decay of an individual nucleus cannot be determined in advance. However, for atoms with large nuclei, a statistically strict law - the law of exponential decay - applies.

These two solutions - a probabilistic process and a generally strict nature - can be understood using quantum mechanics, which describes the processes of the microcosm in terms of wave functions and probabilities.

The purpose of the article is to explain the probabilistic and quantum mechanical definition of radioactive decay, the tunneling effect in alpha decay, as well as the main properties of beta and gamma decay.

2. Possible properties of radioactive decay

N_0 d Consider a system of natural and radioactive nuclei. If the probability of an individual nucleus decaying in a time period Δt is λΔt, then this process is a non-memory (Markovian) process.

Then the following differential equation is written for the number of nuclei:

$$\frac{dN}{dt} = -\lambda N(t)$$

N(0) = N_0 Solution with initial condition:

$$N(t) = N_o e^{-\lambda t}$$

This is the classical law of radioactive decay.

2.1. Exponential distribution and half-life

The probability density for the exact decay time of a nucleus is expressed as:

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$$P(t) = \lambda e^{-\lambda t}$$

The overall probability of this function is 1:

$$\int_0^\infty P(t) = 1$$

Average residence time ⟨t⟩:

$$\langle t \rangle = \int_0^\infty tP(t)dt = \frac{1}{\lambda}$$

The half-life of the decay $T_{1/2}$ is defined as:

$$T_{1/2} = \frac{ln2}{\lambda}$$

2.2 Numerical modeling

The exponential law can be modeled using the Monte Carlo method as follows:

$$t = -\frac{1}{\lambda}\ln(1-r),$$

where r is a uniformly distributed random number in the interval [0, 1].

3. Quantum mechanical definition

3.1. Schrödinger equation and wave function

In quantum mechanics, a particle is represented by a wave function $\psi(\vec{r}, t)$, the square of whose modulus gives the probability density $|\psi|^2$.

For stationary states, the Schrödinger equation is written as:

$$\hat{H}\psi = E\psi$$

bu yerda $\hat{H}$ — Gamilton operatori bo‘lib, kinetik va potensial energiyaning yig‘indisini o‘z ichiga oladi.

Alfa parchalanishda zarra potensial baryer ichida «saqlanadi» va tunnel effekti orqali chiqishi mumkin.

where $\hat{H}$ is the Hamiltonian operator, which contains the sum of kinetic and potential energy.

In alpha decay, the particle is "stored" within a potential barrier and can escape through the tunneling effect.

3.2 Potential and the Coulomb barrier

The potential for an alpha particle is expressed as:

$$V(r) = \begin{cases} -V_o, & r < R \\ \frac{2Ze^2}{4\pi\varepsilon_0 r}, & r \geq R \end{cases}$$

where V_o is the potential depth inside the nucleus, R is the radius of the nucleus, Z is the number of charges in the remaining nucleus, e is the elementary charge, and ε_0 is the dielectric constant of the vacuum.

According to the rules of classical mechanics, if the energy of a particle is $E < V(R)$, it cannot pass through the barrier.

3.3 Quantum Tunneling

From the point of view of quantum mechanics, a particle can appear behind a potential barrier as a result of the tunneling effect.

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The tunneling probability is expressed as:

$$P \approx e^{-2\gamma}$$

there

$$\gamma = \frac{1}{\hbar} \int_{r_1}^{r_2} \sqrt{2m(V(r) - E)}\, dr$$

3.4 Decay Constant

The decay rate is expressed as:

$$\lambda = fP$$

where f is the frequency of a particle attempting to penetrate the barrier, and P is the probability of tunneling.

4. Quantum theory of beta and gamma decay

4.1 Beta decay

A neutron decays into a proton, emitting an electron and an electron antineutrino:

$$n \rightarrow p + e^- + \bar{\nu}_e$$

or vice versa:

$$p \rightarrow n + e^+ + \nu_e$$

These processes occur under the influence of the weak nuclear force.

4.2 Gamma decay

A nucleus passes from its high-energy (excited) state to the ground state by emitting a photon:

$${}^A_Z X^* \rightarrow {}^A_Z X + \gamma$$

This process is described by quantum electrodynamics..

5. Current research and applications

In the study of nuclear fission, spectrometry, various detectors and other advanced experimental methods are used.

Radioactive fission is of great practical importance in the fields of nuclear energy, medicine, archeology and geology.

Conclusion

Radioactive fission is a probabilistic process, based on the basic laws of quantum mechanics. The law of exponential decay and the tunneling effect play an important role in understanding the physical essence of this process.

The interpretation of beta and gamma decays based on quantum field theory is an integral part of modern nuclear physics.

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