

QUANTUM TIME IN NUCLEAR PHYSICS*

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A series of experiments show that the physical time is the same kind of quantum observable as the spatial position. The quantum temporal effects seem to be an important feature of physical processes with the characteristic times shorter than femtoseconds. In this paper, the idea of slow (weak temporal effects) and fast (stronger temporal effects) nuclear processes is considered.

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1. Concepts of time in physics

Newtonian physics is formulated in complete agreement with our everyday experience and has been proven to precisely describe the motion of macroscopic objects. In this approach, time is something that creates the background for all events. It runs always forward at a constant pace, precisely defining the past, present, and future. Causality of events is vital in this formulation of the description of reality.

At the beginning of the 20th century, physics made a big step forward with the introduction of relativity theory and quantum mechanics [1]. The key concept of general relativity is the introduction of space-time, in which time is incorporated in the theory as the fourth dimension. As a direct consequence of the Lorentz transformations, the time interval between two events depends on the velocity of the objects, measured in some external

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coordinate frame. Therefore, the time ordering of two events may be different for different observers. The concepts of relativity theory has been confirmed by numerous observations ranging from elementary particles to cosmic objects.

Quantum mechanics, however, treats time as a parameter, not a dimension. This parameter creates the background for the evolution of quantum systems in the very same manner as in the Newtonian physics. Having the position operator which describes the probability of finding a quantum particle in a given place, there is no such an operator which would allow to calculate the probability of finding the same particle in a given time interval. Neither relativistic quantum mechanics nor quantum field theory solved this problem, because they still do not allow to calculate the time characteristic of a given processes. The theoretical mismatch between the role of time in the quantum theory and in the relativity is accompanied by an experimental evidence that our treatment of time in quantum systems is not correct.

This problem appeared already during the formulation of quantum mechanics, dividing physicists into schools promoting different interpretations of the role of time and the wave function: the Copenhagen school [2], Everett's many worlds interpretation [3], de Broglie–Bohm's hidden variables model [4] and others. As for the time operator itself, this topic was abandoned after the misinterpretation of Pauli's statement, that "time t must necessarily be considered an ordinary number in Quantum Mechanics" [5]. This very strong (and incorrect) claim has been much later refined to a more precise one, that a self-adjoint time operator cannot be constructed if it is to be canonically conjugated to a Hamiltonian with a spectrum bounded from below [6].

Some confusing aspects related to the quantum nature of various phenomena, including time correlations and the collapse of quantum state's wave function, have been examined by numerous authors, *e.g.* [7], even before there was the technical possibility for their experimental verification. One of those attempts was the Wheeler's famous delayed-choice Gedanken-experiment [8], successfully demonstrated on photons [9] and atoms [10]. This and other recent experiments strongly suggest the need for a reevaluation of our approach to the concept of time. The realization of the temporal interference of photons [11] and electrons [12] demonstrates that time should have a similar status as the space coordinates. Furthermore, experiments concerning time disturb our strong believe in causality, *e.g.*, it was shown that photons, which do not coexist in time, may become entangled [13]. The only consistent conclusion from these observations is that, at least at the quantum level, the past and future are not separated and that there must be some information flow possible between them.

The recent advances in experimental quantum physics require a reformulation of the quantum mechanical description of time and time evolution [14–18]. Allowing time to be a dynamical variable imposes a change in our understanding of the nature of quantum processes, such as particle propagation [19], nuclear reactions [20], and neutrino oscillations [21].

2. Time in nuclear reactions — the NN scattering

In what follows, we assume that time behaves differently in the quantum regime. The classical time we experience in our everyday life is the effect of averaging over a big number of quantum events, which results in a uniform time flow and exact causality relations between the events on the macroscopic scale.

The time scale, in which quantum effects emerge, is of the order of 10^{-15} s, as has been shown in experiments with pico- and atto-second lasers. Should these effects be taken into account in the nuclear physics? Let us take the nucleon–nucleon scattering as an example. In such a reaction, the projectile speed can be written as $v = c\sqrt{2E/(mc^2)}$, which for the projectile typical energies of the order of $E \sim 200$ MeV results in the interaction time of the order of 10^{-8} s. We postulate that the basic processes take place on the quantum level. The observed macroscopical effect is the average result of the many individual basic processes. In the scattering example, one may estimate the number of individual quantum steps of evolution to be $10^{-8} \text{ s}/10^{-15} \text{ s} = 10^7$. For such a number, the averaging procedure smears out the quantum effects completely. We may call such a processes slow. On the other hand, the motion of nucleons inside the nucleus is much faster and lasts approximately 10^{-22} – 10^{-15} s. Therefore, the description of the second process should be corrected to include the quantum nature of time. We believe that it may have a substantial impact on the theory of nuclear structure.

Incorporating time as the fourth dimension, the 2-nucleon interaction can be described by the following operator:

$$W \approx \sum_{n=1}^2 \left(a^\mu p_{n\mu} + \frac{c_1}{2} b^{\mu\nu} p_{n\mu} p_{n\nu} \right) + c_2 V(\sigma; x_1, x_2), \quad (1)$$

where n numbers the nucleons, $\mu, \nu = 0, 1, 2, 3$ are the space-time coordinate labels with $x^0 = t$, and the momenta $p_{n\mu} = i\hbar \frac{\partial}{\partial x_n^\mu}$. The ‘mass’ matrix is diagonal $b^{\mu\nu} = \text{diag}(m_t, m, m, m)$ and contains not only the gravitational mass m , but also a ‘mass parameter’ m_t for the time dimension. The constants $c_{1,2}$ are equal to ± 1 and the nucleon–nucleon potential V , being a function of the space-time points, may additionally depend on some quantum numbers σ .

We may now introduce new variables related to the ‘center of mass’ of the two nucleons and their relative distance (in time and space)

$$Y^\mu = \frac{1}{2} (x_2^\mu + x_1^\mu) , \quad y^\mu = x_2^\mu - x_1^\mu \equiv (\xi, ||\vec{r}||) , \quad (2)$$

with the corresponding canonical variables (the ‘momenta’)

$$P_\mu = i\hbar \frac{\partial}{\partial Y^\mu} , \quad q_\mu = i\hbar \frac{\partial}{\partial y^\mu} . \quad (3)$$

In these variables, the operator (1) takes the form

$$W \approx a^0 P_0 + c_1 \left[\frac{(P_0)^2}{4m_t} + \frac{\vec{P}^2}{4m} \right] + c_1 \left[\frac{(q_0)^2}{m_t} + \frac{\vec{q}^2}{m} \right] + c_2 V(\sigma; \xi, ||\vec{r}||) . \quad (4)$$

If W represents a slow process, for which the characteristic time is large when compared to 10^{-15} s, one has to average it over the relative time distance ξ . The time average of an operator A is given by

$$\langle A \rangle_t = \int_R d\xi \chi(\xi)^* A \chi(\xi) , \quad (5)$$

where $\chi(\xi)$ is the temporal part of the quantum state. The averaged W reads

$$W_{\text{slow}} \approx a^0 P_0 + c_1 \left[\frac{(P_0)^2}{4m_t} + \frac{\vec{P}^2}{4m} \right] + c_1 \left[\frac{\langle (q_0)^2 \rangle_t}{m_t} + \frac{\vec{q}^2}{m} \right] + c_2 \langle V(\sigma; \xi, ||\vec{r}||) \rangle_t . \quad (6)$$

In this case, the averaging procedure hides the true form of the interaction potential and everything what can be observed in the experiment is the effective $\langle V(\sigma; \xi, ||\vec{r}||) \rangle_t$.

Let us take, as an example, the simple case in which the potential V has the form of a sum of the temporal and spatial parts, *i.e.*, $V(\sigma; \xi, ||\vec{r}||) = V_t(\sigma; \xi) + V_x(\sigma; ||\vec{r}||)$. The time average of this potential acts on V_t , $\langle V_t \rangle_t = \text{const}$, leaving V_x untouched. Therefore, the discussed procedure results in the appearance of a constant shift

$$\langle V_t(\sigma; \xi) + V_x(\sigma; ||\vec{r}||) \rangle_t = \text{const} + V_x(\sigma; ||\vec{r}||) . \quad (7)$$

The resultant shift hides all the information about V_t for the macroscopic observer. Relation (7) would be more complicated if V were not that simple. It is important to point out that, in general, it is impossible to reconstruct the full potential $V(\sigma; \xi, ||\vec{r}||)$ from the experimentally accessible

$\langle V(\sigma; \xi, ||\vec{r}||) \rangle_t$. Indeed, for given $\chi(\xi)$, there are infinitely many solutions of the equation

$$\langle V(\sigma; \xi, ||\vec{r}||) \rangle_t = \int_R d\xi |\chi(\xi)|^2 V(\sigma; \xi, ||\vec{r}||). \quad (8)$$

For example, let us take $\chi(\xi)$ in the form of a rectangular step in the temporal dimension

$$\chi(\xi) = \begin{cases} \frac{1}{2\xi_t}, & |\xi| \leq \xi_t, \\ 0, & |\xi| > \xi_t, \end{cases} \quad (9)$$

and the very simplified, schematic ‘one-pion exchange’ effective potential

$$\langle V(\sigma; \xi, ||\vec{r}||) \rangle_t = (re^{m_\pi r})^{-1}. \quad (10)$$

Using (8), one may obtain one of the solutions in the form

$$V(\sigma; \xi, ||\vec{r}||) = \frac{2\xi_t}{r} \left[\frac{\pi}{2\xi_t} \cos\left(\frac{\pi\xi}{2\xi_t}\right) - \frac{8m_\pi r \xi^3}{\xi_t^4} \sin\left(\frac{\pi\xi}{2\xi_t}\right) \right] e^{-m_\pi \left(\frac{2\xi^4}{\xi_t^4} - 1\right)r}. \quad (11)$$

This potential reduces to (10) for slow processes, but should be used in its full form if the time scales are short enough.

3. Summary

The need for reformulation of the quantum theory is apparent although still not very popular. We have discussed in detail the theoretical arguments and experimental observations which both lead to the conclusion that the description and interpretation of the evolution of quantum systems should be reevaluated in a systematic manner. Such work has already been started. Following this line of research, in the present work, we argue that quantum time effects should be visible on the level of motion of nucleons inside the nucleus. At the same time, we show that slower processes, like nucleon–nucleon scattering, will not be affected by them due to the simple averaging over time of the temporal component of the scattering potential. A closer examination of this problem will be presented elsewhere.

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