Virtual entities in Science: a virtual workshop

Virtuality in nuclear physics (1930s-1940s): the many meanings of an emerging concept

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Aachen

March 26th, 2021

- Interest for Yukawa's meson theory of nuclear forces

- Bibliographical work (*#virtual; #nuclear*) → different meanings and uses for virtuality

→ **Today's talk focuses on the meaning(s) of the word "virtual" for physicists**

Outline

1. The different uses of virtuality in nuclear physics during the 1930s
2. What did “virtual” mean?
3. How the term virtual gradually merged with different physical values

1. The different uses of virtuality in nuclear physics during the 1930s

THE PRODUCTION AND PROPERTIES OF NEUTRONS

By N. FEATHER, Ph.D.
Trinity College, Cambridge

Historical Introduction

Soon after the electrical theory of the constitution of matter had been generally accepted by men of science, the idea of an atomic or sub-atomic particle having no resultant charge began to be entertained by many workers. At first only the negative electron possessed the dignity of an experimentally isolated entity, but, because matter in bulk is normally uncharged, a positive counterpart of the electron was obviously required. To suggest the existence of a (possibly complex) neutral particle was then merely to go one step farther with the general scheme. Such a particle was finally discovered thirty-five years after the electron was isolated—and just about half that time after the identity of the positive counterpart of the electron had been commonly recognised—and many distinct suggestions regarding neutral particles had meanwhile been made. In the present introduction some of these suggestions will

- “The large cross-section for neutrons of very small energy could only be interpreted in terms of a (real or **virtual**) stationary state of energy very close to the dissociation energy of the nucleus”.
- “From the numerical data it has been inferred that the above-mentioned state of the deuteron is a **virtual** state”.
- “Theoretically, on each set of results alone it should also be possible to decide between a real and **virtual** excited state, but with less certainty than before”.

→ **Theory of neutron scattering**

- “In 1935 Yukawa suggested that the main interaction between proton and neutron is connected with the exchange (**virtual** emission and re-absorption) of a charged particle […]”.
- “For these calculations the magnetic moments of the proton or neutron is assumed to arise on account of the **virtual** emission and re-absorption of a heavy (positive of negative) electron from the particle in the free state”.

→ **Meson theory of nuclear forces**

a) Neutron scattering

APRIL 1, 1936 PHYSICAL REVIEW VOLUME 49

Capture of Slow Neutrons

G. BREIT AND E. WIGNER, *Institute for Advanced Study and Princeton University*

(Received February 15, 1936)

Current theories of the large cross sections of slow neutrons are contradicted by frequent absence of strong scattering in good absorbers as well as the existence of resonance bands. These facts can be accounted for by supposing that in addition to the usual effect there exist transitions to virtual excitation states of the nucleus in which not only the captured neutron but, in addition to this, one of the particles of the original nucleus is in an excited state. Radiation damping due to the emission of

It will be supposed that there exist quasi-stationary (virtual) energy levels of the system nucleus+neutron which happen to fall in the region of thermal energies as well as somewhat above that region. The incident neutron will be supposed to pass from its incident state into the quasi-stationary level. The excited system

- Model to describe the resonant cross-sections of the interaction between an incident neutron and an atomic nucleus.
- First use of the term virtual in the frame of Bohr's model of the compound nucleus.

- From the mid-1930s, the concepts of virtual state and level were regularly used in articles dealing with neutron scattering.
  - Perrin and Elsasser (1935) – "stationary virtual states"; "virtual energy level"
  - Bethe (1935) – "virtual quantum level"

- Later, occurrences of "virtual resonance" appeared.

- Virtual states and levels qualified as arbitrary mathematical constructs.

→ **Implicit knowledge in the scientific community**

LA RICERCA SCIENTIFICA

SUNTI DELLE MEMORIE DI FISICA

Anno VII - Vol. II - 1936 XIV-XV

Sul moto dei neutroni nelle sostanze idrogenate - E. FERMI

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For the nucleus of the neutron-proton or deuterium system, a fundamental ^3S term and a ^1S term must be considered; whether they are real or virtual depends on whether their binding energy is positive or negative.

Nella seconda parte l'A. studia con metodo meccanico quantistico l'urto tra i neutroni lenti e i protoni della paraffina. Quando i neutroni hanno energie maggiori di 1 volt, si possono considerare i protoni come liberi dal legame chimico; il problema si riduce a quello dell'urto di un corpuscolo contro un centro di diffusione fisso. Per il nucleo del sistema neutrone-protone o deuterio ha luogo a considerare un termine fondamentale ^3S ed un termine ^1S; questo sarà reale o virtuale a seconda che la sua energia di legame è positiva o negativa. In funzione delle energie dei termini, w_0 e w_1, e per energia del neutrone molto piccola (però > 1 volt), si ha la sezione d'urto.

Über die Streuung von Teilchen durch Kraftfelder.

Von **Guido Beck** in Leipzig.

Mit 7 Abbildungen. (Eingegangen am 17. März 1930.)

Es wird ein einfaches Schema angegeben, welches gestattet, einzelne Probleme der Teilchenstreuung auf einige typische Spezialfälle zurückzuführen. Die Erscheinungen der Teilchenstreuung lassen sich als Resonanzerscheinung der einfallenden Teilchen mit virtuellen Quantenzuständen im kontinuierlichen Spektrum auffassen und stehen in enger Analogie zu den optischen Erscheinungen an dünnen Blättchen. Die allgemeinen Betrachtungen führen, angewendet auf den von Hartree berechneten Potentialverlauf im Atom zur Holtsmarkschen Theorie des Ramsauereffektes, angewendet auf den von Gamow angegebenen schematischen Potentialverlauf im Kern auf die von Rutherford beobachtete anomale α-Strahlstreuung in qualitativer Übereinstimmung mit den Beobachtungen.

- Labeled as virtual a physical concept previously introduced by Gamow, but also Gurley and Condon, in their theory of nuclear disintegration (developed in the framework of the WKB approximation).

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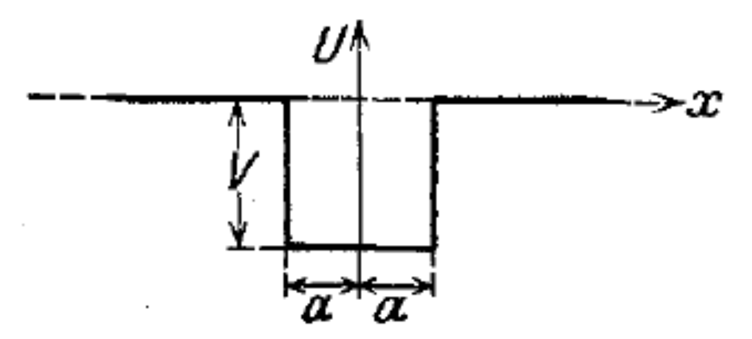
... er allgemein ... Klassische Theorie und Quantentheorie ergeben in diesem Falle übereinstimmend für die gestreuten Teilchen das Rutherfordsche Gesetz:

$$i = \frac{i_0 \cdot z^2 Z^2 e^4}{\ldots} \qquad (1)$$

The phenomena of particle scattering can be understood as resonance phenomena of the incident particles with virtual quantum states in the continuous spectrum.



$$\frac{d^2\psi}{dx^2} + \frac{8\pi^2 m}{h^2}(E - U)\psi = 0,$$

- E < 0 → discrete energy spectrum

  "A quantum state is defined by such an eigenfunction and the associated energy eigenvalue".

- E > 0 → continuous energy spectrum. there are energy values for which particles' density inside of the potential well reaches a maximum and becomes equal to the density outside.

  "We can therefore say that the discrete quantum states continue in a certain sense into the continuous spectrum and we want to denote these states as 'virtual quantum states' in the following".

b) Meson theory of nuclear forces

- Hideki Yukawa postulated a new particle (known today as a pi-meson) as a result of the quantification of a new force field introduced to discuss the interaction of elementary particles in the nucleus.
- The new particle, would be at the origin of an "exchange" force between neutrons and protons.
- Followed a scheme introduced by Heisenberg in nuclear physics that relied on the perturbation theory.

On the Interaction of Elementary Particles. I.

By Hideki YUKAWA.

(Read Nov. 17, 1934)

§ 1. Introduction

At the present stage of the quantum theory little is known about the nature of interaction of elementary particles. Heisenberg considered the interaction of "Platzwechsel" between the neutron and the proton to be of importance to the nuclear structure.(1)

Recently Fermi treated the problem of β-disintegration on the hypothesis of "neutrino"(2). According to this theory, the neutron and the proton can interact by emitting and absorbing a pair of neutrino and electron. Unfortunately the interaction energy calculated on such assumption is much too small to account for the binding energies of neutrons and protons in the nucleus.(3)

To remove this defect, it seems natural to modify the theory of Heisenberg and Fermi in the following way. The transition of a heavy particle from neutron state to proton state is not always accompanied by the emission of light particles, i. e., a neutrino and an electron, but the energy liberated by the transition is taken up sometimes by another heavy particle, which in turn will be transformed from proton state into neutron state. If the probability of occurrence of the latter process is much larger than that of the former, the interaction between the neutron and the proton will be much larger than in the case of Fermi, whereas the probability of emission of light particles is not affected essentially.

Now such interaction between the elementary particles can be described by means of a field of force, just as the interaction between the charged particles is described by the electromagnetic field. The above considerations show that the interaction of heavy particles with this field is much larger than that of light particles with it.

(1) W. Heisenberg, Zeit. f. Phys. 77, 1 (1932); 78, 156 (1932); 80, 587 (1933). We shall denote the first of them by I.
(2) E. Fermi, ibid. 88, 161 (1394).
(3) Ig. Tamm, Nature 133, 981 (1934); D. Iwanenko, ibid. 981 (1934).

On the Interaction of Elementary Particles. II.

By Hideki YUKAWA and Shoichi SAKATA.

(Read Sept. 25, 1937.)

"The quantum of negative or positive charge thus emitted virtually *can be absorbed by 2 or 1, which in turn changes into the neutron or the proton, so that the state of the system, in which the particle 1 is in a proton state, q say, and 2 in a neutron state, m say, is linked together with the initial state through the* ***intermediate states*** *above considered".*

Über die Spinabhängigkeit der Kernkräfte*).

Von **C. F. v. Weizsäcker** in Leipzig.

Mit 1 Abbildung. (Eingegangen am 27. Juli 1936.)

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Nun ist die Austauschkraft aber rein phänomenologisch gegeben und die Wahl ihrer relativistischen Ergänzung ist daher zunächst vollkommen willkürlich. Eine Festlegung erscheint aber als möglich, wenn wir den Zusammenhang der Austauschkraft mit dem Phänomen des β-Zerfalls ausnutzen. Stellen wir uns den β-Zerfall im Sinne der Theorie von Fermi[1]) vor als die Emission eines Elektrons und eines Neutrinos unter gleichzeitiger Umwandlung eines Neutrons in ein Proton, so läßt sich der Prozeß, durch dessen Betrachtung Heisenberg[2]) die Existenz einer Austauschkraft ableitete, folgendermaßen darstellen: Ein Neutron verwandelt sich unter (virtueller) Emission eines Elektrons und eines Neutrinos in ein Proton; ein benachbartes Proton absorbiert die beiden emittierten leichten Teilchen und verwandelt sich dadurch in ein Neutron. Der Prozeß kann quanten-

...

[1]) E. Fermi, ZS. f. Phys. **88**, 161, 1934. — [2]) W. Heisenberg, ebenda **77**, 1, 1932. — [3]) W. Heisenberg, Zeeman-Festschrift, S. 108, Haag 1935.

"If one carries out the perturbation calculation with the Fermi interaction energy between light and heavy particles as a perturbation and calculates the magnetic moment of proton or neutron, then additional terms of the second approximation arise, which resemble the self energies of theses particles in their form and which correspond to the virtual emergence and disappearance of one pair of positron-neutrinos for protons and electron-neutrinos for neutrons".

Werner Heisenberg, "Bemerkungen zur theorie des atomkerns," 1935

A conceptual transfer from QED

- Second order equations in a perturbative treatment reveal transitions through an intermediate state that started to be coined as virtual at the end of the 1930s.

"[…] the transition of the molecule for the purpose of calculations is a purely virtual one which actually cannot occur".

Chandrashekhara Raman, "Investigation of molecular structure by light scattering," 1929

- The same method was applied to determine nuclear forces.

2. What did “virtual” mean?

Traditional features associated to the virtual (through the concept of virtual particle)

- Unobservability
- Short-life
- Potentiality
- Non-conservation of energy

Traditional features associated to the virtual (through the concept of virtual particle)

- Unobservability
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None of these features is constitutive of the concept of virtual state in the sense of Beck and Breit-Wigner.

virtual state ['vər·chə·wəl 'stāt]

(nuclear physics)

An unstable state of a compound nucleus which has a lifetime many times longer than the time it takes a nucleon, with the same energy as it has in the virtual state, to cross the nucleus.

"Thus, the 'virtual level' is not only a convenient mathematical fiction but represents a real physical state wherein the particle spends a considerable time being in a potential".

Askod M. Perelomov and Yakov B. Zel'dovich, *Quantum* mechanics, 1999

An important common point

- Both virtual states and virtual transitions were **mathematical constructs** resulting from **approximations processes**. The WKB approximation for the first, and the perturbation theory for the second.
    - Virtual states, since they were considered in the continuous spectrum and not sharp, could not be strictly defined mathematically as quantum states. Nevertheless, they were effective in explaining real physical phenomena such as resonances.
    - Virtual transitions, since they did not result from quantum states which were eigenfunctions of any operator, could not be strictly defined mathematically as quantum transitions. Nevertheless, they were effective in explaining real physical phenomena, such as Raman scattering.

A Peircian definition?

In physics of the early 1930s, a virtual x is a mathematical construct, not an x, which has the efficiency of an x in explaining physical phenomena

3. How the term virtual gradually merged with different physical values

Physical features of the intermediate state

Dirac, P. A. M. (1927b). The quantum theory of dispersion. *Proceedings of the Royal Society of London A: Mathematical, Physical, and Engineering Sciences*, 114(769), 710–728.

- **The proper energy is not conserved in the transitions**
- **They are unobservable in principle**
- All possible combinations of emission and absorption of light quanta have to be taken into account
- Only the absolute square of the sum over all possible processes through intermediate states corresponds to an observable quantity

A heuristic error

In 1936, Carl D. Anderson and Seth Neddermeyer discovered the muon in cosmic-rays showers. Nevertheless, for about the decade, it was thought that the muon was the meson postulated by Yukawa.

- Such a confusion favored the good reception of Yukawa's work and the meson theory became in the second half of the 1930s a fruitful field of research.
- The meson became widely regarded for its properties, respectively, in cosmic rays and the nucleus.

- The **observable** meson in cosmic-rays began to be opposed to the **unobservable** one in the nucleus.

- The term virtual itself began in this precise context to be directly associated with that of meson, or even particle. Physicists began to talk about **virtual mesons** in the nucleus and **real, actual of even final mesons** in cosmic rays.

- Physicists envisioned how cosmic ray mesons could actually be emitted from the nucleus, developing the idea that virtual mesons could become real mesons if they could receive enough energy → **the virtual as an incomplete and potential process.**

Non-conservation of energy (1)

- A sacred principle regularly regularly attacked with the development of quantum theory.
- Although Wolfgang Pauli had "saved" the principle in 1930 by postulating the neutrino existence, Bohr's suggestion to give it up to explain nuclear phenomena gradually gained credit in the early 1930s. Including with Heisenberg.
- Earlier, Heisenberg was also influenced by the BKS theory, based both on "virtual oscillators" and the assumption that the energy was only statistically conserved in interaction between atoms and radiation, thus dropping strict energy conservation.

involving intermediate states (k, l, m) of higher (viz., 4th) order. These sub-processes do not imply any energy conservation for the "virtual" intermediate states, but only the total process ($i \rightarrow n$) to the *actual* final state. Therefore, whether the states k, l, m cannot, by any means, be assumed to be actual system states insofar as the energy law is concerned (or else there would be transitions in lower order approximations that would contradict the assumption on the formula that was given here), their virtual possibility brings about the transition $i \rightarrow n$ in question. The scattering of light by light rests upon these circumstances.

§ 5. Presentation of the matrix H_{in}^{4} for the scattering of light by light in Dirac's theory

We now apply this perturbation schema to the *system*: radiation field and matter field. For its approximate stationary states, we choose plane light waves and plane matter waves. The *perturbation energy* then exists as the coupling between light and matter,

BEMERKUNGEN ZUR THEORIE DES ATOMKERNS

von W. HEISENBERG, Leipzig

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Die Wickschen Resultate beruhen auf Überlegungen, die denen von Tamm und Iwanenko sehr ähnlich sind; sie sollen hier kurz wiederholt werden:

Führt man die Störungsrechnung mit der Fermischen Wechselwirkungsenergie zwischen leichten und schweren Partikeln als Störung durch und berechnet das magnetische Moment des Protons bezw. Neutrons, so entstehen Zusatzglieder zweiter Näherung, die in der Form ganz den Selbstenergien dieser Teilchen gleichen und die dem virtuellen Entstehen und Wiederverschwinden eines Paares Positron-Neutrino beim Proton, bzw. Elektron-Neutrino beim Neutron entsprechen. Diese Zusatzmomente würden unendlich gross werden, wenn man nicht wie bei den Selbstenergien einen endlichen Ra-

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1) C. Wick, Rend. R. Nat. Acad. Lincei. Im Erscheinen.

”the energy of the system will be in general not conserved in the intermediates state (compare the theory of dispersion”.

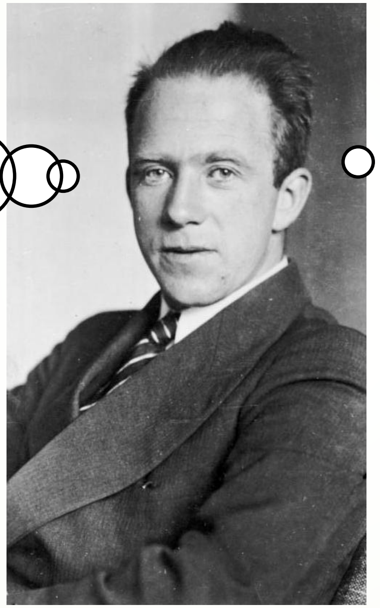
Igor Tamm, “Exchange Forces between Neutrons and Protons, and Fermi’s Theory,” 1934

”The reason for this discrepancy can be sought, as we will now show, in the possibility that the proton has to momentarily split into a neutron + a positron + a neutrino, and then immediately fall back to the proton state (a permanent transition cannot occur, as contrary to the conservation of energy, if as probable, the mass of the proton is less than the sum of the masses of the other particles)”.

Giancarlo Wick, “Teoria dei raggi ß e momenio magnetico del protone,” 1935

Non-conservation of energy

BKS theory (**Virtual** oscillators)



Perturbation theory (**Virtual** transitions)

From this moment, the non-conservation of energy became, for most physicists, the real justification for using the term virtual.

§ 3. Deduction of the Force between Unlike Particles.

When a heavy particle 1 is in a neutron state u_n with the energy W_n and 2 in a proton state v_p with the energy W_p in the absence of the heavy quanta initially, the energy for the unperturbed system is $W_n + W_p$, if we omit the zero point energy $\sum E_k$ for the U-field. The perturbation given by (14) indicates the possibility of the transition of 1 from the neutron to the proton state with the simultaneous emission of a quantum of negative charge and conversely that of 2 from the proton to the neutron state with the simultaneous emission of a quantum of positive charge, although these transitions are energetically forbidden as long as $W_n - M_N c^2 + W_p - M_p c^2 \ll m_U c^2$. The quantum of negative or positive charge thus emitted virtually can be absorbed by 2 or 1, which in turn changes into the neutron or the proton, so that the state of the system, in which the particles 1 is in a proton state, q say, and 2 in a neutron state, m say, is linked together with the initial state through the intermediate states above considered. The

"Of course the emission or absorption of a U-particle only takes place observably when it is consistent with the conservation of energy. In other cases the emission or absorption is merely virtual, as an intermediate state, as is the case in the quantum theory of radiation".

Homi Bhabha, "Nuclear Forces, Heavy Electrons and the ß-decay," 1938

"[...] these are not, of course, actual emission and absorption processes, which would be contrary to the energy principle; they are called, therefore, virtual transitions".

Giancarlo Wick, "Range of Nuclear Forces in Yukawa's theory," 1938

PHYSICAL CONCEPTS OF THE MESON THEORY OF THE ATOMIC NUCLEUS

By Prof. W. Heitler

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convenient. Indeed, the production of the static field $ge^{-\lambda r}/r$ by a proton or neutron is often described in the particle picture as a "virtual emission and reabsorption" of a meson. This picture can often be used with advantage.

What is the precise meaning of this expression ?

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multiple of e.) The word emission in the above expression has thus a very literary meaning. On the other hand, such an emission of a particle with a rest mass μ would be contrary to the law of conservation of energy. While all other conservation laws (charge, momentum, angular momentum, spin, statistical) are fulfilled during this emission, the word 'virtual' means that, in contrast to a real emission, energy need not be conserved. If we

Conclusion

- The term virtual was introduced almost simultaneously to qualify two different mathematical constructs resulting from approximation processes in modern physics at the turn of the 1930s.
- Peirce definition of the virtual, pointing to mathematical characteristics may be helpful to better understand the introduction of the term virtual.
- Historical considerations on the development of the meson theory helps us to understand how the term virtual began to be associated with different values that have changed its meaning, and that explains the current perception of virtuality, including some of its misleading dimensions, such as non-conservation of energy.

Thank you!

ZOOM MEETING

I will be happy to arrange a Zoom meeting with those who wish to continue the discussion later. Please, find me on wonder.me during the individual discussions or write an email to

jeanphilippe.martinez@gmail.com