6.4 Virtual states forced to become real through transfer reactions

(1)

(– likely as it is in nature –)

(— italics)

One of the main subjects which has been discussed in the present monograph concerns the melting of structure and reactions and of bare and virtual states into a higher unity: which can be described in terms of Feynman diagrams where ~~in which~~ particles come in and go out, and eventually interact with the detectors whose clicks can be read in terms of absolute differential cross sections and lifetimes, conveying to observation the properties of renormalized, dressed, physical elementary modes of excitation.

The initial and final asymptotic states of the $(NFT)_{ren}$ (r+s) Feynman diagrams are anchored to the laboratory (incoming beams and target – outgoing particles, including γ-rays and detectors). The intermediate states break open the incoming elements — e.g. a beam of the halo nucleus ^{11}Li, of half life of 8.75 ms, which impinges on a hydrogen target (proton) in an inverse kinematic experiment — to allow the ~~those~~

guiones grandes

elementary modes of excitation which are probed by the experiment, to become active, ~~and~~ interact ~~and dress~~ (melt) with ~~each~~ other modes, and eventually ~~passing~~ pass the information concerning the properties of the resulting physical modes to the outgoing particles and γ-rays.

Among these diagrams, one finds those associated with reactions processes in which a virtual state is acted upon and forced to become real, eventually reaching the detectors. A sort of Hawking radiation to the extent that one concentrates on the (virtual) → (real phenomenon), with the proviso of viewing the action of the ~~reaction~~ external field as the event horizon of the black hole.

An example of such diagrams which describes a possible event associated with the reaction $^{1}H(^{11}Li, ^{9}Li(1/2^-))^{3}H$ is displayed in Fig. β: a virtual quadrupole vibration in the process of renormalizing the $s_{1/2}$ state, or ~~$p_{1/2}$ valence neutrons, or in the process~~ of being exchanged between the partners of the neutron halo Cooper pair has been caught in the act by the pair transfer field produced by the ISAAC-2 facility at TRIUMF, forced to become a real final state and to bring this information to the active target detector MAYA.

(For the complete text see next page)

Empirical renormalization: $(NFT)_{ren}$ $(r+s)$ (Feynman + S-matrix) 0*) 1 4

Most if not all theories able to provide a complete description of structure and reactions of atomic nuclei can hardly avoid the separation between explicit and virtual phase spaces. Once this is recognized, the most physical choice concerning the first type of degrees of freedom is, unarguably: elementary modes of excitation. That is, the response to the variety of external probes of the nuclear system, a choice deeply anchored to the aim that only concepts related to observable quantities enter the theory.

But here ends empiricism 1*) Because the ba[illegible] which potenti[illegible] expe rimen[illegible] not obser- vables. [illegible] their elemen[illegible] renor malize[illegible] and me[illegible] ds. In fact, wh[illegible] oving inside t[illegible] associa ted with that nucleon field alone. It is also partially to be associated with the vibrational

0*) The practical usefulness of the Feynman rules and diagrams made them one of the most essential elements of the scientific training of every theoretical physicist.

Mehra (1996)

~~Komp~~

~~Things that cannot be represented~~

1*) To the extent of attributing the ancient Greek meaning of "find" and "discover" to the word heuristic (ευρισκω) and of "serving to discover" of the Oxford dictionary, one can connotate the above empirical protocol, as heuristic.

Empirical renormalization: $(NFT)_{ren}$ (r+s) (Feynman + S-matrix) *) 1 4

Most if not all theories able to provide a complete description of structure and reactions of atomic nuclei can hardly avoid the separation between explicit and virtual phase spaces. Once this is recognized, the most physical choice concerning the first type of degrees of freedom is ~~unarguably~~ that of elementary modes of excitation. That is, the response to the variety of external probes of the nuclear system, a choice deeply anchored to the aim that only concepts related to observable quantities enter the theory.

But here ends empiricism. 1 *) Because the bare elementary modes of excitation which potentially contains all of the physics that experiment can eventually provide, are not observables. To become so, they have to loose their elementarity and become mixed, dressed, renormalized, ~~loose in a way their "virginity"~~ and melt together into effective fields. In fact, what we call a physical nucleon moving inside the nucleus, is only partially to be associated with that nucleon field alone. It is also partially to be associated with the vibrational

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1 *) To the extent of attributing the ancient Greek meaning of "find" and "discover" to the word heuristic (ευρίσκω) and of "serving to discover" of the Oxford dictionary, one can connotate the above empirical protocol, as heuristic.

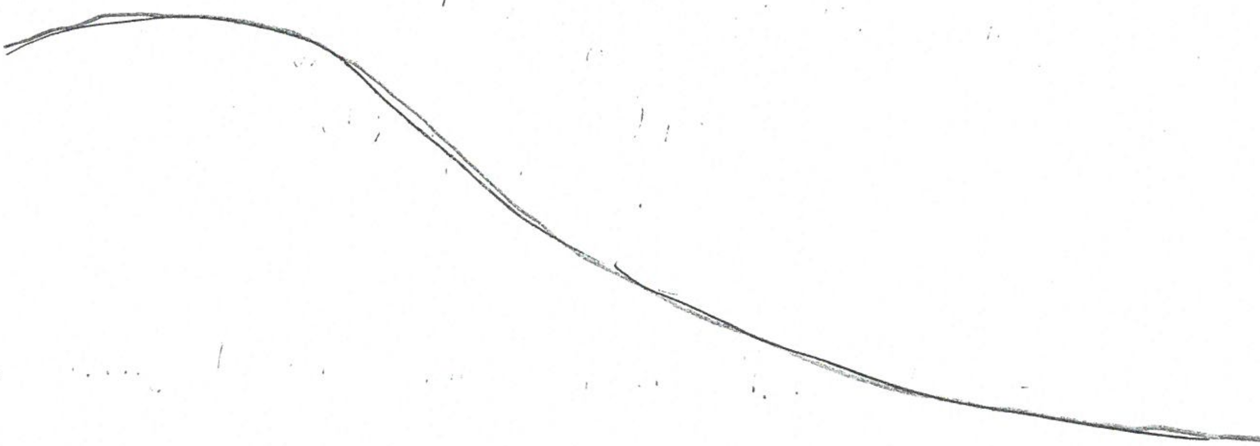
Købenavn 16/08/17.

~~2~~ 5

field, because the two are in interaction.

On the other hand, elementary modes participating in virtual states which intervened upon with an appropriate external field can become on-shell,2*) have to be dressed, fully renormalized modes, poised ~~to be forced~~ to become observables on short call.3**) The reaction $^{11}Be(p,d)\,^{10}Be(2^+)$ provides an embodiment of such constructions. An example ~~that~~ aside from shedding light on retardation mechanisms in clothing processes, implies that particle-vibration coupled intermediate states have to be real states concerning both energy and amplitude, as well as radial shape4***). Thus $(NFT)_{ren}$ is not a calculation ansatz but a quantal requirement.

Let us conclude this section by elaborating on footnote 2*). It ~~has been~~ was posit that intermediate states



3**) As a rule, the collective modes participating in these virtual states are calculated making use of empirical input. Thus, empirical renormalization.

4***) See e.g. Barranco et al (2017), ^{11}Be PRL.

~~lack of built in collectivity, instead of learning what is already well known.~~

2*) The intervened mode has an on-shell energy consistent with the Q-value of the reaction, and thus may not correspond to that of an actual final state in absence of that probe.

are built out, aside from their energy, of fully dressed, renormalized physically observable elementary modes of excitation. Concerning the eventual value of the on-shell-energy, it will naturally depend on the reaction process taking place.

For example, in the reaction $^{11}Be(p,d)^{10}Be(2^+; 3.368\,MeV)$ (Fig. α(b) and (e)) populating the quadrupole vibration of ^{10}Be which, in the virtual $(\tilde{5/2}^+ \otimes 2^+)_{1/2^+}$ state dress the $|\tilde{1/2}^+\rangle$ ground state of ^{11}Be (Fig. α(a)), the on-shell-energy coincides with that of that observed in the inelastic process $^{10}Be(gs \to 2^+)$. On the other hand, unrelated to the energy of +1,28 MeV (continuum, unbound), recorded in the reaction $^{10}Be(d,p)\,^{11}Be(5/2^+)$. København 17/08/17

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~~are built out of, aside from their energy fully dressed, renormalized (real) elementary modes of excitation. quadrupole vibration of the core, ^{10}Be, which dresses the $1/2^+$ ^{11}Be ground state (Fig. α(a)) When populated in the reaction $^{11}Be(p,d)\,^{10}Be(2^+; 3.368\text{ MeV})$, renormalization also applies~~

the $5/2^+$ pickup neutron, while displaying ~~all of~~ the structure properties of the $5/2^+$ resonance ($\tilde{\varepsilon}_{5/2^+} = 1.45$ MeV), it ~~displays~~ has a binding energy (equal to) $\tilde{\varepsilon}_{1/2^+} - \hbar\omega_{2^+} = -3.868$ MeV. This is a natural outcome of (NFT)$_{ren}$ which, through the PVC and the Pauli mechanism, provides the proper clothing of the $d_{5/2}$ orbital so as to allow ~~make~~ it to be ~~able~~ "to exist" inside the $|\tilde{5/2}\rangle$ state as a virtual, intermediate configuration. The associated asymptotic r-behavior results from the coherent superposition of many continuum states.

~~Let us now consider the acting on $|^{11}Be(gs)\rangle$ of an inelastic field which populates the $5/2^+$ resonance.~~

~~Let us then, at variance of what was done above, ~~viceversa~~, intervene the vibrational mode with ~~an inelastic field~~ (Fig. α′(b)). In this case, the external field has to provide an energy equal to $|\tilde{\varepsilon}_{1/2^+} - \tilde{\varepsilon}_{5/2}| = 1.95$ MeV, unraleted to on-shell energy of $|^{10}Be(2^+)\rangle$.~~

We now consider the process in which an inelastic field acting on $|^{11}Be(gs)\rangle$ populates the $5/2^+$ resonance. An important contribution to this excitation results from the action of the external field on the quadrupole vibration of the virtual state $(\widetilde{d}_{5/2} \otimes 2^+)_{1/2^+}$ which renormalizes ~~the~~ the $1/2^+$ state (Figs α′(a) and (b)). In this case, the external field has to provide an energy equal to $|\tilde{\varepsilon}_{1/2} - \tilde{\varepsilon}_{5/2^+}| = 1.95$ MeV, again unrelated to the on-shell energy of $|^{10}Be(2^+; 3{,}868\,\text{MeV})\rangle$ observed in the inelastic process $^{10}Be(gs \to 2^+)$, but needed to dress the bare single-particle valence orbital. Another example of the ductility of virtual states to give rise to physical observables.

6.4.2 Perturbation and beyond

In Q.E.D. at the one-loop diagrams level, the renormalized electron mass m_e, ~~that~~ is the observed (≈ 0.5 MeV) mass, is related to the bare mass m_0, not observable, by $m_e = m_0 \left(1 + \frac{3\alpha}{\pi} \log\left(\frac{\Lambda_{cut}}{m_0}\right)^2\right)$, Λ_{cut} being the cutoff of the divergent integrals (5*). This ~~(see e.g. Bjorken and Drell (1998)). This~~ quantity appears inside the log, and in front of it one has the fine structure constant α which is small ($\approx 1/137$). Therefore, even pushing the cutoff to the Planck scale, $\Lambda_{cut} \sim 10^{19}$ GeV, with $m_0 \sim$ MeV one has $\delta m_e / m_e \approx (3\alpha/4\pi) \log(\Lambda_{cut}/m_0)^2 \approx 0.1$. So δm_e is really a small correction. To reproduce the physical electron mass m_e, one must take a value of m_0 of the same order of magnitude.

(guion grande) Within this context one can compare (plus the effective mass functional) the value of the four parameters which determine the mean field (Saxon-Woods) potential used to calculate the bare single-particle energies of ^{11}Be imposing the condition that the dressed single-particle states best reproduces the

(5*) See e.g. Bjorken and Drell (1998) pp 162–166.

J. D. Bjorken and S. Drell, Relativistic Quantum Mechanics McGraw-Hill, New York (1998).

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experimental findings, with the value of the corresponding parameters of the standard, global Woods-Saxon potential (and of effective mass equal to the observed mass m). The results displayed in Table α, testify to the fact that renormalization in nuclear physics, in particular in the case of halo exotic, parity inverted nuclei, is less "perturbative" than in the case of Q.E.D. This fact becomes even clearer if one compares the overall centroid of the valence orbitals as well as the density of levels associated with the two potentials. Within this context it is of notice that the Lamb (like-) shift taking place between the $s_{1/2}$ and $p_{1/2}$ valence levels has a value of approximately 10% $((\Delta\varepsilon_{1/2^+,1/2^-})_{bare} - (\Delta\varepsilon_{1/2^+,1/2^-})_{ren} \approx (3.11+0.32)$ MeV) of that of the Fermi energy ($\approx$ 36 MeV). This result can be compared with the ratio of the hydrogen $^2S_{1/2} - {}^2P_{1/2}$ Lamb shift ($1058\, MHz \approx 4.3 \times 10^{-9}\, eV$) and the Rydberg constant ($R_H \approx 13.6\, eV$), i.e. $\approx 10^{-10}$, a result which underscores the strong coupled situation one is confronted with in trying to describe the structure of light halo exotic nuclei.

The fact that in spite of this, $(NFT)_{ren}$ $(r+s)$ can provide an overall account

0.04
3.04
3.11

0.50
0.18
0.32

-0.18
$+0.50$
$+0.32$

København 17/8/17. (6) (9)

of an esentially complete set of experimental data which characterizes ^{11}Be, within a 10% error, testifies to the power and flexibility Feynman version of Q.E.D. has. It can be used as paradigm to construct a field theory for both structure and reactions of a strongly interacting finite many-body system like the atomic nucleus.

Examples of $(NFT)_{ren}$ (s+r) diagrams, aside from that discussed in detail in connection with ~~the one discussed above~~ (Fig. α), are displayed in Figs. β and γ. The first describes the process $^{1}H(^{11}Li, ^{9}Li)^{3}H$ providing a quantitative account of the data and first evidence of phonon induced pairing in nuclei. The second points to important work lying ahead, showing one of the most important channels contributing to the optical potential needed to describe the elastic scattering process $^{1}H(^{11}Li, ^{11}Li)^{1}H$.

6.4.3 $(NFT)_{ren}$ (r+s) diagrams, S-matrix

Landau felt that Feynman diagrams, although usually derived from conventional field theory, have an independent basic importance [16]* ~~(Landau (1959))~~. This work is closely connected with both Heisenberg stament that one should introduce only

(16) *) L. Landau, On analytic properties of vertex parts in quantum field theory, Nucl. Phys. 13, 181 (1959).

Fig α. Fig. 3 (likely only 3(I)) paper Hawking.
Fig β. Fig. 2 Phys Scr.
Fig γ. Fig. 12 " "

*) (7) København 18/8/17 (7)

(10)

Observable quantities*) (7) into a quantum theory, and with the scattering matrix. As the wavefunctions themselves cannot be observed and because the Hamiltonian formalism is intimately connected with wavefunction, it may not be the most appropriate eg describe of quantal systems. The quantities to be studied are the scattering amplitudes where particles go in and another set, including eventually γ-rays, come out and directly determine the cross sections of the different physical processes. (8) **)

Within this context see Fig α (e) where curved arrowed lines describe incoming (^{11}Be) and outgoing particles (^{10}Be, γ (not signaled with a curve arrowed), ^{2}H). These particles eventually hit particle- and γ-detectors, and provide the information needed to work out the absolute differential cross sections and lifetimes. Quantities which constitute the meeting point of theory with experiment (see Fig α (c)). Within the same scenario, see Fig β (c) and (d) for incoming and outgoing particles associated with the inverse kinematic reaction $^{1}H(^{11}Li, ^{9}Li)^{3}H$,

(8) **) Inverse kinematic reaction reaction $^{1}H(^{11}Be, ^{10}Be(2^{+}))^{2}H$ where ^{1}H is represented not by the atom but by the proton π and ^{2}He again by the deuteron $d(\pi, \nu)$.

*) (7) W. Heisenberg Quantum-theoretical re-interpretation of kinematic and mechanical relations, Z. Phys. 33, 879 (1925); see the english translation in B.L. Van der Waerden, Sources of Quantum Mechanics Dover, New York (1967).

København 18/8/17 (8) (11)

and*) (9) Figs. β(a) and (b) for the same reaction but now represented in the standard setup: $^{11}Li(p,t)^9Li$. The resulting cross sections, in comparison with the theoretical predictions calculated making use of the corresponding diagrams (10)**) are displayed in Figs. β(e) and (f).

Review paper

(11)***) Potel et al (2013), Figs 7 and 8

simultaneous and non-orthogonality (correction) processes (11)***). The absolute cross section shown in Figs β(e) and (f) contain, of course, all three contributions.

(9)*) It is of notice that in this figure, at variance to Fig. α, protons and neutrons are labeled p and n respectively.

(10)**) It is of notice that in Fig. β only the successive two-nucleon transfer amplitude is represented. Similar graph are calculated regarding

København 17/08/17 I1

12

	V_0 (MeV)	V_ℓ (MeV)	R_0 (fm)	a (fm)
Standard a)	−50	17	2.7 c)	0.65
bare b)	−68.9	14.47	2.15	0.77

a) $m^* = m$;

b) $m^*(r=0) = 0.7\,m$, $m^*(r=\infty) = (10/11)\,m$

c) $R_0 = 1.2\,A^{1/3}$ fm

Table α

Standard and bare parametrization of the mean field potential. Changes of the order of 20–30% are observed. Within this context, in the case of Q.E.D. $\delta m_e/m_e = 0.1$.

Lamb shift

(do not write)

1058 MHz

$1\,eV = 2.42 \times 10^{9}\,MHz$

$1\,MHz = 4.1 \times 10^{-9}\,eV$

$1058\,MHz = 1.058 \times 10^{3} \times Hz = 1.058 \times 4.1 \times 10^{3} \times 10^{-9}\,eV$

$= 4.3 \times 10^{-9}\,eV$

$1\,R_y = 13.6$

$$\frac{105\,MHz}{1\,R_y} = \frac{4.3 \times 10^{-9}\,eV}{13.6\,eV} = 0.32 \times 10^{-9}$$

$$\approx 3 \times 10^{-10}$$

Parity inversion ^{11}Be

$\Delta\varepsilon_b = (\varepsilon_{s1/2} - \varepsilon_{p1/2})_{bare} = 0.14 + 3.01 = 3.15\,MeV$

$\Delta\varepsilon_r = (\quad\quad)_{ren} = -0.57 + 0.21 = -0.36\,MeV$

$\Delta\varepsilon_b - \Delta\varepsilon_r = 3.5 + 0.36 = 3.86\,MeV$

$$\frac{3.86\,MeV}{\varepsilon_F} = \frac{3.86}{36} = 0.11$$