INTERNATIONAL NUCLEAR PHYSICS CONFERENCE
Tokyo, Japan, June 3-8, 2007

SYMPOSIUM FOR THE CENTENNIAL CELEBRATION OF HIDEKI YUKAWA

HIDEKI YUKAWA AND NUCLEAR PHYSICS
FROM THE YUKAWA PARTICLE TO THE QGCW

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ABSTRACT

The remarkable consequences of the Yukawa particle, theoretically proposed in 1935, are reviewed. The production, the decay and the intrinsic structure of the Yukawa particle opened new frontiers with laws and regularities which brought us to the discovery of subnuclear physics and now to the quark-gluon-coloured world (QGCW).

Tokyo, June 3, 2007
ONE HUNDRED YEARS AFTER THE BIRTH OF HIDEKI YUKAWA
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1

INTRODUCTION
The Yukawa ‘particle’ theoretically proposed by Hideki Yukawa in 1935 [1], represents a gold mine which has its roots in

the production,

the decay and

the intrinsic structure

of the Yukawa particle.
The gold mine is still being explored nowadays, and its present frontier is the quark-gluon-coloured-world (QGCW) whose properties could open unprecedented horizons in understanding the Logic of Nature.
2 PRODUCTION
Thanks to Yukawa, to search for particles with masses in-between the electron and the nucleon masses became a very hot topic, during first third of the XXth Century.
In fact, Yukawa proposed to study the production of a particle with a mass in-between (this is the origin of ‘mesotron’, now meson) the light electron, $m_e$, and the heavy nucleon, $m_N$, (proton or neutron).
This mass value was deduced by Yukawa from the range of the nuclear forces.
The first experimental evidence for the existence of a cosmic ray particle having a mass of about 130 times the electron mass was obtained by J.C. Street and E.C. Stevenson in 1937 [2].
One year later, S.H. Neddermeyer and C.D. Anderson (the same fellow who had discovered the anti-electron in 1933 [3]) confirmed the existence of a cosmic ray particle in the mass range predicted by Yukawa and were able to give a much better determination of its mass: 240 electron masses [4].
The meson theory of the strong nuclear forces proposed by Hideki Yukawa appeared to have excellent experimental confirmation but the Yukawa idea sparked an enormous interest in the search for cosmic rays having masses in this ‘intermediate’ range, and here a gold mine was to be found.
In the search for the gold mine opened by Yukawa, a group of young Italian physicists, Marcello Conversi, Ettore Pancini and Oreste Piccioni, decided to study how the negative ‘mesotrons’ were captured by nuclear matter. Using a strong magnetic field in order to clearly separate the negative from the positive rays, they discovered that the ‘negative’ mesotrons were not strongly coupled to the nuclear matter [5].
Fermi, Teller and Weisskopf pointed out that
‘The decay of negative mesotrons in matter’
(this is the title of their paper) [6] was twelve powers of ten longer
that the time needed for the so much wanted Yukawa particle to be captured by a nucleus via the mechanism of the nuclear forces.
In this paper, Fermi, Teller and Weisskopf introduced the symbol $\mu$ (for mesotron) to specify the nature of the negative cosmic ray particle being experimentally investigated.
In this field of frontier physics there is a special link between Japan and Italy. In fact, in addition to Conversi, Pancini, Piccioni and Fermi, another Italian, G.P.S. Occhialini, was needed to complete the understanding of the gold mine opened by Yukawa.
For this further step to be accomplished, the technology needed was the photographic emulsion and Occhialini was the world expert in this technique. With Lattes and Powell, Occhialini discovered [7] that the negative muons were the decay products of another meson, the ‘primary’ one (this is the origin of the symbol \( \pi \)). It is this particle which is produced by the nuclear forces, as wanted by Yukawa.
The $\pi$ discovery provided the ‘glue’ for the nuclear forces and this was great. But this was not the end of the gold mine.
In the sixties, it was realized that if it were not for the \( \pi \) meson it would not have been easy to have so many muons. Their existence could only go via photo-production processes. If another ‘meson’ like the Yukawa one existed in the ‘heavy’ mass region, a third lepton [8], heavier than the muon, could have easily been produced as decay-product of this heavy meson strongly produced by the nuclear forces.
The absence of this third lepton was not to be considered a fundamental absence, but a consequence of the fact that a meson heavier than the third lepton was not there, since the remarkable coincidence of the ($\pi-\mu$) case was unique.
3

DECAY
The discovery by Lattes, Occhialini and Powell [7] allowed the observation of the complete decay-chain-reaction

\[ \pi \rightarrow \mu \rightarrow e , \quad (1) \]

which was the basis to understand the real nature of the cosmic ray particle observed in 1938 by Anderson and Neddermeyer [4], and proved by Conversi, Pancini and Piccioni to have no nuclear coupling with matter [5].
In the Yukawa mass range, the gold mine had not only the $\pi$–meson but also the $\mu$–meson. This last one opened a completely unexpected new field, now called the *leptonic world*. The first member of this new world is the last particle in the decay-chain-reaction (1), the electron. The second member is the muon ($\mu$) which is not any more called ‘meson’; its correct name being ‘lepton’. The lepton $\mu$ has the same electromagnetic properties of the ‘electron’ but with a 200 times heavier mass and no nuclear charge.
This incredible property prompted Rabi to make the famous statement ‘Who ordered that?’ reported by T.D. Lee [8].
The Origin of the Third Family

In honour of A. Zichichi on the XXX anniversary of the proposal to search for the third lepton at Adone


Edited by O. Barnabei, L. Maiani, R.A. Ricci and F. Roversi Monaco

World Scientific
Once again, this is not the end of the gold mine. As a consequence of the decay properties of the Yukawa particle, the gold mine was found to contain the field of the Weak Forces.
In fact, the discovery of the leptonic world opened the field of the universal Fermi interaction and in 1949 Lee, Rosenbluth and Yang [9] proposed the existence of the intermediate boson, called W because it was the quantum of the Weak Forces. It was later discovered that the W weak boson was the source of the breaking of symmetry laws: parity P and charge conjugation invariance C [10].
[10] *Question of Parity Conservation in Weak Interactions*

In the same year (1947) of the $\pi$ meson discovery, another meson, later called ‘strange’, was discovered in the Blackett Lab [11] studying cosmic rays. This strange meson, called $\theta$, was decaying into two Yukawa mesons.
It took nearly ten years to find out that this $\theta$ meson and another one, with equal mass and lifetime, called $\tau$ and decaying into three Yukawa mesons, were not two different mesons but two different decay modes of the same particle, the K-meson, which solved the famous $(\theta-\tau)$ puzzle [12-14].
This was achieved by T.D. Lee and C.N. Yang [10], who proved that no experimental evidence existed to establish the validity of Parity and Charge Conjugation invariance in weak interactions. The experimental evidence came immediately after [15].
The gold mine opened by Yukawa in 1935 gave rise, two decades later, to the discovery that the invariance laws, P and C, are broken in decay processes, involving two and three Yukawa mesons. The violation of P and C generated the problem of PC conservation, and therefore of time reversal, invariance, T, (because of the PCT theorem).
This invariance law was proposed by Landau [16], while Lee, Oehme and Yang (LOY) [17] remarked the lack of experimental evidence for T-invariance. The experimental proof that LOY were on the right track came in 1964 when Christenson, Cronin, Fitch and Turlay [18] discovered that the meson called $K_2^0$ was also decaying into two Yukawa mesons.
The famous Rabi’s statement became ‘Who ordered all that?’ All being the content of the Yukawa gold mine.
To close with the gold mine in the decay of the Yukawa particle, I would like to recall the $2\gamma$ decay of the neutral [19-25] Yukawa meson:

$$\pi^0 \rightarrow \gamma\gamma.$$ 

This generated the celebrated chiral anomaly also known as ABJ (Adler, Bell, Jackiw) anomaly [26], with its remarkable consequences [27] also in the non abelian forces [28].
One consequence is the important ingredient in theoretical model building, called ‘anomaly-free condition’, which explains why the number of fundamental quark-fermions must be equal to the number of fundamental lepton-fermions. This allowed the theoretical prediction to be made for the existence of the heaviest quark, in addition to the b-quark in the 3rd family of elementary fermions, the top-quark.
4

INTRINSIC STRUCTURE
We now turn to the analysis of the intrinsic structure of the Yukawa particle, which is made of a pair of the lightest, nearly-massless, elementary fermions: the ‘up’ and ‘down’ quarks. This allows to understand why chirality invariance – a global symmetry property – should exist in the field of strong interactions. It is the spontaneous breaking of this global symmetry which generates the Nambu-Goldstone boson [29, 30].
[29] A ‘Superconductor’ Model of Elementary Particles and Its Consequences

[30] Field Theories with ‘Superconductor’ Solutions
The intrinsic structure of the Yukawa particle needs the existence of a non-Abelian fundamental force (QCD) acting between the constituents of the \( \pi \)-meson (quarks and gluons) and being originated by a gauge-principle. Thanks to this principle, the QCD quantum is a vector and does not destroy chirality–invariance.
To understand the non-zero-mass of the Yukawa meson, another property of the non-Abelian force (QCD) had to exist: the instantons. Thanks to the instantons, chirality-invariance can be broken also in a non-spontaneous way. If this was not to be the case, the $\pi$ could not be so ‘heavy’; it would have to be nearly mass-less.
Thus the problem arises: can a pseudoscalar meson exist with a mass as large as the nucleon? The answer is Yes: its name is $\eta'$ and represents the final step in the gold mine started with the $\pi$–meson. Its mass is not intermediate, between the very light electron and the very heavy nucleon; the $\eta'$ mass is nearly the same as the nucleon mass.
This η'–meson is a pseudoscalar meson, like the Yukawa π, and was originally called X⁰. Very few believed it could be a pseudoscalar meson. Its mass and its width were too big and there was no sign of its 2γ decay mode.
The missing 2γ decay mode of the X⁰–meson prevented it from being considered the singlet 9th member of the pseudoscalar SU(3)_{uds}–flavour multiplet of Gell-Mann and Ne'eman.
The discovery of the $2\gamma$ decay mode of the $X^0$–meson \cite{31} gave a strong support to its pseudoscalar nature.
Once the $X^0$ was established to be a pseudoscalar meson, its gluonic content was theoretically expected by the QCD instantons.
If the $\eta'$ has a strong gluon component, we should expect to see a typical QCD non-perturbative effect: the leading production in gluon-induced jets.
In fact, the leading effect had been observed in all hadronic processes where some conserved quantum numbers flow, from the initial to the final state, did occur.
The gluon quantum numbers flow would go from an initial state made of two gluons into a final state made of $\eta'$, if this meson had a strong gluon component. In this case the $\eta'$ should be produced in a leading mode.
This is exactly the effect which has been discovered in the production of the $\eta'$–mesons in gluon-induced jets, as reported in Figure 1, where $\eta$ and $\eta'$ production in gluon-induced-jets are compared. The leading effect is not present in the $\eta$ production, while the $\eta'$ has a strong leading effect [33].
Figure 1: The Feynman $x$-distributions for $\eta$ and $\eta'$ production, showing the $\eta'$ leading effect (Figure from Reference 33).
The interest of this finding is that the $\eta'$-meson, in order to be leading in a gluon-induced-jet, must – as mentioned before – have a strong gluonic content. It thus appears that the $\eta'$ is the lowest pseudoscalar state having the strongest contribution from the quanta of the QCD force. The $\eta'$ is the particle which is most directly linked with the original idea of Yukawa, who was advocating the existence of a quantum of the nuclear force field.
The $\eta'$, thanks to its strong gluonic component, is the Yukawa particle in the QCD Era.
Seventy-two years after the original idea of Yukawa that the quantum of the nuclear forces has to exist, we have found that this meson, called $\pi$, has given rise to a fantastic development in our thinking, the last step being the $\eta'$-meson.
To sum up, the η' represents the conclusion of the Yukawa π–meson challenge, and the basic steps are:

1 - The 2γ decay mode of the X⁰–meson is discovered. The X⁰–meson becomes the ninth member of the pseudoscalar multiplet and is called η'.

2 - The η'–meson is theoretically understood as being a mixture of (q̅q) with a strong gluonic component.

3 - The strong gluon content in the η'–meson is experimentally proved to be present with the leading effect in the gluon-induced jets.
5

THE YUKAWA LESSON FOR THE QGCW
There is a further lesson which is coming from the gold mine opened by Hideki Yukawa: the impressive series of totally unexpected discoveries.
Let me quote just three of them:

1. The first experimental evidence for a cosmic ray particle believed to be the Yukawa meson was a lepton: the muon.
2. The decay-chain: $\pi \rightarrow \mu \rightarrow e$ was found to break the symmetry laws of Parity and Charge Conjugation.
3. The intrinsic structure of the Yukawa particle was found to be governed by a new Fundamental Force of Nature, Quantum ChromoDynamics: QCD.
This is perfectly consistent with the great steps in physics: all totally unexpected. The totally unexpected events (UEEC) called by historians, Sarajevo-type-effects, characterize ‘COMPLEXITY’.
A detailed analysis [34] shows that the experimentally observable quantities, which characterize the existence of ‘complexity’ in a given field, do exist in physics; the Yukawa gold mine is a proof of it.
This means that ‘complexity’ exists at the fundamental level, therefore, totally unexpected effects should show up in physics:
• **Effects**, which are impossible to be predicted on the basis of present knowledge.

• Where these effects are most likely to be no one knows. All we are sure of is that new experimental facilities are needed; and this is what is going on in Japan, in Europe and in other regions of the planet.
• In Europe, with the advent of the LHC, it will be possible to study the properties of the Quark-Gluon-Coloured-World (QGCW) [35, 36], which is a world totally different from our world made of QCD vacuum with colourless baryons and mesons. Yukawa would tell us to search for specific effects due to the fact that the colourless condition is avoided.
1st problem –

In the QGCW there are all states allowed by the SU(3)\textsubscript{c} colour group. The number of possible states is by far more numerous than the number of colourless baryons and mesons which have so far been built in all Labs, since the colourless condition is not needed. Question: What are the consequences on the properties of the QGCW?
2nd problem –

Light quarks versus heavy quarks. Are the coloured quark masses the same as the values we derive from the fact that baryons and mesons need to be in a colourless state?

It could be that all six quark flavours are associated with nearly ‘massless’ states, similar to those of the 1st family (u, d).
In other words, the reason why the ‘top’ quark appears to be so heavy ($\sim 10^2$ GeV) could be the result of some, so far unknown, condition related to the fact that the final state must be QCD-‘colourless’.
We know that confinement produces masses of the order of a GeV. Therefore, according to our present understanding, the QCD ‘colourless’ condition could not explain the heavy quark mass. However, since the origin of the quark masses is still not known, it cannot be excluded that in a QCD coloured world, the six quarks are all nearly massless and that the colourless condition is ‘flavour’ dependent.
If this was the case, the masses we measure are heavier than the effective coloured quark masses.

In this case, all possible states generated by ‘heavy’ quarks would be produced in the QGCW at a much lower temperature than the one needed in our world made with baryons and mesons, i.e. QCD colourless states.
Here again, we should try to see if with masses totally different from those expected, on the basis of what we know about colourless baryons and mesons, new **effects** could be detected due to the existence of all flavours (even those which could exist in addition to the six so far detected) at relatively low temperature in the QGCW world.
3rd problem –
To search for effects on the thermodynamic properties of the QGCW.
Are these properties going to be along the ‘extensivity’ and / or ‘non-extensivity’ conditions?
In the QGCW, an enormous number of QCD-open-colour-states allowed by SU(3)\textsubscript{c} will exist; this number is by far higher that the number of baryons and mesons detected so far.

In principle, many different phase transitions could take place and a vast variety of complex systems should show up.

The properties of this ‘new world’ should open unprecedented horizons in understanding the Logic of Nature [37].
4th problem –
Derive the equivalent Stefan-Boltzmann Radiation Law for the QGCW.

In classical Thermodynamics the relation between energy density at emission $U$, and Temperature of the source $T$, is

$$U = cT^4.$$ 

In the QGCW, the correspondence should be

$U \equiv p_\perp$ (transverse momentum)

$T \equiv$ average energy in the CM system.
In the QGCW, the production of ‘heavy’ flavours should be studied

\[ \langle p_\perp \rangle \text{ and } \langle E \rangle. \]

The expectation is

\[ \langle p_\perp \rangle \equiv C \cdot \langle E \rangle^4 \]

and any deviation would be extremely important.
The study of the properties of the QGCW should produce the correct mathematical structure able to correctly describe the QGCW.

The same mathematical formalism should allow to go from QGCW to the Physics of Baryons and Mesons (PBM) and from here to a restricted component of PBM, namely Nuclear Physics, where all properties of the nuclei should find a correct description.
How to study the new world: QGCW

With the advent of the LHC supercollider, we propose the development and the realisation of a new technology able to implement the collision between different particle states $(p, n, \pi, K, \mu, e, \gamma, \nu)$ and the QGCW in order to study the properties of the Quark-Gluon-Coloured-World (QGCW) [35, 36].
An example of how to study the QGCW is illustrated in Figure 2, where beams of known particles (p, n, π, K, μ, e, γ, ν) bombard the QGCW. A special set of detectors will measure the properties of the outcoming particles.
Figure 2: A simplified diagram to illustrate how to study the QGCW; the special set of detectors is not shown.
The QGCW is produced in a collision between heavy ions $(^{208}\text{Pb}^{82+})$ at the maximum energy so far available, i.e. 1150 TeV and a design luminosity of $10^{27}\ \text{cm}^{-2}\text{s}^{-1}$. For this to be achieved, CERN needs to upgrade the ion injector chain comprising Linac3, LEIR, PS and SPS machine \cite{36}. 
Once the lead-lead collision is available, the problem is to synchronize the ‘proton’ beam with the QGCW produced. This problem is being studied at the present time. The detector technology is also under intense R&D since the synchronization needed is at a very high level of precision.
Totally unexpected effects should show up if Nature follows the Logic of Complexity at the Fundamental level [34], following the example of the Yukawa gold mine.
Incoming particles

\[ \{ p, n, \pi, K, \mu, e, \gamma, \nu \} \]

QGCW

Outcoming particles

Figure 2: A simplified diagram to illustrate how to study the QGCW; the special set of detectors is not shown.
6

CONCLUSIONS ON THE GOLD MINE OPENED BY HIDEKI YUKAWA
On the occasion of the Yukawa Centenary Celebrations, we would like to draw attention to the impressive series of conceptual developments linked with his meson: Chirality–invariance, Spontaneous Symmetry Breaking, Anomalies, and Anomaly-Free Condition, Gauge Principle (for Non-Abelian Forces), Instantons and Symmetry Breaking of Fundamental Invariance Laws.
All the pieces of the Yukawa gold mine could not have been discovered if the experimental technology was not at the frontier of our knowledge. Example: the **Cloud-Chambers** (Anderson, Neddermeyer), the **Photographic Emulsions** (Lattes, Occhialini, Powell), the **High Power Magnetic Fields** (Conversi, Pancini, Piccioni) and the **Powerful Particle Accelerators and Associated Detectors** for the discovery – the world over – of the intrinsic structure of the **Yukawa particle** (quarks and gluons).
This means that we must be prepared with the most advanced technology for the discovery of totally unexpected events like the ones found in the Yukawa gold mine. This is the last lesson from Hideki Yukawa
Let me close this lecture by showing Figure 3 which reproduces page n. 4 of my book ‘Subnuclear Physics’ [37], where the picture of Hideki Yukawa is presented together with a photo of the President of the Italian Republic, Sandro Pertini, a strong supporter of the field of physics, which owes so much to Yukawa.

On September 1982 I presented the Erice Statement (signed by 10,000 scientists from 115 countries) to President Pertini and this is how the Special Law for the Erice Prize started to be. The Erice Prize could not have existed without the gold mine opened by Hideki Yukawa.
Figure 3: The close link between Hideki Yukawa and Italy.
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