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).
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 this new 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, the search for cosmic-ray particles with masses in-between (this is the origin of ‘mesotron’, now meson) the light electron, m_e, and the heavy nucleon, m_N, (proton or neutron), became a very hot topic, during the first third of the XXth Century. This intermediate mass value was deduced by Yukawa from the range of the nuclear forces.

The first experimental evidence [2] for the existence, in the cosmic radiation, of particles heavier than ordinary electrons with positive and negative charges but more penetrating power than electrons and much less massive than protons was obtained on March 30, 1937, by Neddermeyer and Anderson (the same fellow who had discovered the anti-electron in 1933). At the meeting of the American Physical Society on April 29, 1937, Street and Stevenson, reported the results of their experiment which gave, for the first time, a mass value of 130 electron masses (m_e) with 25% uncertainty [3]. On August 28 of the same year, Nishina, Takeuchi and Ichimiya submitted to Phys. Rev. the experimental evidence for a positively charged particle with mass between 180 and 260 electron masses [4]. On June 16, 1938, Neddermeyer and Anderson submitted to Phys. Rev. (Letters) a paper where the observation of a positively charged particle with a mass of about 240 electron masses [5] was reported. On January 31, 1939, Nishina and collaborators submitted to Phys. Rev. (Letters) a paper where the discovery of a negative particle with mass (170 ± 9) electron masses was presented [6]. In this paper the authors improved the mass measurement of their previous particle (with positive charge) and concluded that the result obtained, m = (180 ± 20) m_e, was in good agreement with the value of the negative particle. The masses of the negative and positive particles had not to be different.

The meson theory of the strong nuclear forces proposed by Hideki Yukawa appeared to have excellent experimental confirmations but the Yukawa idea sparked an enormous interest in understanding the properties of the cosmic rays 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 [7].

Fermi, Teller and Weisskopf pointed out that ‘The decay of negative mesotrons in matter’ (this is the title of their paper) [8] 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 [9] 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 late fifties, it was realized that if it were not for the $\pi$–meson it would not have been easy to have so many muons. Their production could only go via electromagnetic processes. In fact if another ‘meson’ like the Yukawa one existed in the ‘heavy’ mass region, a third lepton [10], heavier than the muon, could not have easily been produced as decay-product of this heavy meson strongly produced by the nuclear forces, since this heavy meson would strongly decay into many Yukawa mesons. The remarkable coincidence of the ($\pi$–$\mu$) case was unique.

The absence of a third lepton in the so many final states produced in high energy interactions at CERN and other proton accelerators was not to be considered a fundamental absence, but a consequence of the fact that a third lepton could only be produced via electromagnetic processes, as for example ‘time-like’ photons in (p$\overline{p}$) or (e$^+$e$^-$) annihilation. The uniquenesses of the ($\pi$–$\mu$) case sparked the idea of searching for a third lepton in the appropriate production processes. This is how the study for the correct production and decay processes in order to search for a third lepton started [10].
3 DECAY

The discovery by Lattes, Occhialini and Powell [9] allowed the observation of the complete decay-chain-reaction

\[ \pi \rightarrow \mu \rightarrow e \, , \]

which was the basis to understand the real nature of the cosmic ray particles observed during two years (1937-1939) by many authors [2-6], and proved by Conversi, Pancini and Piccioni to have no nuclear coupling with matter [7].

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 [10]. 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 problem of the universal Fermi interactions, which become a central focus of the physics community [11-14]. Lee, Rosenbluth and Yang proposed [13] 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 [15].

In the same year (1947) of the \( \pi \)-meson discovery, another meson, later called ‘strange’, was discovered in the Blackett Lab [16] 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 [17-19].
This was achieved by T.D. Lee and C.N. Yang [15], 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 [20].

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 [21], while Lee, Oehme and Yang (LOY) remarked [22] 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 [23] discovered that the meson called $K^{0}_{2}$ 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 [24-30] Yukawa meson: $\pi^{0} \rightarrow \gamma\gamma$. This generated the celebrated chiral anomaly also known as ABJ (Adler, Bell, Jackiw) anomaly [31], with its remarkable consequences [32] also in the non-Abelian forces [33]. 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 [34, 35].

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 [36, 37]. 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 \(\eta'\)-meson is a pseudoscalar meson, like the Yukawa \(\pi\), and was originally called \(X^0\). Very few believed it could be a pseudoscalar meson. Its mass and its width were too big and there was no sign of its \(2\gamma\) decay mode.

The missing \(2\gamma\) decay mode of the \(X^0\)-meson prevented it from being considered the isotopic 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 [38] gave a strong support to its pseudoscalar nature. Once the \(X^0\) was established to be a pseudoscalar meson, thus becoming the isotopic singlet quoted above, its strong gluonic content become theoretically expected by the QCD instantons [36, 37]. 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 [39] 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 [40].

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 $\eta'$ represents the conclusion of the Yukawa $\pi$-meson challenge, and the basic steps are:

1 - The $2\gamma$ decay mode of the $X^0$-meson is discovered. The $X^0$-meson becomes the singlet ninth member of the pseudoscalar multiplet and is called $\eta'$.

2 - The $\eta'$-meson is theoretically understood as being a mixture of $(q\bar{q})$ with a strong gluonic component.
3 - The strong gluon content in the $\eta'$-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’ [41].

A detailed analysis [41] 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) [42, 43], 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 $\text{SU}(3)_c$ 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 due 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, QCD would not be ‘flavour-blind’ and this would be the reason why 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 physics.

**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? [44] In the QGCW, an enormous number of QCD-open-colour-states allowed by SU(3)\(_c\) 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 [45].

**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

\[
U = p_\perp \text{ (transverse momentum)}
\]
$T = \text{average energy in the CM system.}$

In the QGCW, the production of ‘heavy’ flavours should be studied versus $\langle p_{\perp} \rangle$ and versus $\langle E \rangle$. The expectation is

$$\langle p_{\perp} \rangle = C \cdot \langle E \rangle^4$$

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 finally find a complete 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) [42, 43].

An example of how to study the QGCW is illustrated in Figure 2, where beams of known particles ($p, n, \pi, K, \mu, e, \gamma, \nu$) bombard the QGCW. A special set of detectors will measure the properties of the outcoming particles.

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 [43].

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 [41], following the example of the Yukawa gold mine.
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, symmetry breaking of fundamental invariance laws, anomalies, and ‘anomaly-free condition’, existence of a third family of fundamental fermions, gauge principle for non-Abelian forces, instantons and existence of a pseudoscalar particle made of the quanta of a new fundamental force of Nature acting between the constituents of the Yukawa particle.

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’ [46], 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.

Hideki Yukawa.

REFERENCES

[1] Interaction of Elementary Particles
Models and Methods in the Meson Theory


[7] On the Disintegration of Negative Mesons

[8] The Decay of Negative Mesotrons in Matter

[9] Processes Involving Charged Mesons
C.M.G. Lattes, H. Muirhead, G.P.S. Occhialini e C.F. Powell, Nature 159, 694 (1947);
Observations on the Tracks of Slow Mesons in Photographic Emulsions

[10] Heavy Leptons


[12] Mesons and Nucleons
O. Klein, Nature 161, 897 (1948).

[13] Interaction of Mesons with Nucleons and Light Particles

[14] Energy Spectrum of Electrons from Meson Decay

[15] Question of Parity Conservation in Weak Interactions

[16] *Evidence for the Existence of New Unstable Elementary Particles*


[17] *On the Analysis of τ–Meson data and the Nature of the τ–Meson*

R.H. Dalitz, *Phil. Mag.* **44**, 1068 (1953);

[18] *Isotopic Spin Changes in τ and θ Decay*

R.H. Dalitz, *Proceedings of the Physical Society* **A69**, 527 (1956);

[19] *Present Status of τ Spin-Parity*


[20] *Experimental Test of Parity Conservation in Beta Decay*


[21] *On the Conservation Laws for Weak Interactions*


[22] *Remarks on Possible Noninvariance under Time Reversal and Charge Conjugation*


[23] *Evidence for the 2π Decay of the K^0_2 Meson*


[24] To explain the experimental observation of the charge independence of nuclear forces, Kemmer pointed out [25] that, in addition to Yukawa’s charged meson, a neutral pion had to exist. The production of a neutral meson decaying into two photons was suggested by Lewis, Oppenheimer and Wouthuysen [26] in order to explain the soft component in cosmic radiation. The missing member of the pion triplet was discovered in cosmic rays at Bristol by Carlson (Ekspong since 1951) et al. [27] and, using the cyclotron at Berkeley, by Bjorklund et al. [28] and by Panofsky et al. [29]. «It was generally felt that the neutral pion marked the end for particle searches» [30]: this is what was said, forty-seven years after its discovery, by a prominent member of the physicists who discovered the neutral pion. Instead of the end of particle searches, the \( \pi^0 \rightarrow \gamma\gamma \) marked the opening of a new horizon in subnuclear physics.

[25] *Charge-Dependence of Nuclear Forces*


[26] The Multiple Production of Mesons

[27] The Neutral Mesons

[28] High Energy Photons from Proton-Nucleon Collisions

[29] The Gamma-Ray Spectrum from the Absorption of $\pi^-$-Mesons in Hydrogen


[31] A PCAC Puzzle: $\pi^0 \rightarrow \gamma\gamma$ in the $\sigma$–Model
J.S. Bell and R. Jackiw, *Nuovo Cimento* A60, 47 (1969); *Axial-Vector Vertex in Spinor Electrodynamics*


[33] Anomalous Ward Identities in Spinor Field Theories

[34] A ‘Superconductor’ Model of Elementary Particles and Its Consequences

[35] Field Theories with ‘Superconductor’ Solutions

[36] Computation of the Quantum Effects due to a four-Dimensional Pseudoparticle

[37] How Instantons Solve the $U(1)$ Problem

[38] Evidence for a New Decay Mode of the $X^0$–Meson: $X^0 \rightarrow 2\gamma$

[39] *The "Leading"-Baryon Effect in Strong, Weak, and Electromagnetic Interactions*
The complete sequence of experimental results is reported in ‘*The Creation of Quantum ChromoDynamics and the Effective Energy*’, L.N. Lipatov (ed), which contributions by V.N. Gribov, G. ’t Hooft, G. Veneziano and V.F. Weisskopf; first published by the University and the Academy of Sciences of Bologna, Italy (1998); World Scientific Series in 20th Century Physics, Vol. 25 (2000).

[40] *Evidence for $\eta$ Leading*
L. Cifarelli, T. Massam, D. Migani and A. Zichichi, in ‘*Highlights: 50 Years Later*’, Erice 1997, World Scientific (1998); see also
*Thesis*
D. Migani, July 1997, Bologna University.

[41] *Complexity Exists at the Fundamental Level*

[42] The first experiments to study the QGCW have been proposed and implemented under the guidance of T.D. Lee with the relativistic heavy ion collider (RHIC) at BNL.

*From Reductionism to Holism*

[43] *The QGCW Project*
A. Zichichi et al., CERN-LAA Preprint, October 2006; see also
*Logical Reasoning in Experimental Physics: Past and Future*
A. Zichichi, in Gerardus ’t Hooft Liber Amicorum to celebrate his 60th anniversary (2006).


[45] *The Logic of Nature, Complexity and New Physics: From Quark-Gluon Plasma to Superstrings, Quantum Gravity and Beyond*

[46] *Subnuclear Physics - The first fifty years*
A. Zichichi, a joint publication by University and Academy of Sciences of Bologna, O. Barnabei, P. Pupillo and F. Roversi Monaco (eds), Italy (1998); World Scientific Series in 20th Century Physics, Vol. 24 (2000). The cover page is reproduced in Figure 4.
Figure 4