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On the Interaction of Elementary Particles. ~~IV~~.

II, ~~Generaliza~~ ~~Formulation~~ ~~Scheme~~
Generalization of the Mathematical Scheme

By Hideki Yukawa

(Read ~~Sept~~ Nov. 28, 193~~6~~)

1

On the Interaction of Elementary Particles. II,

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(Read Nov. 28, 1936)

Abstract

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§1. Introduction

In the paper[1] published early in 1935, the present author introduced a new field, which was responsible both for the short range force between the neutron and the proton and for the β-disintegration. ~~It was shown that this field was~~ This field was ~~shown~~ shown to be accompanied by quanta with the elementary charge +e or −e and the mass about $\frac{1}{10}$ of that of the proton. ~~Such quanta, which if it ever was were~~ It was shown further that such quanta could not be emitted by by ordinary nuclear reaction and might be present only in the cosmic ray. ~~At that time~~ There ~~was~~ had been, however, no evidence in favour of the existence of such ~~heavy~~ quanta, ~~so that further development of the theory~~ ~~the author hesitated to develop the theory further.~~ until late, when ~~Recent~~ researches of Anderson and Neddermeyer[2] and Street and Stevenson[3] and Nishina, Takeuchi and Ichimiya ~~and Nishina~~ others ~~seem to~~ indicated the existence ~~of~~ in the cosmic ray of particles, which can be identified neither with ~~the~~ electrons nor with ~~the~~ protons, as long as ~~if~~ we accept the present quantum theory. ~~Thus the existence of the charged particles with intermediate mass predicted by the theory become very probable, and it seems, so that~~ ~~and~~ Thus the existence of the charged particles with intermediate mass became very probable[4], and it seems reasonable to identify them ~~which can naturally be identified~~ with heavy quanta above considered.[5]

5) Yukawa, Proc. Phys.-Math. Soc. Japan 19, 712, 1937.

Hereafter this paper will be referred to as I.

1) Yukawa, Proc. Phys.-Math. Soc. Japan 17, 48, 1935.

2) Anderson and Neddermeyer, Phys. Rev. 50, 273, 1936; 51, 884, 1937.

3) Street and Stevenson, ibid. 51, 1005, 1937.

4) According to the preliminary result obtained by Nishina and his coworker, the mass of the new particles ~~lies~~ between nearly $\frac{1}{6}$ and $\frac{1}{7}$ the protonic mass, which is in fair agreement with the theoretical ~~pred~~ is about $\frac{1}{10}$ expectation.

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(2)

Our aim is to ~~deal with~~ elucidate ~~the relation between~~ the phenoma
~~concerning~~ ~~of~~ the nuclear ~~structure~~ transformation, β-disintegration and ~~the~~ cosmic
ray, in the light of the new field theory, ~~and~~ instead and to give ~~a~~
phenomena
from a unifyed point which is the common background
~~that~~ by

In this paper, we ~~should like to~~ begin with the mathematical formulation
of ~~the mathematical scheme~~ the general scheme, ~~defering~~ ~~deferring~~ and
the solution of the concrete problems being
~~deal~~ to deal with.

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Thus the most serious drawback in my theory seems to be removed.

~~Op~~ Similar conclusion was reached by Oppenheimer and Serber[6] and by Stückelberg[7]. It should be noticed, however, that there ~~a~~ are still many points ~~in the~~ my theory to be completed or ~~corrected or completed~~ ~~although~~ by further development of the theory.

Firstly, ~~only the only exchange force of Heisenberg type between like unlike nuclear particles was deduced from the scalar potential in I.~~ ~~we~~ We have to consider the interaction of ~~the~~ heavy quanta with the electromagnetic field in detail. If ~~we consider the~~ this take only ~~the~~ scalar potentials into account, the mathematical formulation will be the same with that given by Pauli and Weisskopf[8], except ~~that~~ the ~~mass~~ larger mass and the presence of source and sink for ~~due to the presence of the~~ transition of the heavy or light particles. (§ 2) Various processes†,

Secondly, only exchange force of Heisenberg type between ~~the neutron and the proton~~ unlike heavy particles was deduced in I. ~~Like par~~ Forces between like particles can be obtained by considering higher order processes as in the usual neutrino-electron field theory, whereas the exchange force of Majorana type between unlike particles can be included, ~~onto~~ only if ~~tensor field~~ potentials is introduced instead of ~~for~~ those of four vector of tensor ~~by~~ character ~~character~~. (§4) ~~There Recent experimental~~ It is argued recently ~~that~~ by many authors[9] that ~~the~~ experimental results on the scattering and ~~the~~ binding of nuclear particles can be explained by assuming the same ~~same~~ forces between like ~~particles as well as as those between unlike particles and~~ that further

9)

6) Oppenheimer and Serber, Phys. Rev. 51, 1113, 1937.
7) Stückelberg, Phys. Rev. 52, , 1937.
8) Pauli and Weisskopf, Helv. Phys. 7, 709, 1934.

† which can be raised ~~are given rise~~ by the passage of heavy quanta through matter, will be mentioned (~~discussed~~ ~~enumerated~~) and their bearing on ~~the phenomena~~ cosmic ray phenomena will be discussed. (§3).

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(i.e. Majorana, Heisenberg, Bartlett and Wigner) (4)

a certain combination of four types of forces ~~will~~ is can be selected ~~necessary~~ so as to be consistent with ~~all the~~ the experiment ~~on~~ on the whole. ~~Then~~ Unfortunately ~~we can not reproduce~~ these consequences ~~strictly~~ can not be reproduced strictly in our theory, unless ~~we~~ further assumptions are made, as pointed out by Oppenheimer[5] and Serber[6]. ~~It should be kept in mind, however, that the present existing experimental data are not sufficient for the unique~~ determining ~~ample enough~~ ~~seems to be in~~,

The existing experimental data, ~~are not~~ ample, ~~however~~, ~~are not~~ sufficient for determining the nuclear forces uniquely, ~~so that~~ These ~~finer detail~~ ~~parts~~ points (This is not a serious defect of our theory, ~~since however~~, since Nevertheless)

Thirdly, ~~the magnetic anomalous~~ theoretical deduction of magnetic moments of the ~~proton~~ ~~neutron and the proton~~ heavy, proton and the neutron will be an important problem in our theory, as long as ~~a~~ wave equations of Dirac type ~~is~~ are assumed for the heavy particle. Detailed discussion of this problem will ~~not~~ be made ~~in this~~ in other place by Sakata[10]. (~~however~~)

Fourthly, ~~the original~~ the theory of β-decay given in I ~~corresponds to~~ was equivalent to that of Fermi[11]. We can ~~no~~ easily modify it into the form ~~which is equivalent to~~ corresponding to that of Konopinski and Uhlenbeck[12]. Recently ~~experimental results seems to show that~~, however, it was shown that neither ~~Fermi's original f nor K.-U.~~ Fermi nor of K.-U. is ~~su~~ ~~sufficient~~ the formula of for the complete explanation of the experiments results, ~~so that~~

except ~~that when the energy of~~ ~~disintegration is very~~ when the energy of disintegration is very large.

10) Sakata, Proc. Phys.-Math. Soc. ~~Japan~~ Japan 19, in press.
11) Fermi, Zeits. f. Phys. 88, 161, 1934.
12) Konopinski and Uhlenbeck, Phys. Rev. 48, , 1935.

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so that we should like to ~~defer~~ put off further discussions of this problem.

§ 2. Quantization of U-field

~~The field~~ The wave equations ~~for~~ (3) ~~and (4)~~ in I for U-field in vacuum can be derived from (3) in I and its conjugate complex (1) (2) the Lagrangian

$$\overline{L}_U = \iiint L_U\, dv,$$

where

$$L_U = \frac{1}{4\pi}\left\{\frac{1}{c^2}\frac{\partial \tilde{U}}{\partial t}\frac{\partial U}{\partial t} - \operatorname{grad}\tilde{U}\operatorname{grad}U - \lambda^2\tilde{U}U\right\}.$$

The ~~canonically conjugate operator~~ canonically conjugate variables to U and $\tilde{U}$ are

$$U^\dagger = \frac{\delta \overline{L}_U}{\delta \frac{\partial U}{\partial t}} = \frac{1}{4\pi c^2}\frac{\partial \tilde{U}}{\partial t}$$

and

$$\tilde{U}^\dagger = \frac{1}{4\pi c^2}\frac{\partial U}{\partial t}$$

respectively, which satisfy the commutation relations ~~of~~

$$U^\dagger(\vec{r},t)U(\vec{r}',t) - U(\vec{r}',t)U^\dagger(\vec{r},t) = -i\hbar\,\delta(\vec{r},\vec{r}')$$

$$\tilde{U}^\dagger(\vec{r},t)\tilde{U}(\vec{r}',t) - \tilde{U}(\vec{r}',t)\tilde{U}^\dagger(\vec{r},t) = -i\hbar\,\delta(\vec{r},\vec{r}'), \quad (3)$$

$$\tilde{U}(\vec{r},t)U(\vec{r}',t) - U(\vec{r}',t)\tilde{U}(\vec{r},t) = 0 \qquad \tilde{U}^\dagger(\vec{r},t)\tilde{U}^\dagger(\vec{r}',t) - U^\dagger(\vec{r}',t)\tilde{U}^\dagger(\vec{r},t) = 0$$

The Hamiltonian for the U-field becomes thus

$$\overline{H}_U = \iiint H_U\, dv, \quad (4)$$

where

$$H_U = \frac{\partial U}{\partial t}U^\dagger + \tilde{U}^\dagger\frac{\partial \tilde{U}}{\partial t} - L_U$$

$$= 4\pi c^2\tilde{U}^\dagger U^\dagger + \frac{1}{4\pi}\operatorname{grad}\tilde{U}\operatorname{grad}U + \frac{\lambda^2}{4\pi}\tilde{U}U \quad (5)$$

In the presence of the heavy particle, the Hamiltonian

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for the total system is given by

$$\bar{H}_M = \iiint \tilde{\Psi}\left[\frac{\vec{p}^{\,2}}{2M} - \frac{g}{2}\{\tilde{U}(\tau_1 - i\tau_2) + U(\tau_1 + i\tau_2)\} + \frac{D}{2}\tau_3\right]\Psi\, dv \qquad (7)$$

$$\bar{H} = \bar{H}_U + \bar{H}_M, \qquad (6)$$

where and $\vec{p} = -i\hbar\,\mathrm{grad}$

M, D ~~$\vec{p}$~~ and (τ_1, τ_2, τ_3) ~~are~~ the ~~average~~ average and the difference of masses of the neutron and the proton, mass, ~~momentum and~~ isotopic spin operators ~~of the heavy particle and D is the difference of mass~~ of the neutron and the ~~$\vec{p} = -i\hbar$ grad~~ ~~proton~~

$\tilde{\Psi}$, Ψ are the quantized wave functions for the heavy particle satisfying the commutation relations,

$$\left.\begin{aligned}
&\tilde{\Psi}(\vec{r}, \tau_3, t)\,\Psi(\vec{r}', \tau_3', t) + \Psi(\vec{r}', \tau_3', t)\,\tilde{\Psi}(\vec{r}, \tau_3, t) = \delta_{\tau_3\tau_3'}\,\delta(\vec{r}, \vec{r}') \\
&\Psi(\vec{r}, \tau_3, t)\,\Psi(\vec{r}', \tau_3', t) + \Psi(\vec{r}', \tau_3', t)\,\Psi(\vec{r}, \tau_3, t) = 0 \\
&\tilde{\Psi}(\;,\;)\,\tilde{\Psi}(\;,\;) + \tilde{\Psi}(\;,\;)\,\tilde{\Psi}(\;,\;) = 0
\end{aligned}\right\} \qquad (8)$$

~~From~~ By using the Hamiltonian (7) and the commutation relations (3) and (8), the theory can be developed on the line similar to that of the ordinary quantum electrodynamics. We can, for example, deduce the wave equations (4) (5) in I for the U-field in the presence of the heavy particle and ~~the wave eq~~ ~~further~~ the wave equations for the heavy particle in the presence of the U-field, which are identitical with (6) in I, except for the ~~sign~~ positive signe before the term containing g in ~~stead~~ place of the negative sign. This results ~~in~~ further in the change of signe of the ~~exchange~~ potential of the energy between the neutron and the proton. Namely, the ~~interaction~~ potential energy of ~~two~~ heavy ~~(II)~~ particles 1 and 2 at a distance r

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becomes
$$-\frac{g^2}{2}\left(\tau_1^{(1)}\tau_1^{(2)}+\tau_2^{(1)}\tau_2^{(2)}\right)\frac{e^{-\lambda r}}{r}$$
instead of
$$+\frac{g^2}{2}\left(\qquad\qquad\right)\frac{e^{-\lambda r}}{r}$$
as given in I, so that the neutron and the proton attracts with each other when their ordinary spins are anti-parallel in contradiction with the fact that H^2 has spin 1 in the normal state[1]. (13)[11] ~~This~~ difficulty of similar kind will appears later ~~also~~, when the Majorana type of force is taken into account. ~~This This can be~~ We can perhaps get rid of this diff., if we consider the vector potentials, $\vec{B}, \tilde{\vec{B}}$. In this case, the Hamiltonian ~~for the scalar~~ involving potentials ~~$U, \tilde{U}$ changes signe and~~ $\vec{B}, \tilde{\vec{B}}$ say can ~~be written~~ becomes in the form

$$\overline{H}_U=\iiint H_U\,dv \qquad (9)$$

$$H_U=-4\pi c^2\dot{\tilde{U}}^{\dagger}\dot{U}^{\dagger}-\frac{1}{4\pi}\operatorname{grad}\tilde{U}\operatorname{grad}U-\frac{\lambda^2}{4\pi}\tilde{U}U$$
$$+4\pi c^2\sum_{i=1}^{3}\dot{\tilde{\vec{B}}}^{\dagger}\dot{\vec{B}}^{\dagger}+\frac{1}{4\pi}\sum_{i=1}^{3}\operatorname{grad}\tilde{B}_i\operatorname{grad}B_i+\frac{\lambda^2}{4\pi}\sum_i\tilde{B}_iB_i, \qquad (10)$$

if we persist in the ~~parallel~~ analogy between the heavy and the light quanta. On the other hand the Hamiltonian for the heavy particle becomes

$$\overline{H}_M=\iiint\tilde{\Psi}\left\{\frac{1}{2M}\left[\vec{p}+\frac{g}{2}\{(\tau_1-i\tau_2)\tilde{\vec{B}}+(\tau_1+i\tau_2)\vec{B}\}\right]^2\right.$$
$$\left.+\frac{g}{2}\{\tilde{U}(\tau_1-i\tau_2)+U(\tau_1+i\tau_2)\}\right\}\Psi\,dv, \qquad (11)$$

The Hamiltonian for the total system being again

$$\overline{H}=\overline{H}_U+\overline{H}_M. \qquad (12)$$

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§3. Interaction of U-field with the Electro-Magnetic Field.

So far we have altogether neglected the interaction of U-field with the electromagnetic field, ~~which~~ ~~...~~ ~~appears~~ ~~always~~, ~~when the proton~~ ~~should be~~ ~~appears, for example, in the presence of the~~ ~~should be considered~~ ~~proton~~. ~~but the inclusion of the~~ it can be included in the usual manner, ~~as follows~~. Namely ~~grad U in (10) should be replaced by~~ grad $\tilde{B}$, ~~and~~ grad $\tilde{U}$ and grad B

$$\cancel{\left(\mathrm{grad} + \frac{ie}{\hbar c}\vec{A}\right)U} \quad \text{etc}$$

~~and~~

$$\cancel{\left(\mathrm{grad} - \frac{ie}{\hbar c}\vec{A}\right)\tilde{U}}$$

~~respectively~~ and the term of the form

Namely, we start from the Lagrangian for the U-field

$$\overline{L}_U = \iiint L_U\, dv, \qquad (13)$$

where

$$L_U = \frac{1}{4\pi}\left\{-\frac{1}{c^2}\left(\frac{\partial\tilde{U}}{\partial t} - \varepsilon\frac{ie}{\hbar}V\tilde{U}\right)\left(\frac{\partial U}{\partial t} + \varepsilon\frac{ie}{\hbar}VU\right)\right. \qquad (14)$$

$$+\left(\mathrm{grad}\,\tilde{U} + \varepsilon\frac{ie}{\hbar c}\vec{A}\tilde{U}\right)\left(\mathrm{grad}\,U - \varepsilon\frac{ie}{\hbar c}\vec{A}U\right) + \lambda^2\tilde{U}U\Big\}$$

$$+\frac{1}{4\pi}\sum_{i=1,2,3}\left\{\frac{1}{c^2}\left(\frac{\partial\tilde{B}_i}{\partial t} - \varepsilon\frac{ie}{\hbar}V\tilde{B}_i\right)\left(\frac{\partial B_i}{\partial t} + \varepsilon\frac{ie}{\hbar}VB_i\right)\right.$$

$$-\left(\mathrm{grad}\,\tilde{B}_i + \varepsilon\frac{ie}{\hbar c}\vec{A}\tilde{B}_i\right)\left(\mathrm{grad}\,B_i - \frac{\varepsilon ie}{\hbar c}\vec{A}B_i\right)$$

$$\left. -\lambda^2\tilde{B}_iB_i\right\}.$$

and $V, \vec{A}$ are the scalar and the vector potentials of the electro-magnetic field

~~The canonical conjugate van~~ The observables canonical conjugate to U ~~and~~ $\tilde{U}$, $\tilde{B}$, $\tilde{U}$ and $\tilde{B}$ becomes

$$U^{\dagger} = \frac{1}{4\pi c^2}\left(\frac{\partial\tilde{U}}{\partial t} - \varepsilon\frac{ie}{\hbar}V\tilde{U}\right) \qquad \tilde{U}^{\dagger} = -\frac{1}{4\pi c^2}\left(\frac{\partial U}{\partial t} + \varepsilon\frac{ie}{\hbar c}VU\right)$$

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$$\tilde{B}_i^{\dagger} = \frac{1}{4\pi c^2}\left(\frac{\partial \tilde{B}_i}{\partial t} - \varepsilon\frac{ie}{\hbar}V\tilde{B}_i\right) \qquad \tilde{B}_i^{\dagger} = \frac{1}{4\pi c^2}\left(\frac{\partial B_i}{\partial t} + \varepsilon\frac{ie}{\hbar}VB_i\right) \quad (15)$$

respectively, so that the Hamiltonian takes the form

$$\bar{H}_U = \iiint H_U\, dv, \qquad (16)$$

where

$$\begin{aligned} H_U = & -4\pi c^2\tilde{U}^{\dagger}U^{\dagger} - \frac{\varepsilon ie}{\hbar}(U^{\dagger}VU - \tilde{U}^{\dagger}V\tilde{U}) \\ & - \frac{1}{4\pi}\left(\mathrm{grad}\,\tilde{U} + \frac{\varepsilon ie}{\hbar c}\vec{A}\tilde{U}\right)\left(\mathrm{grad}\,U - \frac{\varepsilon ie}{\hbar c}\vec{A}U\right) \\ & - \lambda^2\tilde{U}U \\ & + 4\pi c^2\sum_i\Big\{\tilde{B}_i^{\dagger}B_i^{\dagger} + \frac{\varepsilon ie}{\hbar}(B_i^{\dagger}VB_i + \tilde{B}_i^{\dagger}V\tilde{B}_i) \\ & + \frac{1}{4\pi}\left(\mathrm{grad}\,\tilde{B}_i + \frac{\varepsilon ie}{\hbar c}\vec{A}\tilde{B}_i\right)\left(\mathrm{grad}\,B_i - \frac{\varepsilon ie}{\hbar c}\vec{A}B_i\right) \\ & + \lambda^2\tilde{B}_iB_i\Big\}. \end{aligned} \quad (17)$$

On the other hand, ~~These equations~~ the non-relativistic Hamiltonian for the heavy particle in the presence of the electromagnetic field is given by

$$\begin{aligned} \bar{H}_M = \iiint \tilde{\Psi}\Big[& \frac{1}{2M}\left(\vec{p} - \frac{e}{c}\frac{1-\tau_3}{2}\vec{A}\right)^2 + \frac{D}{2}\tau_3 + e\frac{(1-\tau_3)}{2}V \\ & + \frac{g}{2}(\tau_1 - i\tau_2)\vec{B}_i + \frac{g}{2}(\tau_1 + i\tau_2)\vec{B} \\ & - \frac{g}{2}\{\tilde{U}(\tau_1 - i\tau_2) + U(\tau_1 + i\tau_2)\}\Big]\Psi\, dv, \end{aligned} \quad (18)$$

so that the ~~total~~ Hamiltonian for the system containing the heavy particles, U-field and electro-magnetic field becomes

$$\bar{H} = \bar{H}_M + \bar{H}_U + \bar{H}_{RE}, \qquad (19)$$

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where

$$\bar{H}_E = \frac{1}{8\pi}\iiint (\vec{E}^2 + \vec{H}^2)\,dv. \qquad (20)$$

Further, we should like, to ~~It should be assumed~~ that $U, \vec{B}$ and $\tilde{U}, \tilde{\vec{B}}$ ~~should~~ satisfy ~~a~~ auxiliary conditions

$$\left.\begin{aligned} &\frac{1}{c}\frac{\partial U}{\partial t} + \mathrm{div}\,\vec{B} = 0, \\ &\frac{1}{c}\frac{\partial \tilde{U}}{\partial t} + \mathrm{div}\,\tilde{\vec{B}} = 0 \end{aligned}\right\} \qquad (21)$$

~~which are intimately connected with the equation of continuity for the heavy of for the number~~

$$\cancel{\frac{\partial}{\partial t}\left\{\tilde{\Psi}\frac{(\tau_1 \pm i\tau_2)}{2}\Psi\right\} + \mathrm{div}\,\Pi = 0}$$

$$\cancel{\Pi = \frac{-i\hbar}{2M}\left\{\tilde{\Psi}\,\mathrm{grad}\,\frac{\tau_1 \pm i\tau_2}{2}\Psi - \Psi\,\mathrm{grad}\,\tilde{\Psi}\frac{\tau_1 \pm i\tau_2}{2}\right\}}$$

~~The reason~~ which are necessary for deriving the ~~interaction~~ relativistically invariant forces between heavy particles. Namely, the Hamiltonian in the absence of the electromagnetic field $\tilde{H}_U = \iiint H_U dv$.

with $$H_U = -4\pi c^2 \tilde{U}^\dagger U^\dagger - \frac{1}{4\pi}\{\mathrm{grad}\,\tilde{U}\,\mathrm{grad}\,U + \lambda^2 \tilde{U} U\}$$
$$+ 4\pi c^2 \sum_i \tilde{B}_i^\dagger B_i^\dagger + \frac{1}{4\pi}\{\mathrm{grad}\,\tilde{B}_i\,\mathrm{grad}\,B_i + \lambda^2 \tilde{B}_i B_i\},$$

can be written in the form, by using (21),

$$H_U = \cancel{\frac{1}{4\pi c}\mathrm{div}\,\vec{B}} \frac{1}{4\pi}\mathrm{div}\,\tilde{B}_i\,\mathrm{div}\,B_i - \frac{1}{4\pi}\{\mathrm{grad}\,\tilde{U}\,\mathrm{grad}\,U + \lambda^2 \tilde{U} U\}$$

§ 4. Deduction of Static Interaction between the Neutron and the Proton.

Deduction of static interaction between the neutron and the proton can be made in a manner similar ~~that by~~ of Fermi[1])

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(1) E. Fermi, Rev. Mod. Phys. 4, 131, 1932; W. Heitler, Quantum Theory of Radiation, ~~p. 46~~, Oxford, 1936, p. 46.

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§ Quant

§ Quant

§ Properties of Heavy Quanta

§ Magnetic Moment of Heavy Particles.

§ Interaction of Heavy Particles

~~Station~~

§ Passage of Heavy Quanta through Matter.

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第 110 回物理談話會

9 月 30 日 木 曜午後 4 時 30 分から理學部大講義室に於て下記の講演を行ひます

伊藤順吉君

Note on Resonance in Transmutation of Light Nuclei
(Kalckar, Oppenheimer and Serber, Phys. Rev. Aug 15, 1937)

岡谷辰治君

Viscosity に就て

尚以上に先立って午後 4 時 × 分から下記の通り學生の輪講があります

山口省太郎君

Unidirectional Measurement of Cosmic Ray Latitude Effect
(Johnson and Read, Phys. Rev. April 1, 1937)

注意、文化講義がありますので輪講の開始を 4時 に致します。

10 9 27