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$\sum_i \frac{\sigma_i^{(1)}\sigma_i^{(2)}}{2} = \frac{-1 \pm 2}{2}$

DEPARTMENT OF PHYSICS
OSAKA IMPERIAL UNIVERSITY.

第六回 理論コロキウム講演.
(昭和十三年五月七日 土曜)

DATE ~~April~~ May

NO. 1

On the Interaction of Elementary Particles. IV

9 - 17.

§3. Theory of the Deuteron.

Neutron と Proton とから成る system に対する non-relativistic wave equation は, 重心の運動を separate すると,

$$\left\{\frac{\hbar^2}{M}\Delta + E - V\right\}\psi = 0$$

の如く書ける. 但し,

$$V = \varepsilon\left\{g_1^2 + g_2^2(\vec\sigma^{(1)}\vec\sigma^{(2)}) - g_2^2\frac{(\sigma^{(1)}\mathrm{grad})(\sigma^{(2)}\mathrm{grad})}{\varkappa^2}\right\}\frac{e^{-\varkappa r}}{r}$$

$$\varepsilon_\pm = \mp 1 \quad \text{for} \begin{cases} \text{symmetric state} & {}^3S, {}^1P, {}^3D, \cdots \\ \text{antisymmetric state} & {}^1S, {}^3P, {}^1D, \cdots \end{cases}$$

V を書き直せば

$$V = \varepsilon_\pm\Big[g_1^2 + \frac{2}{3}g_2^2(\vec\sigma^{(1)}\vec\sigma^{(2)}) \cancel{+ \frac{(\vec\sigma^{(1)}\vec\sigma^{(2)})}{3}}$$

$$+ g_2^2\left\{\frac{(\vec\sigma^{(1)}\vec\sigma^{(2)})}{3} - \frac{(\vec\sigma^{(1)}\vec r)(\vec\sigma^{(2)}\vec r)}{r^2}\right\}\left(1 + \frac{3}{\varkappa r} + \frac{3}{\varkappa^2 r^2}\right)\Big]\frac{e^{-\varkappa r}}{r}$$

~~sin~~ Triplet state に対しては $(\vec\sigma^{(1)}\vec\sigma^{(2)}) = +1$, Singlet state に対しては -3

~~Si~~ $(\vec\sigma^{(1)}\vec r)(\vec\sigma^{(2)}\vec r) = \begin{pmatrix} z & x-iy \\ x+iy & -z \end{pmatrix}_1 \begin{pmatrix} z & x-iy \\ x+iy & -z \end{pmatrix}_2$

V は ~~本~~ $\vec r \times \vec p$ なる orbital angular momentum とは commute ~~する~~ しない, しかし, total angular momentum

$$(\vec r \times \vec p) + \frac{\hbar}{2}(\vec\sigma^{(1)} + \vec\sigma^{(2)})$$

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In this way the singlet states ^1S, ^1P ...

Further V is invariant with respect to the exchange of $\sigma^{(1)}$ and $\sigma^{(2)}$ so that singlet and triplet states do not combine with each other.

Thus, the coupling between two states with different azimuthal quantum numbers are possible, whereas that between two states with diff. inner quantum numbers are not.

とは commute する. だから l の異なる state の intercomb. はあるが, j の異なる state の intercomb はない。
又 $(\vec{\sigma}^{(1)}\vec{\sigma}^{(2)})$ or $\frac{1+\vec{\sigma}^{(1)}\vec{\sigma}^{(2)}}{2}$ は V と commute する. だから s の異なる state 即ち triplet, singlet の intercombination はない。

$\vec{j} = \vec{l}+\vec{s}, \ldots, |l-s|$ †

Triplet. $s=1$	^3S (sym)		^3P (ant)		^3D (sym)		^3F (anti)	
l	0		1		2		3	
j	1	$^3S_1$	2	$^3P_2$	3	$^3D_3$	4	$^3F_4$
			1	$^3P_1$	2	$^3D_2$	3	$^3F_3$
			0	$^3P_0$	1	$^3D_1$	2	$^3F_2$

∴ ^3S と combine するのは $^3D_1$ だけである.

Singlet $\quad {}^1S_0 \quad {}^1P_1 \quad {}^1D_2 \quad {}^1F_3$

Singlet state は互に intercomb もせぬ。

Singlet state ^1S, ^1P, ... $\qquad \sigma^{(1)}\sigma^{(2)} = -3$

$$\begin{pmatrix} z & x-iy \\ x+iy & -z \end{pmatrix}_1 \begin{pmatrix} z & x-iy \\ x+iy & -z \end{pmatrix}_2 \cdot \frac{1}{\sqrt{2}}\left\{\begin{pmatrix}1\\0\end{pmatrix}_1\begin{pmatrix}0\\1\end{pmatrix}_2 - \begin{pmatrix}0\\1\end{pmatrix}_1\begin{pmatrix}1\\0\end{pmatrix}_2\right\}$$

$$= \frac{1}{\sqrt{2}}\left\{\begin{pmatrix}z\\x+iy\end{pmatrix}_1\begin{pmatrix}x+iy\\-z\end{pmatrix}_2 - \begin{pmatrix}x-iy\\-z\end{pmatrix}_1\begin{pmatrix}z\\x+iy\end{pmatrix}_2\right\} = -\frac{r^2}{\sqrt{2}}\left\{\begin{pmatrix}1\\0\end{pmatrix}_1\begin{pmatrix}0\\1\end{pmatrix}_2 - \begin{pmatrix}0\\1\end{pmatrix}_1\begin{pmatrix}1\\0\end{pmatrix}_2\right\}$$

$$\frac{(\vec{\sigma}^{(1)}\vec{r})(\vec{\sigma}^{(2)}\vec{r})}{r^2} = -1.$$

$$V = -(2g_2^2 - g_1^2)\frac{e^{-\kappa r}}{r}$$

† Symmetric と Antisymmetric との intercombination は起らない。

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Triplet state. Braunschweig, 1931
$\boxed{{}^3S_1,\ {}^3D_1}$ Wigner, Gruppentheorie, S, 208,

$$\chi_{-1} = \begin{pmatrix}0\\1\end{pmatrix}_1\begin{pmatrix}0\\1\end{pmatrix}_2 \qquad \chi_0 = \frac{1}{\sqrt{2}}\left\{\begin{pmatrix}1\\0\end{pmatrix}_1\begin{pmatrix}0\\1\end{pmatrix}_2 + \begin{pmatrix}0\\1\end{pmatrix}_1\begin{pmatrix}1\\0\end{pmatrix}_2\right\}$$

$$\chi_1 = \begin{pmatrix}1\\0\end{pmatrix}_1\begin{pmatrix}1\\0\end{pmatrix}_2 .$$

$${}^3S_1 : \frac{u(r)}{\sqrt{4\pi}\, r}\chi_{-1} \quad , \left(\frac{u(r)}{\sqrt{4\pi}\, r}\chi_0 , \quad \frac{u(r)}{\sqrt{4\pi}\, r}\chi_1 . \right)$$

$${}^3D_1 : \quad \Psi_{-1} = \sqrt{\frac{1}{10}}\left(Y_0\chi_{-1} - \sqrt{3}\,Y_{-1}\chi_0 + \sqrt{6}\,Y_{-2}\chi_1\right)$$

$$\Psi_0 = \sqrt{\frac{1}{10}}\left(\sqrt{3}\,Y_1\chi_{-1} - 2Y_0\chi_0 + \sqrt{3}\,Y_{-1}\chi_1\right)$$

$$\Psi_1 = \sqrt{\frac{1}{10}}\left(\sqrt{6}\,Y_2\chi_{-1} - \sqrt{3}\,Y_1\chi_0 + Y_0\chi_1\right)$$

$$\left.\begin{aligned} Y_0 &= \sqrt{\frac{5}{4\pi}}\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right) \\ Y_{\pm1} &= \sqrt{\frac{15}{8\pi}}\sin\theta\cos\theta\, e^{\pm i\varphi} \\ Y_{\pm2} &= \frac{1}{4}\sqrt{\frac{15}{2\pi}}\sin^2\theta\, e^{\pm 2i\varphi} \end{aligned}\right\} \begin{aligned} &= \sqrt{\frac{5}{4\pi}}\cdot\frac{3}{2}\left(\cos^2\theta - \frac{1}{3}\right) \\ &= \sqrt{\frac{5}{4\pi}}\cdot\sqrt{\frac{3}{4}}\sqrt{2}\sin\theta\cos\theta\, e^{\pm i\varphi} \\ &= \sqrt{\frac{5}{4\pi}}\sqrt{\frac{3}{8}}\sin^2\theta\, e^{\pm 2i\varphi} \end{aligned}$$

χ_{-1} と combine するものは Ψ_{-1}, etc.
そこで、$j_z = -1$ の状態に相当して,

$$\psi = \frac{u(r)}{r}\frac{\chi_{-1}}{\sqrt{4\pi}} + \frac{v(r)}{r}\Psi_{-1}$$

なる形の solution を求める.

$$\frac{(\vec{\sigma}^{(1)}\vec{r})(\vec{\sigma}^{(2)}\vec{r})}{r^2} = \begin{pmatrix}\cos\theta & \sin\theta\, e^{-i\varphi} \\ \sin\theta\, e^{i\varphi} & -\cos\theta\end{pmatrix}_1 \begin{pmatrix}\cos\theta & \sin\theta\, e^{-i\varphi} \\ \sin\theta\, e^{i\varphi} & -\cos\theta\end{pmatrix}_2$$

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$$\frac{(\vec{\sigma}_1^{(1)}\vec{r})(\vec{\sigma}^{(2)}\vec{r})}{r^2}\chi_{-1} = \cos^2\theta\,\chi_{-1} - \sqrt{2}\cos\theta\sin\theta\, e^{-i\varphi}\chi_0 + \sin^2\theta\, e^{-2i\varphi}\chi_1$$

$$\text{〃}\quad \chi_0 = -\sqrt{2}\cos\theta\sin\theta\, e^{i\varphi}\chi_{-1} + (1-2\cos^2\theta)\chi_0 + \sqrt{2}\sin^2\theta\, e^{-i\varphi}\chi_1$$

$$\text{〃}\quad \chi_{+1} = \sin^2\theta\, e^{2i\varphi}\chi_{-1} + \sqrt{2}\cos\theta\sin\theta\, e^{i\varphi}\chi_0 + \cos^2\theta\,\chi_1$$

$$\left\{\frac{(\vec{\sigma}^{(1)}\vec{r})(\vec{\sigma}^{(2)}\vec{r})}{r^2} - \frac{(\vec{\sigma}^{(1)}\vec{\sigma}^{(2)})}{3}\right\}\begin{pmatrix}\chi_{-1}\\ \chi_0\\ \chi_1\end{pmatrix} = \begin{pmatrix} (\cos^2\theta-\frac{1}{3})\chi_{-1} - \sqrt{2}\cos\theta\sin\theta\, e^{-i\varphi}\chi_0 + \sin^2\theta\, e^{-2i\varphi}\chi_1 \\ -\sqrt{2}\cos\theta\sin\theta\, e^{i\varphi}\chi_{-1} - 2(\cos^2\theta-\frac{1}{3})\chi_0 + \sqrt{2}\sin^2\theta\, e^{-i\varphi}\chi_1 \\ \sin^2\theta\, e^{2i\varphi}\chi_{-1} + \sqrt{2}\cos\theta\sin\theta\, e^{i\varphi}\chi_0 + (\cos^2\theta-\frac{1}{3})\chi_1 \end{pmatrix}$$

$$\chi_{-1} = \begin{pmatrix}1\\0\\0\end{pmatrix} \quad \chi_0 = \begin{pmatrix}0\\1\\0\end{pmatrix} \quad \chi_1 = \begin{pmatrix}0\\0\\1\end{pmatrix}.$$

$$\frac{(\vec{\sigma}^{(1)}\vec{r})(\vec{\sigma}^{(2)}\vec{r})}{r^2} - \frac{(\vec{\sigma}^{(1)}\vec{\sigma}^{(2)})}{3} = \begin{pmatrix} \cos^2\theta-\frac{1}{3} & -\sqrt{2}\cos\theta\sin\theta\, e^{+i\varphi} & \sin^2\theta\, e^{+2i\varphi} \\ -\sqrt{2}\cos\theta\sin\theta\, e^{-i\varphi} & -2(\cos^2\theta-\frac{1}{3}) & \sqrt{2}\sin\theta\cos\theta\, e^{+i\varphi} \\ \sin^2\theta\, e^{-2i\varphi} & \sqrt{2}\cos\theta\sin\theta\, e^{-i\varphi} & \cos^2\theta-\frac{1}{3} \end{pmatrix}$$

$$\Psi_{-1} = \sqrt{\frac{1}{10}}\begin{pmatrix} Y_0 \\ -\sqrt{3}Y_{-1} \\ \sqrt{6}Y_{-2}\end{pmatrix} = \sqrt{\frac{1}{10}}\cdot\sqrt{\frac{5}{4\pi}}\cdot\begin{pmatrix} \frac{3}{2}(\cos^2\theta-\frac{1}{3}) \\ \sqrt{2}\sin\theta\cos\theta\, e^{-i\varphi} \\ \sin^2\theta\, e^{-2i\varphi}\end{pmatrix}$$

$$= \sqrt{\frac{1}{10}}\sqrt{\frac{5}{4\pi}}\,\frac{3}{2}\Big(\qquad\Big) = \sqrt{\frac{1}{4\pi}}\cdot\frac{1}{\sqrt{2}}\cdot\frac{3}{2}$$

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$\sin\theta\cos\theta$

$\sqrt{2}\{(\cos^2\theta-\frac{1}{3})\sin\theta\cos\theta+\sin^2\theta\cos\theta\}$

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$\sqrt{2}-\frac{\sqrt{2}}{3}$ $(1-\frac{1}{3})$

$\cos^4\theta-\frac{2}{3}\cos^2\theta+\frac{1}{9}$

$\frac{10}{9}-\frac{2}{3}\cos^2\theta=\frac{8}{3}$ $\frac{2}{9}$

$$\left(\frac{(\vec\sigma^{(1)}\vec r)(\vec\sigma^{(2)}\vec r)}{r^2}-\frac{(\vec\sigma^{(1)}\vec\sigma^{(2)})}{3}\right)\Psi_{-1}$$

$$=\sqrt{\frac{1}{10}}\sqrt{\frac{5}{4\pi}}\frac{\sqrt2}{2}\begin{pmatrix}\cancel{\frac{3}{4}}(\cos^2\theta-\frac{1}{3})^2+\cancel{\frac{3}{4}}\cdot 2\sin^2\theta\cos^2\theta+\sin^4\theta \\ -\sqrt2\cos\theta\sin\theta(\cos^2\theta-\frac13)e^{-i\varphi}+2\sqrt2(\cos^2\theta-\frac13)\sin\theta\cos\theta e^{-i\varphi}+\sqrt2\sin^2\theta\cos\theta e^{-i\varphi} \\ \{\sin^2\theta(\cos^2\theta-\frac13)-2\sin^2\theta\cos^2\theta+\sin^2\theta(\cos^2\theta-\frac13)\}e^{-2i\varphi}\end{pmatrix}$$

$$=\sqrt{\frac{1}{10}}\sqrt{\frac{5}{4\pi}}\frac{3}{2}\begin{pmatrix}\frac{8}{9}-\frac{2}{3}(\cos^2\theta-\frac13) \\ +\frac{2\sqrt2}{3}\sin\theta\cos\theta e^{-i\varphi} \\ -\frac23\sin^2\theta\cdot e^{-2i\varphi}\end{pmatrix}$$

$$=-\frac{2}{3}\Psi_{-1}+\sqrt{\frac{1}{10}}\sqrt{\frac{5}{4\pi}}\cdot\frac{4}{3}\cdot\chi_{-1}=-\frac{2}{3}\Psi_{-1}+\frac{1}{\sqrt2}\cdot\frac43\cdot\frac{\chi_{-1}}{\sqrt{4\pi}}$$

$$\left(\frac{(\vec\sigma^{(1)}\vec r)(\vec\sigma^{(2)}\vec r)}{r^2}-\frac{\vec\sigma^{(1)}\vec\sigma^{(2)}}{3}\right)\frac{\chi_{-1}}{\sqrt{4\pi}}=\begin{pmatrix}\cos^2\theta-\frac13 \\ \sqrt2\cos\theta\sin\theta e^{-i\varphi} \\ \sin^2\theta e^{-2i\varphi}\end{pmatrix}\frac{1}{\sqrt{4\pi}}$$

$$=\frac{\Psi_{-1}}{\sqrt{4\pi}\sqrt{\frac{1}{10}}\sqrt{\frac{5}{4\pi}}\cdot\frac32}=\frac{\frac23\Psi_{-1}}{}\quad\frac23\sqrt2\,\Psi_{-1}.$$

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$$V = -\left\{ (g_1^2 + \tfrac{2}{3} g_2^2) \pm g_2^2 \left(\frac{(\sigma^{(1)} r)(\sigma^{(2)} r)}{r^2} - \frac{\sigma^{(1)} \sigma^{(2)}}{3} \right) \left(1 + \frac{3}{\varkappa r} + \frac{3}{\varkappa r}\right) \right\} \frac{e^{-\varkappa r}}{r}$$

$$V \Psi_{+1} \frac{\chi_{-1}}{\sqrt{4\pi}} = \frac{2}{3}\sqrt{2}\, \Psi_{+1} - (g_1^2 + \tfrac{2}{3} g_2^2) \frac{e^{-\varkappa r}}{r} \frac{\chi_{-1}}{\sqrt{4\pi}}$$

$$+ g_2^2 \left(1 + \frac{3}{\varkappa r} + \frac{3}{\varkappa^2 r^2}\right) \frac{e^{-\varkappa r}}{r} \cdot \frac{2}{3}\sqrt{2}\, \Psi_{-1}.$$

$$V \Psi_{-1} = -(g_1^2 + \tfrac{2}{3} g_2^2) \frac{e^{-\varkappa r}}{r} \Psi_{-1}$$

$$+ \frac{2\sqrt{2}}{3} \frac{\chi_{-1}}{\sqrt{4\pi}} * - \frac{2}{3} g_2^2 \left(1 + \frac{3}{\varkappa r} + \frac{3}{\varkappa^2 r^2}\right) \frac{e^{-\varkappa r}}{r} \Psi_{-1},$$

$$\left\{ g_2^2 \left(1 + \frac{2}{\varkappa r} + \frac{3}{\varkappa^2 r^2}\right) \frac{e^{-\varkappa r}}{r} \right)_{-1}$$

$$\Psi = \frac{u(r)}{r} \frac{\chi_{-1}}{\sqrt{4\pi}} + \frac{v(r)}{r} \Psi_{-1}.$$

wave equation is

$$\frac{\hbar^2}{M} \frac{d^2 u}{dr^2} + \left\{ E + (g_1^2 + \tfrac{2}{3} g_2^2) \frac{e^{-\varkappa r}}{r} \right\} u$$

$$- \frac{2\sqrt{2}}{3} g_2^2 \left(1 + \frac{3}{\varkappa r} + \frac{3}{\varkappa^2 r^2}\right) \frac{e^{-\varkappa r}}{r} \cdot v = 0$$

$$\frac{\hbar^2}{M} \left(\frac{d^2 v}{dr^2} - \frac{6}{r^2} v \right) + \left\{ E + (g_1^2 - \tfrac{2}{3} g_2^2) + \tfrac{2}{3} g_2^2 \left(1 + \frac{3}{\varkappa r} + \frac{3}{\varkappa^2 r^2}\right) \left(\frac{1}{\varkappa r} + \frac{1}{\varkappa^2 r^2} \right) \frac{e^{-\varkappa r}}{r} \right\} v$$

$$- \frac{2\sqrt{2}}{3} g_2^2 \left(1 + \frac{3}{\varkappa r} + \frac{3}{\varkappa^2 r^2}\right) \frac{e^{-\varkappa r}}{r} u = 0$$

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Vの形が ~~a~~ $r=0$までそのまゝとすれば、上の式から $r=0$で vはV'又はそれ以上の0にならないといけない。それは下の式~~から~~と矛盾する。~~従って~~故に、Vの形は$r<r_0$ではずっと違っていると考へねばならぬ。

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§2.

Kernkräfte　　Flügge, Kemmer,

$$V = -M_{12}\Sigma_{12}P_{12} - H_{12}P_{12} + B_{12}\Sigma_{12} + W_{12}.$$

$$M_{12} = \frac{10}{12}V_{12}$$

$$H_{12} = -\frac{2}{12}V_{12}$$

$$B_{12} = \frac{5}{12}V_{12}$$

$$W_{12} = -\frac{1}{12}V_{12}$$

$$V = -V_{12}\left\{\frac{10}{12}\frac{(1+\vec\tau^{(1)}\vec\tau^{(2)})}{2}\frac{(\cancel{1}1+(\vec\sigma^{(1)}\vec\sigma^{(2)}))}{2} - \frac{2}{12}\frac{(1+\vec\tau^{(1)}\vec\tau^{(2)})}{2}\right.$$
$$\left. -\frac{5}{12}\frac{1+\vec\sigma^{(1)}\vec\sigma^{(2)}}{2} \cancel{1} + \frac{1}{12}\right\}$$

$$= -V_{12}\left\{\frac{(\vec\tau^{(1)}\vec\tau^{(2)})}{2}\frac{(1+\vec\sigma^{(1)}\vec\sigma^{(2)})}{2}\cdot\frac{10}{12} - \frac{\vec\tau^{(1)}\vec\tau^{(2)}}{2}\frac{2}{12}\right\}$$

$$= -V_{12}\left\{\frac{5}{24}(\tau^{(1)}\tau^{(2)})(\sigma^{(1)}\sigma^{(2)}) + \frac{1}{8}\sigma^{(1)}\sigma^{(2)}\right\}$$

$W+B+H+M=1$:　$\frac{5}{24}$ − $\frac{2}{24}$　~~囲~~ $-1+5-2+10=12$

$W-B-H+M=\frac{1}{2}$:　$-1-5+2+10=6$

$4W+2B-2H-M=0$: heavy nuclei の binding energy が[illegible]くならぬ. $-4+10-4-10=0$

$2W+2B-H-M=0$: ~~spin~~ heavy nuclei の spin が余り大きくならない. $-2+10+2-10=0$.

$2W+B-2H-M \leq 0$: 0-charge の heavy nuclei が存在しない.

$2+5+2-10 \leq = -1$.

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NO. 2

neutron-proton force の

この Ansatz に従って、 $\frac{\tau_1^{(1)}\tau_1^{(2)}+\tau_2^{(2)}\tau_2^{(1)}}{2}$ の[illegible]

$$\frac{\tau^{(1)}\tau^{(2)}+\tau_2^{(1)}\tau_2^{(2)}+\tau_3^{(1)}\tau_3^{(2)}}{2}=\begin{cases}-3/2\\+1/2\end{cases}$$

$$^3S : {}^1S = \frac{3}{2}\left(g_1^2+\frac{2}{3}g_2^2\right) : \frac{-1}{2}\left(g_1^2-2g_2^2\right)$$

$$= 3g_1^2+2g_2^2 : 2g_2^2-g_1^2$$

$= 2:1$ あらしめれば

$$3g_1^2+2g_2^2 = 4g_2^2-2g_1^2$$

$$5g_1^2 = 2g_2^2$$

前の Ansatz では. $g_1^2+\frac{2}{3}g_2^2 : 2g_2^2-g_1^2 = 2:1$

$$3g_1^2+2g_2^2 = 12g_2^2-6g_1^2$$

$$\cancel{5g_1^2 = 2g_2^2}$$

$$9g_1^2 = 10g_2^2$$