A measurement of the ratio of intensities of the NaCl\(^{25}\) \(\nu=0\) and NaCl\(^{25}\) \(\nu=3\) lines gives a value for the vibrational frequency \(\omega(35)=378\ \text{cm}^{-1}\), if the dipole moment is assumed independent of vibrational state. Including a reasonable variation of the dipole moment, this measurement may be in error \(\pm 15\%\) percent. It agrees well, however, with a value of 380 \(\text{cm}^{-1}\) obtained by Levi.

| Table I. Measured lines of the \(J=1\to2\) pure rotational transition of NaCl. |
|-------------------------|------------------|-----------------|
| Isotopic species        | Vibrational state | Frequency in megacycles/sec |
| NaCl\(^{25}\) \(\nu=0\) | 1                | 26051.1 \(\pm 0.075\) |
|                        | 2                | 25666.5          |
|                        | 3                | 25473.9          |
| NaCl\(^{25}\) \(\nu=0\) | 1                | 25307.5          |
|                        | 2                | 25120.3          |

At approximately 715°C, the \(J=5\to6\) transition of CsCl was observed, and lines listed in Table II were measured. These give

| Table II. Measured lines of the \(J=5\to6\) pure rotational transition of CsCl. |
|-------------------------|------------------|-----------------|
| Isotopic species        | Vibrational state | Frequency in megacycles/sec |
| CsCl\(^{133}\) \(\nu=5\) | 1                | 25380.0 \(\pm 0.15\) |
|                        | 6                | 25180.1          |
|                        | 7                | 25061.0          |
|                        | 8                | 24941.2          |
| CsCl\(^{133}\) \(\nu=0\) | 1                | 24798.2          |
|                        | 2                | 24685.7          |
|                        | 3                | 24571.4          |
|                        | 4                | 24337.9          |

![Frequency values for NaCl and CsCl](https://example.com/frequencies.png)

The observed spectrum of KCl gave molecular constants in agreement with those found by measurement of rotational transitions in molecular beams. A rich spectrum of lines between 25,000 Mc and 23,500 Mc was observed in TICI vapor at approximately 305°C. This spectrum showed no obvious regularities, and cannot be produced by a diatomic molecule, so that the vapor of TICI must contain a considerable amount of dimers or some other combination of Ti and Cl.

It may be noted that the \(r\) value of NaCl is 4 percent less than the value of 3.024 \(\pm 0.03\) obtained from electron diffraction measurements of the average over-all vibrational states at 1200°C, but falls within the experimental error of molecular beam measurements, which is 2.88 \(\pm 0.03\). Likewise, the \(r\) value for NaCl is 5 percent less than the value of 2.48 \(\pm 0.03\) obtained by electron diffraction measurements. This discrepancy is unexplained.

The value of \(\alpha\) for NaCl\(^{25}\) obtained from molecular beam measurements of the product of the dipole moment and the moment of inertia is 15.6 \(\pm 1.5\). The large discrepancy between this result and the directly measured value given here may be due to an incorrect assumption about the variation of the dipole moment with vibration state.

We are very grateful to Mr. C. O. Dechart, foremost of the Columbia Radiation Laboratory machine shop, for considerable aid in the design and construction of the apparatus, as well as to Mr. A. P. Marshall and others of the machine shop staff. We also appreciate the help of Mr. A. Javan and Mr. W. A. Hardy with several of the experimental measurements.

---

1. Work supported jointly by the Signal Corps and ONR.

---

**Letters to the Editor**

\(\gamma\)-Meson Decay and \(\beta\)-Radioactivity

LOUIS MICHEL

Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark

(Received April 14, 1952)

The decay \(\mu^+\to e^++2\nu\) cannot be consistently explained by indirect interaction through any known virtual particles. Thus we are led to suppose a direct interaction between the four fermions \(\mu, e, \nu, \bar{\nu}\).

If we restrict ourselves to the kind of interaction terms used in \(\beta\)-radioactivity (no derivatives of the wave functions; however, the use of imaginary and/or pseudoscalar coupling constants would not modify formula (1)), the theoretically predicted possible energy spectra\(^1\) for the secondary electrons are (with the normalization \(rP(E)\delta(E)=1\), where \(r\) is the \(\mu\)-meson mean life and \(E\) is the electron energy):

\[ rP(E)\delta(E)=\rho(4E/W)[3(W-E)+\rho(4E-3W)], \]

where \(\rho\) is a parameter satisfying \(0<\rho<1\). The agreement with experimental results is very satisfactory and \(\rho\) may be obtained from experiments.\(^2\)

**Direct interaction**.—With four Dirac wave functions \(\psi\) or \(\bar{\psi}\) (I shall write \(\bar{\psi}\) for both types of functions), we can form only five linearly independent scalars \(J\), and the most general interaction Hamiltonian density is

\[ H=\Sigma_{J}J_{\lambda}+\text{Hermitian conjugate}. \]

A set of five linearly independent \(J\) is usually constructed as follows: with two \(\bar{\psi}\) in a given order one can form five Lorentz covariants \(S, V, T, A, P\); each \(J\) is then a scalar product of one of these covariants by corresponding covariant made with the two other \(\bar{\psi}\) (also in a given order). If the order of the \(\bar{\psi}\) in \(J\) is changed, the new \(J\) is a linear combination of the old ones. This corresponds in \(H\) to a change of reference system for the five-dimensional vector space of the \(g\). The only vector \(g\) invariant for all permutations corresponds to the Critchfield and Wigner interaction.\(^4\)

If two \(\bar{\psi}\) are identical (this occurs for instance when there are two indistinguishable particles), there are only three linearly independent \(J\) and this corresponds to a projection on three dimensions of the five-dimensional \(g\) space. Therefore we have to consider two cases:

1. The two emitted neutrinos are experimentally distinguishable (for example, by the sign of their magnetic moment). This case can occur if the neutrinos are described by Dirac's hole theory and the two emitted neutrinos are particle and antiparticle, respectively. Then \(0<\rho<1\).
2. The two emitted neutrinos are identical particles. This may occur if the emitted neutrinos are both particles or both antiparticles in Dirac's hole theory, or if they are described by Majorana's theory\(^4\) according to which all neutrinos are identical. Then \(0<\rho<\frac{1}{2}\).

**The triangle of interactions.**—Several authors\(^4\) have shown that direct interactions with the same magnitude for coupling constants can explain \(\beta\)-radioactivity, \(\mu\)-meson decay and \(\mu\)-meson capture by heavy nuclei. It is then natural to test first the simplest hypothesis that the "same" interaction is responsible for these three phenomena.

But it is clear that the direct interaction of one set of four fermions can be compared to the direct interaction of another set of four fermions only if a one-to-one correspondence between the particles of the two sets is agreed on. It can be shown that except for minor questions of signs (immaterial for \(\beta\)-radioactivity) it is sufficient to have a correspondence between pairs of particles. The "triangle" suggests such a correspondence

\[ (\mu, \nu)\leftrightarrow(\bar{\psi}, \bar{\psi})\to(\mu, \nu). \]

If one refers to the usual notations of \(\beta\)-radioactivity, calling \(f_1\) the five coupling constants (\(f_1\) for the "scalar" interaction, \(f_2\) for the "vector" interaction, and so on \(\cdots\)), \(\rho\) is given by
LETTERS TO THE EDITOR

(1) different neutrinos:

\[
0 \leq \rho = \frac{3}{4} \left( (f_1 - f_2)^2 + (f_3 + f_4)^2 + 2(f_5 + f_6)^2 \right) \leq 1;
\]

(2) identical neutrinos:

\[
0 \leq \rho = \frac{\left( f_1 + f_2 - 2(f_3 + f_4) \right)^2}{2(3f_5 + 6f_6 - f_4)^2 + 16(f_5 - f_6)^2 + 2(f_5 + f_6 - 2(f_3 + f_4))^2} \leq \frac{3}{4}.
\]

Another quadratic relation [different for (1) and (2)] between \( f_i \) is given by the ratio

\[
\frac{\text{(neutron mean life)}}{\text{(p-meson mean life)}}.
\]

A better knowledge of the nature of the direct interaction responsible for \( \beta \)-radioactivity, of the neutron mean life and of the energy spectrum of the secondary electrons from \( \mu \)-meson decay will allow one to answer the following questions:

(a) Can a "same" direct interaction explain \( \beta \)-radioactivity and \( \mu \)-meson decay?

(b) Are the two neutrinos emitted in \( \mu \)-meson decay identical or not?

From the present experimental data it can already be concluded that question (a) cannot be answered separately.

I wish to express my sincere appreciation to Professor N. Bohr for the opportunity to work at the Institute for Theoretical Physics. I am also grateful to the French Service des Poudres for its understanding and its financial support.

* The content of this letter was communicated at the Copenhagen Conference, July 1951.

Now at Laboratoire de Physique, Ecole Polytechnique, Paris 5, France.

Calculations have been made for some particular couplings by Tjomno, Wheeler, and Rau, Revs. Modern Phys. 21, 144 (1949) and for the general coupling by L. Michel, Nature 163, 559 (1949).

A. Lagarrigue and C. Peyrou, C. R. Acad. Sci. 233, 478 (1951), and J. Phys. et radium, 12, 848 (1951) have given a statistical method for the determination of the most probable value of \( \rho \) from a set of measurements of the energies of the secondary electrons from \( \mu \)-meson decay. Their experimental results and those of Leighton, Anderson, and Serif, (Phys. Rev. 75, 1432 (1949)) give \( \rho = 0.19 \pm 0.15 \).


* The content of this letter was communicated at the Copenhagen Conference, July 1951.

Now at Laboratoire de Physique, Ecole Polytechnique, Paris 5, France.

Calculations have been made for some particular couplings by Tjomno, Wheeler, and Rau, Revs. Modern Phys. 21, 144 (1949) and for the general coupling by L. Michel, Nature 163, 559 (1949).

A. Lagarrigue and C. Peyrou, C. R. Acad. Sci. 233, 478 (1951), and J. Phys. et radium, 12, 848 (1951) have given a statistical method for the determination of the most probable value of \( \rho \) from a set of measurements of the energies of the secondary electrons from \( \mu \)-meson decay. Their experimental results and those of Leighton, Anderson, and Serif, (Phys. Rev. 75, 1432 (1949)) give \( \rho = 0.19 \pm 0.15 \).


