CHARGE INDEPENDENCE AND SATURATION OF NUCLEAR FORCES

Thursday morning, Professor E. P. Wigner presiding.

Marshak opened the conference by welcoming the conferees and stressing the informality of the sessions. Wigner started off by remarking that the purpose of the first session was to serve as an introduction to high energy physics and to make those of us who know only about low energy physics not to feel badly. He then gave a short historical introduction stating that the charge independence hypothesis originated in 1936 with the experimental work of Tuve et al. on proton-proton scattering followed by the analysis of Breit and Feenberg who showed that p-p scattering was very similar to n-p scattering in the singlet state. The consequences of these analyses for nuclear structure were first pointed out by Wigner through the first approximation which neglected the spin dependence the forces and any difference between the heavy particle interactions. This supermultiplet theory was improved in the second approximation by introducing the spin dependence, that is, the known difference between singlet and triplet scattering, since tensor forces were not yet known. It is now known that the second approximation possesses a substantial validity.

The extension of the charge independence hypothesis to the meson theory of nuclear forces was first carried out by Heitler and by Kemmer, but very little was done after the beginning. When the situation was reviewed by Wigner in 1942, he showed that the then existing experimental evidence was still inadequate to make any definite statements about the validity of the charge independence hypothesis. This situation persisted until new data on n-p and p-p scattering were available and a new method of analysis was developed by Breit, Landau and Smorodinsky, Bethe, and Blatt. Recently, there has been work on the inherent limitations of the theory; that is, even if the nuclear forces are in fact charge independent, the electrostatic forces which are also known to exist will influence the selection rules which are derived on the basis of charge independence.

Wigner then proposed four general topics for discussion: (1) What is the role in physics at large of such regularities as charge independence? He remarked that this is a very general subject, but is likely to come up again and again. Mainly, what should it mean that we have a kind of symmetry which is not complete? We have in fact another interaction which is similar in that the symmetry is also not complete, namely, the electrostatic interaction. Thus the exact equality of proton -proton and positron-positron forces which holds at large distances fails at short distances. This can be reformulated by stating that the proton-proton and positron-positron interaction are exactly alike insofar as they are transmitted by the electromagnetic field. Similarly, the hypothesis of charge independence for heavy particle interactions can be formulated by stating that they are exactly alike insofar as they are transmitted by the meson field. It is tempting to speculate what this means more generally. In this connection Wigner remarked that the term charge independence is most unfortunate since in fact it has nothing to do with charge. The proper name for this phenomenon is invariance with respect to rotations in isotopic spin space.

(2) Consequences for low energy nuclear phenomena; selection and intensity rules. Just as symmetry with respect to ordinary rotation has selection rule consequences for practically every process, for example, scattering, light emission, etc., similarly, invariance with respect to rotations in isotopic spin space has consequences for nearly every process. Some of these selection rules have been known for a long time, but others have been pointed out only relatively recently. Evidence for these selection and intensity rules comes from (a) nuclear reactions and alpha decay, (b) beta decay, (c) electromagnetic radiation, (d) stable states of nuclei, and (e) meson transitions. The last is a much larger subject than all the others put together and will be discussed in other sessions of the conference.

(3) Inherent limitations of the theory. There are two possible origins for such limitations. (a) The electrostatic interaction will introduce deviations. This is largely a theoretical subject, but to some extent practical in that in some cases the electrostatic interaction distorts the results to such degree as to give gross apparent contradictions to the basic hypothesis. These effects have been investigated by Thomas with regard to mirror nuclei, somewhat more theoretically by Tibarri and Radicati, and by the group at Princeton. (b) Complications in matrix elements on account of mesons. All selection and intensity rules are based on the assumption that we are calculating the matrix elements of an operator. The role of mesons is less simply described than that of electromagnetic radiation in atoms where, for example, dipole radiation is given by the matrix elements of x, y, and z, and higher multipoles by more complicated expressions. However, Jacobson and Wick have shown that this limitation is not relevant and that the selection rules are given correctly in spite of the complication of the matrix elements.

(4) Question of potential. That is, to what degree can low energy phenomena be described by a potential and by two particle interactions? In this connection we should discuss (a) Lévy's work, (b) general questions of saturation, and (c) "new fangled methods" of derivation of all of these rules, for example, as given by Van Hove. Wigner then called upon Christy to discuss topic 2 (a) that is, selection and intensity rules in nuclear reactions and alpha decay.

Christy started by stating that, as is well known, charge independence can be described in terms of isotopic spin wave functions for the neutron and the proton and the operators associated with the isotopic spin. Because of the fact that the isotopic spin matrices have identical commutation relations with the Pauli spin matrices, the selection rules for isotopic spin can be identified as being essentially the same as those one obtains for angular momentum. If the operator τ_z has eigenvalues -1 for a proton and 1 for a neutron, then the charge on the proton is described by the operator $e(1-\tau_z)/2$ and the charge on the neutron by the same operator. The x and y components of together with τ_z form a vector in isotopic spin space, but only the z component of this vector has a direct, simple physical interpretation in terms of total charge.

The first step in deriving selection rules for the isotopic spin is to identify the total isotopic spin T for various nuclear states. Just as the total angular momentum J can be determined by counting the number of levels into which a given state splits under an applied magnetic field, the coulomb field automatically splits states of different T. Therefore, we have to identify the number of different charge projections rather than the components of J along the z axis; that is, the number of different isobars in which a given nuclear state manifests itself is simply $(2T+1)$. This identification can be made with some assurance for the low energy levels of some light nuclei. For example, in alpha particle nuclei such as carbon and oxygen there are no corresponding isobars at low energies of excitation; therefore, since the multiplicity of all low energy levels of carbon and oxygen is 1, these levels must have isotopic spin $T=0$. In the case of $A=10$, that is, Be^{10}, B^{10}, and C^{10}, the difference between the ground states is only a few Mev. Again, the ground state of B^{10} has no counterpart and must have $T=0$, but the ground states of Be^{10} and C^{10} and an excited state of B^{10} at 174 Mev form a triplet with apparently corresponding properties and hence with $T=1$. The correspondence can readily be seen in an energy level diagram for the three nuclei where the coulomb corrections have been removed. For nuclei with half integral spin, for example Li^7 and Be^7, there are two nuclei with corresponding ground states and corresponding first excited states when coulomb energy corrections are made; there is also evidence for correspondences between states of higher excitation energy. The next isobars occur at 15 or 20 Mev excitation so that if there is charge independence one can say that all the low states have $T=1/2$. It is not always easy to make this sort of identification in all cases (e. g. when the levels are dense) without detailed measurements of the nuclear properties of the levels.

As we have seen, the selection rules we expect, follow in direct analogy with those for J. Thus, in any nuclear reaction between two particles, $T=T_1$ and $T=T_2$, the compound state will have $|T_1 - T_2| \leq T \leq T_1 + T_2$, and if this state breaks up into two nuclei of definite T, the same selection rules would apply. Unfortunately, in most cases this selection rule does not obviously exclude anything. This is true because in the cases where the levels are identified, that is, in light elements, the isotopic spins are 1/2, 0, 1, and if one of the reacting particles (e. g. a proton) has $T=1/2$, then all possibilities can exist. For example, a proton on Li^7 can give states of isotopic spin either 0 or 1 and there are no obvious selection rules. But it is possible to get exclusive rules in special reactions where $T=0$; for example, there are no corresponding n-n or p-p states to the deuteron which therefore has $T=0$, and the alpha particle also has $T=0$, so that when either is used the isotopic spin of the nucleus cannot change. Hence in the reaction $O^{16}(d,\alpha)N^{14}$, strict selection rules may appear. One must be careful because the simple fact that a reaction does not happen is not evidence for a particular selection rule unless it is known certainly that there is no other reason for the reaction not occuring. In this reaction O^{16}, the deuteron, and the alpha particle all have $T=0$ so that we conclude that only $T=0$ states of N^{14} can be formed. It is possible to test this prediction since both 0 and I states of N^{14} are known. Most of the excited states of N^{14} have $T=0$ with an occasional state of $T=1$; hence, the working of this selection rule is sufficient to explain the fact that N^{14} can be made in its ground state and certain other states but is not made in a T = 1 state. That is, particle groups corresponding to the first T = 1 level are weak by at least a factor of 100, and how much more is not known. At this point, Serber commented that this reaction can be explained in terms of a weaker selection rule than the full charge independence hypothesis (cf. discussion by Kroll below). Christy went on to remark that also in the inelastic scattering of deuterons by B^{10} the first isotopic spin state 1 is not formed, which again is plausibly explained in terms of the constancy of the isotopic spin.

Christy noted that selection rules can also appear in the emission and absorption of electromagnetic radiation, if one assumes that the coupling between nuclear particles and the electromagnetic field is by virtue of the charge on the proton, i.e. represented by the operator $(1 - \tau_z)$. The selection rules for this operator are the selection rules for the component of a vector, that is, in strict analogy to the well known selection rules for electric dipole radiation, namely, $\Delta T = \pm 1$, or 0. The proviso that the coupling is only to the charge of the proton ignores all complications due to the electromagnetic properties of the virtual meson clouds surrounding the nucleon. For electric dipole radiation there is a further restriction. Ordinarily an operator which is a component of a vector allows no zero-zero transition but the charge operator $e(1 - \tau_z)/2$ has a constant term as well as the component of a vector. However, in the special case of electric dipole radiation this term contributes a matrix element proportional to the summation over the nucleons of $r_i/2$, which is the position of the center of mass of the nucleons, which is fixed and does not radiate; hence $T = 0 \rightarrow T = 0$ transitions are forbidden for electric dipole radiation. Unfortunately, there is one well known exception to this selection rule, namely, the gamma ray transitions in O^{16}. The levels have been definitely identified by angular correlation experiments, and there is in fact a gamma ray transition from the state of J = 1 and negative parity to a state of J = 0; this must be an electric dipole transition and the low states in oxygen are presumably T = 0. However, the relevant fact that needs to be shown is whether or not this transition is anomalously long for electric dipole radiation; this has not been measured but is conceivably observable. Evidence might also be obtainable from the competition with transitions to other states, but this evidence is at present unavailable. In most cases, the low states of a nucleus involve a change in isotopic spin so that the above selection rule does not operate. Alpha decay clearly gives no change in isotopic spin for an allowed transition. In the case of beta decay, the Fermi selection rules are given by the operators τ_+ or τ_- which convert a neutron into a proton or a proton into a neutron. These are linear combinations of components of the vector τ, but the summation of τ_+ or τ_- over all the nucleons commutes with the isotopic spin operator; hence, for Fermi's selection rules $\Delta T = 0$. However, for Gamow-Teller selection rules, the operator is a summation over the nucleons of $\sigma_i \tau_i$. Since this weights the various nucleons differently, one has only the selection rules for the component of a vector, namely, $\Delta T = \pm 1$, 0. Usually, this gives no check because when T changes by one unit, as for example in the transition from He^6 to Li^6 the spin also changes by one unit and we know that we must use Gamow-Teller selection rules. Conversely, in the cases where the spin does not change, for example, in the transition from Be^7 to Li^7, the isotopic spin also does not change.

Wigner commented that it seems pretty far fetched to talk about the connection between p-p and p-n forces and then talk about rotation in isotopic spin space. In this connection it is well to recall Slater's work on atomic spectra, where it became apparent that if there was no spin it would be a good thing to invent it in order to express the Pauli principle; there is no isotopic spin, but it is a good thing to invent it in order to express in a mathematical way the regularities that have been mentioned. He would also like to state that it would be very helpful to have a new Condon and Shortley written on the subject. Of course, the theoretical physicist says "I know the selection rules for isotopic spin operators because I know them for the spin operators". But it would be nice to have rules written up, and we are very far from this. For example, electric dipole transitions have the same matrix element as first forbidden beta transitions; hence one can calculate the matrix element of one from the other and so on. There is a whole slew of such regularities, and it would be very valuable to see if they can be checked. Finally, Wigner remarked that there never has been as much theoretical thinking done on a subject the experimental foundation of which was as inadequate as this one. (Laughter)

At this point, Breit raised the question of what experimental evidence there is that T is a good quantum number and where he would find calculations showing what would go wrong if it were not. Christy's statement that the best experimental evidence still comes from the elementary particle scattering was questioned (cf. discussion primarily by Blatt and Bethe below). Wigner emphasized the intensities of beta transitions, while Serber stressed the equality of energy levels. However, Serber said that one should not overstate the case from low energy experiments because of possible interpretation in terms of weaker selection rules (cf. Kroll's remarks below.) In response to a question from Wick as to what is meant by "low energy", Wigner attempted to say "where the interpretation is reasonably unambiguous" which provoked considerable laughter; he therefore qualified to regions where only S wave scattering occurs, namely, below 4.5 Mev.

Blatt objected that even 4.5 Mev may be too high, and described the situation with regard to scattering as follows: In the region below 2 Mev the scattering can be described by two parameters, namely, the scattering length and effective range. The scattering length is charge dependent so that any correspondence between scattering lengths can be stated only very roughly; further, there is no corresponding state in the proton-proton system to the triplet S state of the neutron-proton system. Hence there is really only one parameter to check charge independence, namely, whether or not the singlet effective ranges for the two systems are equal. In response to objections from the floor he countered that the charge corrections to the scattering length are not easy to make accurately but perhaps one might say that there is a second parameter. The situation with respect to the singlet effective range seemed dubious three or four years ago but by now the value for the proton-proton effective range is about 2.7 x 10^{-13} cm. as compared with the neutron-proton effective range of 2.5±0.3. The possible disagreement indicated by the Brookhaven data at 4 - 4.5 Mev is uncertain because at this energy the next term P in the expansion $k \operatorname{ctn}\delta = -1/a + r_0 k^2/2 + Pk^4 + \ldots$ comes in, and the P coefficient depends on the shape of the well. Blatt, therefore, concludes that the low energy evidence for charge independence is inadequate except for the corresponding levels in light nuclei. Breit's comment that Snow had obtained agreement with the Brookhaven experiment by using a repulsive core was restated by Blatt as equivalent to stating that such a model gives P 0, while P 0.15 does not give nearly as good agreement. However, the introduction of tensor forces without a repulsive core would reduce P to zero for Yukawa potentials. In response from a question from Jastrow as to how the situation differed from the analysis given by Salpeter, R. G. Sachs commented that Salpeter's analysis depended upon the neutron-proton capture cross section which really is not well enough known even theoretically to be used.

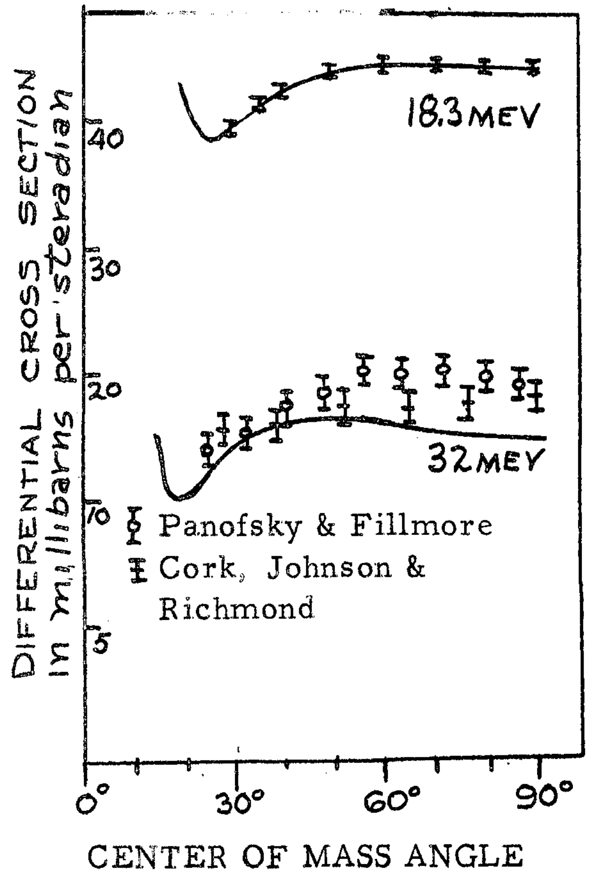
Bethe commented that the new experiments on scattering are more reliable than the capture cross section and made a positive and a negative remark. The positive remark was that it is still remarkable that the scattering lengths indicate potentials of equal strength to about 1%. The negative remark, made at the request of Salpeter, was that Schwinger has pointed out that the magnetic interaction is different in the neutron-proton and proton-proton system, and that this difference can account for the difference in scattering length. This, however, depends on the shape of the well, and works with the Yukawa potential essentially because two nucleons like to be close together in that case and the magnetic interaction for an S state, which is essentially a contact interaction, is therefore enhanced. It does not work for a square well because the wave function does not become so large at short distances, and it was found that Levy's repulsion at short distances will also depress the magnetic interaction. Oppenheimer commented that there are inherent limitations on charge symmetry and soon we will have to worry about the different electrical properties, dissociation of nucleons, and all the rest of it. That these effects can be big enough for some purposes we know from Schwinger's work. That we should be able to calculate them today, he would find very surprising.

At this point Pais offered to present a new calculation with Lévy's potential for the proton-proton system by two of his students, Martin and Verlet. However, Oppenheimer thought that a review of Lévy's work would be in order as "it is not completely clear from his papers, it is not completely clear to him, and not completely clear to anyone".

Pais, therefore, summarized Lévy's work as follows: With incredible faith Lévy says that he will investigate the symmetric pseudoscalar meson theory with pseudoscalar coupling, that is, the interaction $G\bar{\Psi}\gamma_5\tau_\alpha\Psi\phi_\alpha$. If you begin to play with this interaction and to orient yourself with regard to the constant G, you find that $G^2/4$ hc is of the order of magnitude 10. Then come the well known hesitations, since this orientation is obtained by calculating in a very low order. Then you say "what the hell, if I have a power series expansion and expand with respect to a parameter which is as large as this one, what can I believe of all this?" Lévy, in essence, looked at the nuclear forces following from the PS (PS) interaction taking the G^2 and G^4 terms into account. In this approximation one already finds a strong repulsive contact-like interaction which is smeared out by relativistic effects but is still very singular. He then makes a kind of guess, but it turns out to be very fruitful to follow up the consequences of this guess. He says, at small distances I have a very eminent history which tells me that I don't know what I'm talking about, and I have this very strong interaction which seems to be very dominant there. So I divide the distance into an inner and an outer region. I shall believe the specific shape given by the theory in the outside region and assume that I have a hard core inside. It is immediately obvious that this approach can only work at low energies, since at higher energies the more detailed structure of the interaction at small distances must be quite vital (Oppenheimer - "This is an understatement"). Lévy's claim for dropping terms higher than G^4 is that these terms will be important only in the inside region. Oppenheimer not[illegible]t this is not true of all terms since there are terms of an arbitrarily high order in G which occur as a multiplicative constant times Lévy's potential V_4, which he did not find out until after the calculation was completed. Therefore, his theory contains in fact three parameters rather than two, one of which is arbitrarily set equal to 1. Wentzel in fact has an argument to show that this constant should be considerably smaller than 1. At any rate, since the precise forms for V_2 and V_4 do not tell one much, Pais did not write[illegible]n down, but instead listed the parameters of the theory which are $G^2/4\pi = 9.7 \pm 1.3$ and $r_c = (0.38 \pm 0.03)\hbar/\mu c$. There are only two parameters since the meson mass is equal to the experimentally observed π meson mass in this theory. From these two parameters, the deuteron binding energy and the singlet scattering length, Lévy then fits the six numbers: the triplet effective range, the singlet effective range, the triplet scattering length, the singlet scattering length, the percentage of D state, and the quadrupole moment of the deuteron approximately. R. G. Sachs objected that two of these parameters are already essentially included by assuming the [illegible]ding energy of the deuteron and the zero energy singlet scattering length; further, the quadrupole moment is out by 20%, while a change of strength of the tensor force by a factor of 100 would only change the quadrupole moment by 10%, and the percentage D state is hardly known. Further, the[illegible]umption of the π experimental rest mass means that he is only working on a small correction to the effective ranges. Oppenheimer objected to the last statement because the large V_4 leads one to expect no a priori magnitude for the effective ranges. Bethe finds it remarkable t[illegible] a repulsive core which really corresponds to two mesons and has half the desired range still gives the right scattering. Blatt objected that it was a little unfair to say that the percentage D state was not at all a check, since when you change the tensor force, although you do not change the quadrupole moment very much you do get completely unreasonable D state admixtures, and one can argue that this quantity is known within the range of 1 to 8%, although not precisely.

Oppenheimer summarized the si[illegible]ation as follows: we could argue a great deal about the right percentage of D state. But, starting with a not unreasonable theoretical program and making only a finite number of mistakes, Lévy has obtained a better overall charge symmetric description over a wide range of energies than people who have been treating the problem empirically. He thinks that this is not without interest.

Pais then reported on the calculations of Martin and Verlet on the proton-proton scattering to be expected from the Lévy potential at 18.3 and 32 Mev. They calculate S, P and D phase shifts and obtain the agreement with experiment indicated in figure below. To obtain this agreement, they find that the original latitude in the coupling constant given by Lévy is too large and that in fact it must be chosen as 10.36 ± 0.02. The agreement at 18 Mev appears perfect although there are discrepancies of about 10% at 32 Mev, which is the order of magnitude of the discrepancies Lévy found in calculating the n-p scattering at 40 Mev. The potential and phase shifts are given in the table. (It should be stressed that the P and D phases are born approximatio ases obtained with Coulomb wave functions and therefore may well be completely misleading; cf. discussion by Wick, below.



P-P scattering from Levy potential as calculated by Martin and Verlet
N.B. P&D waves calculated in <u>born approximation</u>

Calculations of Martin and Ver

$$V(r) = \infty, \quad r < r_c$$

$$V(r) = V_c + S_{12} V_t \qquad r > r_c$$

where

$$V_c(r) = \frac{G^2}{\pi}\left(\frac{\mu}{2M}\right)^2 \left\{ \frac{(\vec{\tau}_1\cdot\vec{\tau}_2)\,(\vec{\sigma}_1\cdot\vec{\sigma}_2)}{3} \quad \frac{e^{-\mu r}}{r} \right\} - 3\left(\frac{G^2}{4\pi}\right)^2 \frac{1}{\mu r^2}$$

$$\times \left\{ \frac{2}{\pi} K_1(2\mu r) + \frac{\mu}{2M}\left[\frac{2}{\pi} K_1(\mu r)\right]^2 \right\}$$

$$V_t(r) = \frac{G^2}{4\pi}\left(\frac{\mu}{2M}\right)^2 \frac{\vec{\tau}_1\cdot\vec{\tau}_2}{3} \left[1 + \frac{3}{\mu r} \quad \frac{3}{(\mu r)^2}\right] \frac{e^{-\mu r}}{r}$$

$$\frac{G^2}{4\pi} = 10.36 \pm .02 \qquad r_c = 0.38\, \hbar/\mu c$$

Phase Shift	18 Mev	32 Mev
$^1S_0$	52.8°	44.85°
$^3P_0$	6.82°	11.79°
^3P	-1.45°	-1.62°
$^3P_2$	1.85°	3.79°
$^1D_2$	0.35°	0.97°

Certain objections were raised. In particular, Sachs wanted to know why the P wave at 4 Mev as measured at Wisconsin is so low and whether this is in agreement with Lévy's potential. Oppenheimer remarked that this is in fact a beautiful feature of Lévy's model. Thus the bucking of the core and the attractive potential tends to reduce the odd state phases, which is a gross effect that does not follow from a charge symmetric theory but does follow in this particular case. However, Jastrow admitted that this particular feature, which is characteristic of his model, also, although it is energy independent over wide regions, does not fail at very low or very high energies and hence that the low observed P phases at 4.5 Mev might prove to be a difficulty with the Lévy potential. At this point Wick questioned how precisely the phase shifts were calculated at 32 Mev. This brought out the point that in fact they were calculated from coulomb wave functions in born approximation. Wick considers this procedure extremely questionable since at 32 Mev he is almost certain that the $^3P_0$ phase shift is greater than 30°. He went on to add that this is in fact a typical feature of Lévy's potential, namely, the enormous attraction in the $^3P_0$ state, and that since the $^3P_0$ gives a very small front to back asymmetry, it may indeed be the qualitative reason for the flat angular dependence of the proton-proton scattering and at the same time of the symmetry about 90° of the neutron-proton scattering.

Breit remarked that R. M. Thaler and J. Bengston at Yale have made an analysis of n-p and p-p high energy scattering data which succeeds in giving good fits to experiment entirely without D waves but with S and three different ^3P waves. These fits have been made consistently with the hypothesis of charge independence. The existence of the fits shows that there are other ways of reconciling the hypothesis of charge independence with observation than those discussed in terms of potentials so far. Also, in connection with the discussion of the repulsive core potential he stated that approximate corrections for retardation to the nucleon-nucleon interaction have been worked out on the pseudoscalar theory. The effect increases slowly with energy at low energies but at 300 Mev the preliminary calculations indicate large corrections to the static values. It was suggested that the slowness of the increase of the corrections may be related to the success in fitting 30 Mev data by the Lévy-Jastrow potential which has been reported by Jastrow.

Kroll was asked at this point to explain his and Foldy's weaker selection rules which had been mentioned earlier. These selection rules follow from charge symmetry and do not require charge independence. From them, one finds that, for instance, the $0^{16}(d,\alpha)N^{14}$ reaction for which certain states are apparently forbidden is equally explicable assuming only charge symmetry and not charge independence; also the dipole transition in 0^{16}, ... is not in fact forbidden, would be just as strong evidence against charge symmetry as it ...d be against charge independence. This can be shown by considering any reaction of the type which, expressed in isotopic spin language, consists of the transition of two particles each with isotopic spin 0 to a set of two other particles one of which has isotopic spin 0 and the other possesses states of both isotopic spin 0 and isotopic spin 1. Since isotopic spin 0 implies equal numbers of neutrons and protons, it is clear that the initial state is self-conjugate with respect to an interchange of neutrons and protons. Consequently, the initial state can be characterized as symmetric or anti-symmetric with respect to such an interchange and if there should prove to be charge independence, the symmetric states have even isotopic spin while the anti-symmetric states have odd isotopic spin. However, even if T is not a good quantum number, transitions from symmetric to anti-symmetric states are still prohibited. Hence, the selection rules for all such reactions are the same whether one assumes charge symmetry or charge independence. Therefore, the only good experimental evidence from low energy region for charge independence is the existance of isotopic spin multiplets, that is, corresponding energy levels. Similarly the electric dipole operator is odd with respect to neutron-proton interchange and hence can only connect states of opposite charge parity. Since $T=0$ states all have even parity, again zero-zero transitions are forbidden.

Feenberg commented that the selection rule against dipole transitions is removed by taking into account the neutron-proton mass difference; hence, the selection rule merely reduces the probability of electrical dipole transitions by a factor of 10^6, which is not such a large factor for such transitions. Feynman asked whether the second order effect of the distortion of the wave functions due to coulomb forces was not a much bigger effect. Wigner replied that this has been calculated by Radicati and also at Princeton and in particular for 0^{16} this only gave a 10^{-3} effect in the transition probability.

R. G. Sachs: a comment on Christy's discussion made to him, but not to general meeting. It concerns the apparent violation of the isotopic spin selection rule $T=0 \rightarrow T=0$ forbidden for an electric dipole transition in 0^{16}. Feenberg remarked on the possible importance of the neutron-proton mass difference. There is an effect which seems to be of far greater importance. The selection rule arises as a direct consequence of the fact that the dipole moment can be expressed rather directly in terms of the pos... of the center of mass of the nucleons. ...ever, at an energy as high as that (7 Mev) associated with the 0^{16} transition in question, the contribution of the magnetic quadrupole moment (sometimes referred to as a retardation term in the electric dipole moment) must be included, and this is not simply related to the coordinate of the center of mass. One can estimate (see Phys. Rev. 88, 824 (1952)) that the lifetime for the forbidden transition is of the order of $(Mc^2/Kw)^2$ times that of the allowed dipole transition, hence only some (2×10^4) times slower. It can be concluded that a lifetime measurement is essential for a test of the selection rule.

Fermi added that Telegdi experimentally finds in the photo-disintegration of C^{12} into three alpha particles that the 17 Mev level is relatively sharp, indicating a rather strong selection rule. Gell-Mann, arguing like Christy in terms of dipole transitions being forbidden for $T=1$ states, ties this fact into the isotopic spin multiplets of neighboring elements. It remains to investigate whether the intensity of this reaction bears out this interpretation. Wigner commented that although individual mirror nuclei beta transitions are evidence for charge symmetry only and not charge independence, the systematic trend of the ft values for such transitions would fail by a factor of 4 to agree with the experimental values if only charge symmetry and not charge independence was operative.

Feldman briefly presented the following implications of charge independence for high energy nucleon-nucleon scattering. His results are obtained in the scattering matrix formalism and hence are completely independent of any hypotheses about the nature of the interaction. There are $p+p \rightarrow p+p$, $n+p \rightarrow n+p$, and $n+p \rightarrow p+n$ (since the momenta and spins are specified) and two complex amplitudes (singlet and triplet) to describe them. Hence one gets in general restrictive inequalities only and not equalities relating the cross sections. There are three such inequalities; in the center of mass system they are: $[\sigma_{np}(\theta)]^{1/2} + [\sigma_{np}(\pi-\theta)]^{1/2} \geq [\sigma_{pp}(\theta)]^{1/2}$; $[\sigma_{pp}(\theta)]^{1/2} + [\sigma_{np}(\theta)]^{1/2} \geq [\sigma_{np}(\pi-\theta)]^{1/2}$;

and $[\sigma_{pp}(\theta)]^{1/2} + [\sigma_{np}(\pi-\theta)]^{1/2} \geq [\sigma_{np}(\theta)]^{1/2}$; which are also applicable if the incident nucleons are unpolarized. The second and third relations are not interesting because of the symmetry of the neutron-proton scattering about 90^o; however, the first relation is of interest since it could be violated depending on whose experimental data you believe. This test is most critical, clearly at 90^o where one must have $\sigma_{np}(90^o) \geq 1/4\, \sigma_{pp}(90^o)$. Thus, the Berkeley scattering data at 260 Mev gives $\sigma_{np}(90^o) = 1.3 \pm 0.2$ mb and $\sigma_{pp}(90^o) = 3.8 \pm 0.2$ mb, or a ratio $[\sigma_{pp}/\sigma_{np}]\,(90^o) = 2.8 \pm 0.5$ which agrees with the charge independence inequality. However, if one takes $\sigma_{pp}(90^o) = 4.9 \pm 0.4$ mb as measured by Rochester or Harwell, then the ratio becomes 3.8 ± 0.6, which could violate the charge independence hypothesis. This emphasized the importance of precise measurements of $\sigma_{np}(90^o)$ and $\sigma_{pp}(90^o)$, particularly at high energies.

Weisskopf then presented a brief account of a preliminary investigation of the saturation problem of nuclear forces carried out by Drell and Huang, using Lévy's potential and Lévy's optimism. He expressed Lévy's potential as $V^{(2)} = V_2^{(2)} + V_4^{(2)}$. Here the superscript (2) denotes a two body force and i...

introduced because of the generalization to n body forces given below. V_2 is the exchange tensor force while V_4 is the ordinary repulsive force. Weisskopf remarked parenthetically that this potential is very nice since it throws light on a point which had always been puzzling until now. It had been n :ed that the effective range of the tensor force is greater than that of the central force, while the singularity given by meson theory always indicated a shorter effective range; this is now understood since V_4 contributes to the central force and its (repulsive) singularity cuts down the effective central force range. In Lévy's spirit, there are only two unknowns in this theory, namely, the core radius and the coupling constant; as in Lévy, radiative corrections are essentially dropped in higher order (by setting the unknown coefficient of V_4 equal to one.) It would be very difficult to derive the general $V^{(n)}$ but one can deduce the leading terms in analogy to Lévy's $V_4^{(2)}$. Both the form and the multiplicative constant of these potentials are given exactly within the framework of this program. They are of the form:

$$V_4^{(2)} = \lambda^2 \frac{K_1 (X_{12} + X_{21})}{X_{12} X_{21}}$$

$$V^{(3)} = \xi \lambda^2 \frac{K_1 (X_{12} + X_{23} + X_{31})}{X_{12} X_{23} X_{31}} \qquad \lambda = \frac{G^2}{4\pi} \frac{\mu}{2M}$$

The generalization to n body forces is obvious. (Wentzel remarked that he had given precisely this formula in a paper written ten years ago; Weisskopf granted this but added that they had merely calculated the constant ξ in front of this expression as given by the pseudoscalar theory). As had also been shown by Wentzel, the sign of these forces alternate as the number of particles increases. It is noted that the Lévy two-body force alone is even worse than the Serber exchange force with respect to saturation because of the large central force; the repulsive core is of such small volume as not to help, since if nuclei collapsed to this core, the densities would be very much greater than the observed nuclear densities. However, the repulsive three body force is sufficient to give saturation if the higher order forces, that is, the 4, 5 and body forces are neglected. Drell and Huang indicate that there is some reason to hope for the convergence of the series of multibody forces.

The saturation calculation is carried out in a primitive way just as it would have been done by Wigner in 1936 ("You permit me :all this primitive?"). That is, the average values of the potentials are found using free particle wave functions averaged over the position of the particles taking account of the regions excluded by the cores. To escape all surface and electrostatic effects, the calculation is carried out for infinite nuclear matter and the resulting density found; a density of $\rho=1$ corresponds to the observed nuclear density. Only the two and three body forces are included, and of course the kinetic energy, with the hope that these will give a minimum at $\rho=1$. The probable convergence of the series of n body forces is due to the fact that it is very unlikely to find several particles within one another's ranges, because of the pauli principle, even if the cores are neglected. Exchange effects due to the exclusion principle are included but not exchange effects due to the exchange character of the forces. Since this calculation uses Lévy's constants and Levy's optimism, there is nothing free and all is given. The result is shown in the figure below.

It is seen that a minimum does occur at ρ=1.1 and corresponds to an energy of 12 Mev as compared to the experimental value 14. This is too encouraging, as a great deal has been left out. It should be stressed that the core is not important for the many-particle problem, since, if two particles cannot get together, then neither can three. There are three points to be considered if one wishes to improve upon the above calculation: (1) Levy's optimism may not be justified, (2) we are suffering from an illusion if we say that we know the constants that have been inserted here because we do not know about convergence, and (3) imagine that everything goes fine. It is still possible that we may be just lucky. But there is still trouble with regard to the shell model. That is, although the cores are unimportant for the saturation problem once collapse due o the 2 body potential is prevented, they are large enough to prevent the particles from moving freely in this infinite nuclear matter as would be required by the independent particle model. Therefore, one still has to investigate the problem of whether there is some mechanism that reduces the effect of the repulsive cores to zero in nuclear matter.

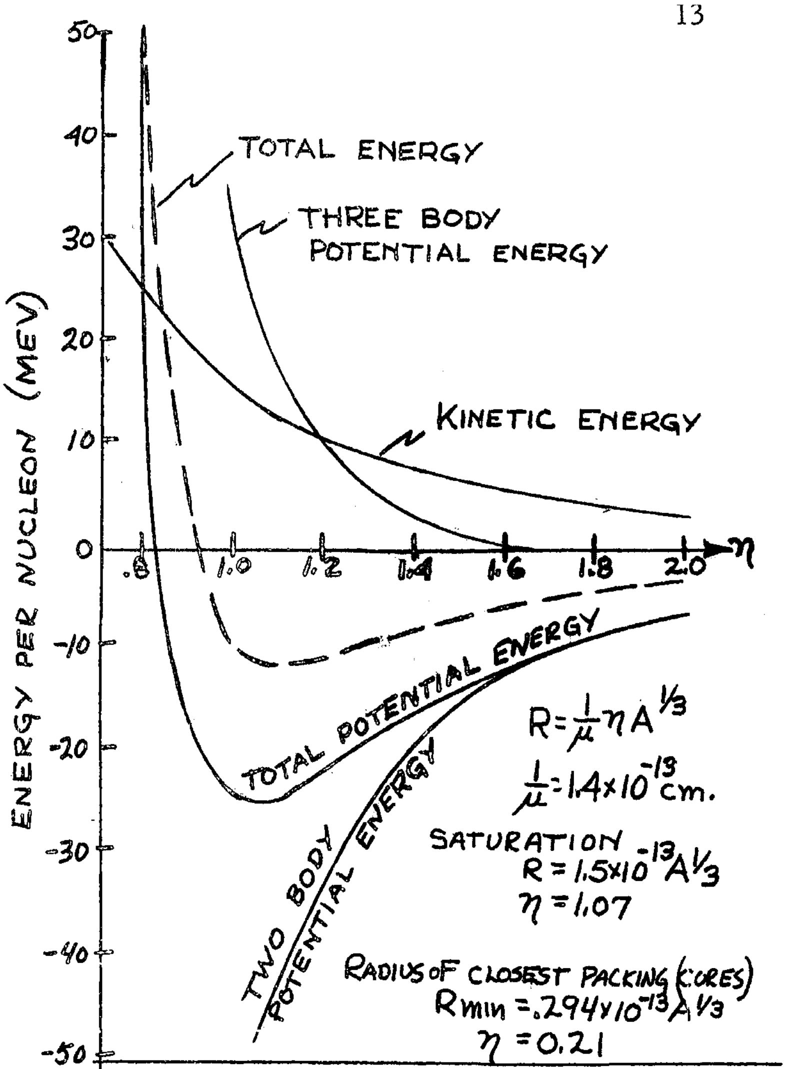


FIGURE 2
SATURATION of NUCLEAR FORCES
DRELL & HAUNG

Serber asked whether it had been investigated if such nuclear matter were against the lining up of all the spins parallel due to the tensor forces. Weisskopf admitted that this has not been done gh he thought it likely to be unimportant. Wentzel commented that the non nge part of the problem can be done rigourously and has been done by him in a recent paper in Helvetica Physica Acta using calculations based on pair theory. By "exchange" is meant exchange terms associated with the energy, not exchange forces. Weisskopf commented that he was not yet sure, but it seemed present that the exchange terms might be very important for the convergence of this procedure; that is, they subtract 15% for the 2 body forces, 35% for the 3 body force and about 65% for the 4 body force. The basic Feynman diagram for the 3 body force here considered given below. The generalization to 4 and 5 particles has all sorts of combinations which must be summed over. Their contributions to the potential energy are presently being calculated.