PAST LESSONS AND FUTURE IMPORTANCE OF POLARIZATION*

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1. Introduction: Past Lessons From a Ph.D Thesis

Why is Lipkin giving this talk? The real answer is that Viki Weisskopf couldn't make it. Krisch and Joseph were desperate! This is the best they could do. However, Lipkin does have the following good polarization credentials.

1. Experiments with Polarized Beams¹ (1948-50).
2. Real Polarization Experiments² (1957-62).
3. Calculation of effects of betatron oscillation resonances on cyclotron beams³ (1950).
4. One of the inventors of W spin⁴ and $SU(6)_W$.
5. Invented H spin⁵ for calculation of polarization effects in nucleon-nucleon scattering.
6. Knew all about BMT since early childhood. BMT means Brooklyn-Manhattan Transit and is one of the main New York subway lines. Today it is dangerous to travel on the BMT. At this conference we learned why. Siberian snakes have been introduced into the BMT.

I did a scattering experiment with polarized beams for a Ph.D. thesis at Princeton in 1950. Nobody knew then that electron and positron beams from β -ray sources were polarized. Because a magnetic spectrometer was used to select beam energy, the electrons remained longitudinally polarized, scattered like unpolarized electrons, and gave the correct result. If I had been crazy enough to use an electrostatic energy selector which transformed the polarization from longitudinal to transverse, I would have discovered parity non-conservation, spent years trying to get rid of these crazy instrumental effects, and never received a degree.

Nobody would have believed that any left-right asymmetry found in the primitive experiments of those days was serious evidence for violation of a sacred conservation law. Consider the simple experiment shown in Fig.1a with a beam scattered at 90° in both directions by a foil at a 45° angle with the beam. Of course there is a right-left asymmetry, but it is not evidence for parity violation. It is produced by double scattering with the first scattering in the plane of the foil and a second scattering either at 45° if it is to the left, or 135° if it is to the right as shown in Fig.1b. Many instrumental effects like this were not properly understood in those days. Theorists were inventing

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wild and wrong theories to explain the spurious shapes of the β spectrum found in experiments with improperly prepared sources.

Fig.1: Left-Right Asymmetry in Electron Scattering

Today's polarization experiments are very different from the experiments thirty years ago, and it is instructive to recall the details of my thesis experiment. My thesis supervisor, Prof. Milton G. White had suggested Bhabha scattering with radioactive sources. At that time e^+e^- scattering had not yet been observed, and there was even some questioning of whether the contribution of the annihilation diagram would in fact be seen.

After considerable work on the Bhabha scattering problem I finally calculated realistically the expected counting rate with the strongest available positron sources, the best detectors and the best geometry. Today's experiment with colliding e^+e^- beams give Bhabha scattering as a strong signal generally considered as background. But in 1950 the scattering on a solid target with 10^{23} electrons was still insufficient to give a reasonable signal. I had to drop the project.

But to save the thesis I found another use for my half-built positron scattering experiment. Mott scattering of 1 MeV positrons had never been measured, and there was very little evidence that the positron was a spin-1/2 particle obeying the Dirac equation and having a Dirac magnetic moment. My experiment was the first to observe the magnetic corrections to the Rutherford formula. While the work was in progress, Martin Deutsch published the results of his beautiful positronium experiments,⁶ showing that the positron indeed has spin-1/2 and the Dirac moment and that positronium decays into two and three photons as expected.

All kinds of difficulties arose in obtaining reasonable β -ray sources for scattering experiments. The Ash Wednesday Catastrophe, when the Princeton cyclotron burned down, completely destroyed the program to use a ^{63}Zn source prepared by bombarding copper in the Princeton cyclotron. A longer lived source was needed, 9 hr ^{66}Ga , which could survive the trip by private plane from a cyclotron in Washington D.C. There was the Oak Ridge Catastrophe when a β^- source of ^{144}Ce was prepared and deposited on my source holder from an acid solution without realizing that enough acid residue remained to eat through the source holder. I used this "sealed" source while the ^{144}Ce slowly leaked through the holder on to the scattering chamber, solenoid and me.

Eventually I had to discard the contaminated clothes and scattering chamber and to spend several weeks decontaminating the solenoid.

In 1957 immediately after hearing that parity was not conserved, I realized that β -rays must be polarized and that a slight modification of my thesis experiment would find the effects. Unfortunately, our physics building at the Weizmann Institute was not yet built and the experiment was set up under primitive conditions behind the stage of the auditorium. Just before our first measurements Frauenfelder's preprint arrived announcing the discovery of β -ray polarization.⁷ Fortunately, there was still much to do in β -ray polarization experiments and we were able to contribute to this research.²

From this experience a number of past lessons have been learned.

1. Estimate statistics before building apparatus.
2. Don't use oil to cool magnets.
3. Never trust chemists who say that a radioactive source is safely sealed.
4. Most important of all for this conference, big polarization effects are found where theorists don't expect them.

There is also one comment on how things have changed since 1950.

The days when a student in particle physics could design his own experiment, build his own apparatus and take his own data are gone forever. Today's experiments are collaborations between specialists who often do not understand one another's fields.

In the polarization game people who make polarized beams, people who make polarized targets and people who design polarization experiments must talk to one another and understand one another's physics.

Bringing these people together is an important part of these polarization conferences.

2. Past Lessons From Ancient History

It is important to recall the effects of polarization in classical physics. Amplitudes, phases, coherence and polarization are all good classical physics. It is incoherence which is a new quantum effect. Interference of polarized light was completely understood and beautifully described in classical physics. But an unpolarized beam makes no sense in classical physics.⁸ The existence of unpolarized light is evidence for the quantum nature of light!

It is also instructive to note what great men have said in the past about polarization. There was Wien's paradox and its resolution by Planck.⁹ Wien proposed the gedanken experiment illustrated in Fig.2 with a polarizer polarizing light vertically, a Faraday rotation by 45° and an analyzer for 45° polarized light.

Fig.2: Wien's Paradox

The light coming in from the left was polarized, rotated 45° and passed out through the analyzer. But incident light from the right would be polarized at 45° , rotated 45° to horizontal, and be unable to pass through the polarizer on the left. Thus light could pass through this apparatus from left to right and not from right to left. A cold body on the left could radiate light through the apparatus to a hot body on the right and no light would return the other way in violation of the second law of thermodynamics. The resolution of the paradox by Planck is given at the end of this talk.

For another past lesson, let us look back at the state of nuclear physics in 1950. Nuclei were obviously very complicated systems with strong forces--there was no possibility of using an atomic or shell model. Statistical models furnished the only reliable methods for treating nuclei. Experimental discovery of magic numbers forced reexamination of shell models. Simple models didn't work. The key to the nuclear shell model was strong spin-orbit forces.

Once again spin effects were crucial and much bigger than expected. This led to a breakthrough in a direction previously considered nonsense by theorists.

Once upon a time physicists believed that nucleons and pions were elementary like electrons and photons, and that Yukawa's theory of nuclear forces was the analog of QED for strong interactions. Then the Δ was discovered, and then the ρ and other pion resonances, and it became apparent that neither the pion nor the nucleon was elementary and that both had a composite structure. Today pions and nucleons seem to be very similar objects, instead of being very different like the electron and photon, and made of the same basic building blocks: spin $1/2$ quarks bound by colored gluons. But perhaps history will repeat itself. Maybe 25 years from now a lecture at the polarization conference will include the statement "Once upon a time physicists believed that quarks and gluons were elementary, and that Quantum Chromodynamics (QCD) was the analog of QED for strong interactions. Then.....???"

Some suggestions already are appearing that quarks and leptons are not elementary but made of more fundamental objects called rishons or preons.¹⁰ The name rishon comes from a Hebrew word which has several interpretations. It is also a short form for the name of a town between

Tel Aviv and Rehovot, famous for its winery. A standard excursion for tourists staying in Tel Aviv includes a trip to Rehovot to visit the Weizmann Institute with a stop at Rishon to visit the winery. My friends in public relations at the institute used to complain about the difficulty of explaining anything to these tourists after they had imbibed freely at the winery. So I like to think of rishon physics as the kind of physics done under the influence of Rishon.

But we do not enter into such speculations, and examine the situation as it appears today. We have the new QXD model for everything, where $X = A, B, C, D, E, F, G$, etc. So far there are only models for $X = C, E, F$ and G , but no doubt the others will eventually be discovered as well.

We have the standard model of weak interactions with V and A interactions, only left and no right handed charged currents, both left and right-handed neutral currents, and 100% polarization in β -decay. We also have an $SU(2) \times U(1)$ symmetry and two kinds of particles, quarks and leptons. There are suggestions to unify these particles in a higher symmetry like $SU(5)$ containing $SU(2) \times U(1)$ and to gauge this symmetry with gauge bosons yet to be discovered. This will be the gauge theory of the world.

But in 1950 there was another standard model of weak interactions with S and T interactions, equal left and right handed charged currents, no neutral currents, and no polarization in β -decay. Nobody had measured this, but everyone knew there was no polarization. There was also an $SU(2) \times U(1)$ symmetry for isospin and strangeness and two kinds of particles, strange and nonstrange. There were suggestions to unify these particles in a higher symmetry like $SU(3)$ containing $SU(2) \times U(1)$ and to gauge this symmetry with gauge bosons recently discovered, ρ , ω and K^* . This was to be the gauge theory of the world. It was called the eightfold way.

It is amusing that in the great excitement about non-Abelian gauge theory, this original non-Abelian gauge model for hadron dynamics has faded away. There is no longer a gauge theory of strong interactions mediated by the octet of vector mesons ρ , ω , and K^* coupled to conserved vector currents. The $SU(3)$ group originally introduced by Gell-Mann and Ne'eman is now called flavor and dismissed as an irrelevant complication in the QCD description of strong interactions.

3. Mass Scales and the Importance of Spin in Hadron Physics

Constituent quark models for hadrons have been compared with analogous constituent models for atoms and nuclei. But there are important differences, characterized by a set of different scales. Any bound state has several features with the dimensions of length or mass: 1) the mass of the bound state or its Compton wave length; 2) the size of the bound state or the Bohr radius; 3) the excitation energy for orbitally excited states; 4) the fine or hyperfine structure arising from spin-dependent interactions. These four mass scales are listed in Table I for four different bound state models.

Table I

Scales of Bound States

Bound States	Mass M	Size nc/r	Excitation Energy ΔE	Hyperfine Energy
Positronium	1 MeV	1/137 MeV	$1/(137)^2$ MeV	$1/(137)^3$ MeV
Nuclei	A GeV	50-100 MeV	5-10 MeV	-----
Hadrons	1 GeV	200 MeV	600 MeV	300 MeV
Electrons	1/2 MeV	$\gg 1$ GeV	$\gg 1$ GeV	?

In atomic physics, represented by positronium as the simplest system bound by atomic forces with all constituents having equal masses, the four scales decrease monotonically in steps of 1/137. In nuclei the scales decrease monotonically in steps of about an order of magnitude. But in hadrons these scales are all approximately equal, and the excitation energy and hyperfine energy are roughly equal and larger than the energy defined by the size. Also listed are electrons, since models have been proposed which attempt to describe quarks and leptons as bound states of even tinier objects. The scales for these models are completely opposite to those of conventional bound states. A number of very peculiar difficulties remain to be resolved, which are not discussed further here. Brodsky referred to one point--the anomalous magnetic moment.¹¹

The moral of Table I for this conference is that spin effects are much more important in hadron physics than in atomic or nuclear physics. This is expressed quantitatively by noting that the N- Δ mass difference which is a spin splitting is much larger than the binding energy of the deuteron.

$$M_{\Delta} - M_N \gg M_p + M_n - M_d . \quad (1)$$

4. Multiquark Spectroscopy and Dibaryon Resonances

One reason for the success of the quark model was its prediction that the observed hadron states should be those constructed from a quark-antiquark pair and from three quarks. But the question of the possible existence of multiquark states keeps arising and is still open. The whole issue of multiquark spectroscopy¹²⁻¹⁸ has been thoroughly confused by the baryonium fiasco.^{12,13}

This is an example of how the bag model should not be used. Large numbers of states were predicted and the literature was then searched for experimental evidence for such states. Unfortunately, there was not sufficient feedback from the real world, both on the theoretical and on the experimental sides. The result was a wild goose chase which ended with most of the so-called experimental evidence for baryonium disappearing as statistical fluctuations.

The past lesson to be learned from this experience is that theorists and experimentalists must communicate better and really under-

stand one another's work. It is not enough to merely take the numerical results from one another's papers and treat them as gospel truth.

Physics is an experimental science. We discover new things by doing good experiments. Theoretical models help to understand experiments and guide experimentalists to new, fruitful experiments. A good model picks out leading effects, gets agreement with good experimental data, and predicts new phenomena which are found in experiment. A bad model picks out misleading effects, looks for agreement with bad experimental data, and predicts new phenomena which are not found experimentally. The nonrelativistic quark model has been very successful. Many experimental results otherwise not related have been brought together and described by this model¹⁹⁻²⁵ and many new predictions and suggestions for new experiments have been made. However, the bag models²⁶ have not yet proved themselves. Bag model calculations generally only reproduce results already known from the nonrelativistic quark model. Their predictions and suggestions for new experiments have not yet been fruitful. And the baryonium bag model has been particularly bad.

Different models are needed to describe hadron structure because nobody knows how to solve the relativistic many-body problem remaining even after the glue and the ocean of pairs are neglected. Simplified models are invented which can be solved, each at the price of omitting some of the physics. Each is useful for different types of data; namely those where the physics omitted is not important. The M.I.T. bag model²⁶ reduces the relativistic n -body problem to a relativistic one-body problem. It is useful for testing relativistic effects, but neglects two-body correlations of the type successfully demonstrated in the calculation of the neutron charge radius and in the Isgur-Karl²⁷ treatment of strange baryons with unequal mass quarks. The harmonic oscillator shell model is nonrelativistic, but furnishes a shell model which can be solved exactly and which includes two-body correlations. It is the only model in which the center-of-mass motion is treated exactly and spurious excitations are simply separated. Another potential model which has been used is the Quigg-Rosner logarithmic potential.²⁸ Although this potential is not tractable for the three-body problem, many results are obtained without full calculations using the scaling properties of the potential; in particular results relating meson and baryon spectra.

To investigate multiquark systems, we need a model that works for two and three-body systems and is easily extended to treat more particles. The bag model has too much freedom and not enough experimental constraints. It can be made to fit almost anything and has little predictive power. It is particularly unreliable for multiquark systems because the confinement is put in by hand for each n body system, and there is no simple unambiguous prescription for how confinement varies with n . When the bag model Hamiltonian is defined for the quark-antiquark meson system, there is no unambiguous prediction for extension to the n quark system and no prediction that the diproton is unbound.

We begin by noting that there is no bound diproton and no bound dipion.¹³ This means that when two protons or two pions are brought together so that the quarks in one hadron are able to feel the short-range forces from the quarks in the other hadron, the resultant forces are insufficient to produce a bound state. But before jumping to the conclusion that there are no bound multiquark states of any kind, let us examine other possible dihadrons carefully.

Is there a bound dikaon? Jaffe¹⁴ contends that the scalar $\delta(980)$ and the $S^*(980)$ are states of two quarks and two antiquarks, including one strange quark pair. They thus have the constituents of a kaon pair and have a mass just below the mass of two kaons. They might be considered as bound $K\bar{K}$ states. But because the $\delta\pi$ and $\pi\pi$ channels are open at the $K\bar{K}$ threshold, the δ and S^* decay into $\eta\pi$ and $\pi\pi$ respectively, and it is very difficult to establish whether or not they really have the structure of a bound $K\bar{K}$ pair.

But if these scalar mesons are indeed bound $K\bar{K}$ states, the same kind of interactions that bind a K and a $\bar{K}$ can also bind a K with a charmed D meson. If such bound states exist below the DK threshold, they can have peculiar quantum numbers for which no other channels are open for decays by strong interactions. These new possibilities exist for a four-body system when there are four flavors.^{15,16} Such exotic mesons with charm and strangeness might be the first exotic states discovered.

There might also be bound states of a baryon B and an anti-charmed $\bar{D}$ meson. If these have masses below the BD threshold, they would be "anticharmed baryons" with exotic quantum numbers (the wrong sign of charm for a normal charmed baryon) which could not decay by strong interactions.¹³

Such "threshold exotics" which do not have open channels for strong decays would give unambiguous signatures for a multiquark hadron. It is therefore of interest to look for them experimentally. The possible theoretical basis for their existence has been examined recently¹⁷ as a guide for how and where to look. The basic physics underlying the possible existence of threshold exotics is the crucial role of spin forces first noted by Jaffe¹⁴. Although color electric forces saturate and do not lead to binding between color singlet hadrons, color magnetic forces are strong and do not saturate in this way. This is simply expressed by the relation (1) that the $N-\Delta$ splitting is much larger than the binding energy of the deuteron and is discussed in detail in Ref.16. The deuteron binding energy tells us how much binding energy might be gained by ordinary spin-independent forces when two hadrons are brought together. The $N-\Delta$ splitting tells us how much energy is available in the spin-dependent interactions. This energy might produce binding of two hadrons brought close together if their spins and color are recoupled from the configuration of two spin-singlet-color-singlet states to the configuration which minimizes the energy. But how can we estimate the binding of such states?

Some simple estimates have been given for four-quark meson states. But dibaryon resonances are six-quark systems and lead to a complicated six-body problem. The color electric energy is already a minimum in the two-nucleon configuration. The simplest six-quark configuration s^6 has all six quarks in the same orbit in a shell or bag model. Naively this should be the lowest state. But Harvey²⁹ has shown that although promoting two quarks to the p-shell giving the S^4p^2 configuration loses color electric energy, it can gain even more hyperfine energy because of greater freedom in color-spin couplings allowed by Pauli principle. Also complicated two-body correlations like diquark-quadriquark can gain energy. None of these effects are treated simply or reliably in any model! It is a wide open field for experiment!

5. Single Quark Transitions and Polarization

Fig.3: The Single Quark Transition

Many of the topics discussed at this conference are all described by the same basic diagram shown in Fig.3 showing a transition between two three-quark baryon states in which one quark changes its state and the other two are spectators. But each case is treated by specialists who do not realize that the same diagram occurs elsewhere. There must be a unified picture of baryon structure and dynamics that relates all phenomena described by the single-quark transition of Fig.3. Difficulties arising in one case may be resolved by clues from another. In particular, the effect of SU(6) breaking in wave functions should be related.

We know that SU(6) is broken because the nucleon and Δ are not degenerate, because the charge radius of the neutron is not zero,³⁰ and because QCD tells us that the spin dependent part of one gluon exchange breaks SU(6). Theorists have attempted to connect these three phenomena. These basic ideas should be incorporated into any model which attempts to break SU(6) to describe polarization phenomena. But such breaking must preserve the Fermi statistics of colored quarks. SU(6) is no longer the ad hoc symmetry of its original formulation. The introduction of color and Fermi statistics for quarks requires SU(6) wave functions for color singlet baryons with totally symmetric spacial wave functions. Any SU(6) breaking must introduce correlations between spin-flavor and space which break the maximum space symmetry. This occurs in the models for the charge radius of the neutron and the models which break SU(6) near $x \approx 1$, by having the quark carry all the flavor and spin of the hadron.^{25,31} But SU(6) breaking cannot be treated like SU(3) symmetry breaking in mesons by defining a spatially independent mixing angle in the spin-flavor space.

The production of polarized hyperons discussed at this conference may be described by the variation of Fig.3 shown in Fig.4.

Fig.4: Polarized Hyperon Production

The hyperon may be produced by the removal of a u-quark from the proton and its replacement by an s-quark from the sea. But why are they polarized? Nobody expected it. Qualitative agreement is obtained with ad hoc model of a polarized s-quark.³² Opposite signs of Σ and Λ polarization arise naturally from Fig.4 since the spins of the Λ and Σ are parallel and antiparallel to the spins of the s-quark.

$$\vec{s}_{\Lambda} \parallel \vec{s}_s \quad \vec{s}_{\Sigma} \not\parallel \vec{s}_s \quad (2)$$

But there is Clebsch of 1/3 which does not seem to show up in the data!

The same diagram also describes the strangeness exchange reactions shown in Fig.5.

Fig.5: Strangeness Exchange in Meson Baryon Reactions

$$K^- + p \rightarrow (\Lambda, \Sigma, \Sigma^*) + M^0 \quad (3)$$

where M^0 is a neutral meson, e.g. π^0 , ρ^0 , η , η' , ω , ϕ , f and f' . These reactions have the same baryon vertex as in polarized s model for hyperon polarization. They also show disagreement with the simple predictions for the Σ vertex. The predictions for the Σ here also have a factor of $1/3$ which does not show up in the data!³³ Perhaps these two strangeness exchange vertices are related.

6. Baryon Magnetic Moments

Magnetic moments of hadrons are spin effects which have taught us past lessons and also have future implications. The successful SU(6) prediction³⁴ began a revolutionary development in our understanding of hadron structure. The old standard model predicted that

$$\mu = \mu_{\text{Dirac}} + \mu_{\text{Anom}}(g) \quad (4)$$

where the anomalous moment depended on the strong interaction coupling constant g . Nobody noticed that the experimental moments satisfied

$$\left(\frac{\mu_p}{\mu_n}\right) \approx -\frac{3}{2} \quad (5)$$

because only the anomalous moments were expected to be related. There was no reason for the total moment to be simple! The SU(6) prediction (5) came as a great mystery.

Now we have a simple quark model which gives simple predictions for total moments.³⁵ And there are new measurements³⁶ of μ_Λ , μ_{Ξ^0} and μ_{Ξ^-} . The value of μ_Λ agrees with two quark model predictions with fantastic precision.^{20,21} But there are serious difficulties with μ_{Ξ^0} , μ_{Ξ^-} and μ_{Σ^+} , which do not fit any model.^{13,36,37} Better measurements of μ_{Σ^-} are needed.

We first note the serious troubles with the Ξ^- moment. Simple SU(6) predicts

$$\mu(\Xi^-) = \mu(\Sigma) = \mu(\Lambda) = \mu_s = \mu_d, \quad (6)$$

since the Ξ^- and Σ^- only have quarks with charge $-1/3$ contributing to the moment. We can view the SU(3) breaking as changing the mass of the d -quark in Ξ^- to make it different from that of the s -quark. Most models predict the direction of the breaking to make

$$|\mu(\Xi^-)| \leq |\mu(\Lambda)| = 0.61 \quad (7a)$$

The standard quark model with SU(3) breaking predicts³⁵

$$\mu(\Xi^-) = -0.52 \quad (7b)$$

But

$$\mu(\Xi^-)_{\text{exp}} = -0.75 \pm 0.06 . \quad (7c)$$

There is no good explanation for this. But configuration mixing might upset the simple predictions.

We therefore introduce a simple model-independent analysis of μ_p and μ_n valid for any configuration of u and d quarks with isospin symmetry. Isospin enables the separation of the u and d quark contributions to μ_p and μ_n . We assume that the wave function of the u quarks in the proton is the same as that of the d quarks in the neutron and vice versa. We also assume that the quark magnetic moments are proportional to their charges.

$$\mu_u = -2\mu_d \quad (8)$$

Then the contributions $\mu_f(H)$ of the quarks of flavor f to the magnetic moment of hadron H satisfy the relations

$$\mu_u(p) = -2\mu_d(n) \quad (9a)$$

$$\mu_u(n) = -2\mu_d(p) \quad (9b)$$

Then

$$\mu(p) = \mu_u(p) + \mu_d(p) = -2\mu_d(n) + \mu_d(p) \quad (10a)$$

$$\mu(n) = \mu_u(n) + \mu_d(n) = -2\mu_d(p) + \mu_u(n) \quad (10b)$$

Solving these equations for $\mu_u(p)$ and $\mu_d(p)$ gives

$$\mu_u(p) = \frac{2}{3} (2\mu_p + \mu_n) = 2.45 \quad (11a)$$

$$\mu_d(p) = (2\mu_n + \mu_p) = 0.34 \quad (11b)$$

We now compare the magnetic moments of the proton and Σ^+ . The difference between the proton and Σ^+ wave functions are again described by Fig.3, see Fig.6.

Fig.6: Comparison of Proton and Σ^+ Wave Functions

If the u-quarks in the proton and Σ^+ have the same wave functions, as indicated in Fig.6,

$$\mu_u(p) = 2.45 \text{ n.m.} = \mu_u(\Sigma^+) . \quad (12a)$$

The strange quark in the Σ^+ should contribute something less than the d-quark in the proton. But it should have the same sign

$$\mu_d(p) = 0.34 > \mu_s(\Sigma^+) > 0 \quad (12b)$$

So

$$\mu(\Sigma^+) > \mu_u(p) = 2.45 \text{ n.m.} \quad (12c)$$

The quark model predicts

$$\mu_s(\Sigma^+) = \frac{m_d}{m_s} \mu_d(p) \approx 0.23 \quad (13a)$$

This gives

$$\mu(\Sigma^+) = 2.68 \quad (13b)$$

But experimentally

$$\mu(\Sigma^+) = 2.30 \pm 0.14 < \mu_u(p) = 2.45 \quad (13c)$$

Although the disagreement with inequality (13c) is only one standard deviation, the disagreement with the prediction (13b) is significant. This cannot be fixed by reducing the strange quark contribution, since the bound (13c) is obtained by eliminating the strange quark completely.

A similar analysis of the magnetic moments of the proton and Ξ gives

$$\mu_{\Xi^0} - \mu_{\Xi^-} = \mu_u(\Xi^0) - \mu_d(\Xi^-) \quad (14a)$$

$$-1.24 + 0.75 = -3\mu_d(\Xi^-) \quad (14b)$$

Thus

$$\mu_d(\Xi^-) = 0.16 \pm 0.02 \text{ n.m.} \quad (15a)$$

But

$$\mu_d(p) = 0.34 \text{ n.m.} \quad (15b)$$

But both discrepancies (13) and (15) suggest that nonstrange quarks have smaller moments in hyperons than in nucleons. One possible explanation is pion exchange which would enhance the contribution in the nucleon of the nonstrange quarks but would have no effect in hyperons.³⁸

The contribution of the strange quark in the Ξ is given by

$$\mu_{\Xi^0} + 2\mu_{\Xi^-} = 3\mu_s(\Xi) = -2.74 \pm 0.12 \quad (16a)$$

$$\mu_s(\Xi) = -0.91 \pm 0.04 \quad (16b)$$

In the naive quark model

$$\mu_S(\Xi) = \frac{4}{3} \mu_S = \frac{4}{3} \mu_\Lambda = -0.81 \pm 0.01 \quad (16c)$$

The strange quark seems to behave roughly the same in the Λ and the Ξ , although there is a 12% difference which is $2\frac{1}{2}$ standard deviations. Better measurement of the Ξ^- moment would tie this down further. A good measurement of the Σ^- moment would help settle many questions, e.g.

- 1) Is the nonstrange quark in the Σ intermediate between N and Ξ or down to the same value as Ξ ?
- 2) Is the strange quark in the Σ the same as in the Λ and the Ξ ?

7. Polarization in 90° Nucleon-Nucleon Scattering

The large polarization effects observed in 90° p-p scattering³⁹ are still puzzling to theorists. The special symmetries in the kinematics of 90° scattering of identical particles are very simply described by noting that the directions of the incident and scattered beams and the normal to the scattering plane describe define a Cartesian coordinate system. The polarization states are then defined in a manner which treats the three Cartesian axes on the same footing, rather than choosing one as an axis of quantization. The three basic states for spin 1 are chosen to be those corresponding to plane transverse polarization rather than circular polarization: i.e. using the Cartesian components of a vector, (x, y, z) rather than the spherical components ($x \pm iy, z$). If we define our axes for each beam with respect to its own momentum as ℓ for longitudinal, n for normal to the scattering plane, and s for sideways (transverse in the scattering plane), we can define the three nonvanishing amplitudes for 90° scattering of identical particles very simply.

$$L = \langle S=1; S_\ell=0 | T | S=1; S_\ell=0 \rangle = \langle H=1; H_\ell=0 | T | H=1; H_\ell=0 \rangle \quad (17a)$$

$$N = \langle S=0 | T | S=0 \rangle = \langle H=1; H_n=0 | T | H=1; H_n=0 \rangle \quad (17b)$$

$$S = \langle S=1; S_\ell=0 | T | S=1; S_\ell=0 \rangle = \langle H=1; H_s=0 | T | H=1; H_s=0 \rangle \quad (17c)$$

The T-matrix is diagonal in this basis, and all the matrix elements of the 4 x 4 matrix vanish except those given by Eqs.(17).

The amplitudes are also given in the H-spin basis defined in Ref.(5). H-spin is an SU(2) group based on helicity, so that H_ℓ is just helicity. The states with $H_\ell = 0$ have opposite helicity and those with $H_\ell = \pm 1$ have the same helicity.

The asymmetry parameters are simply described in terms of these amplitudes; namely

$$-A_{ss} = (|L|^2 + |N|^2 - |S|^2)/(|L|^2 + |N|^2 + |S|^2) \quad (18a)$$

$$-A_{\ell\ell} = (|S|^2 + |N|^2 - |L|^2)/(|S|^2 + |N|^2 + |L|^2) \quad (18b)$$

$$A_{nn} = (|S|^2 + |L|^2 - |N|^2)/(|S|^2 + |L|^2 + |N|^2) \quad (18c)$$

The well known sum rule for the A's is evident from Eqs.(18).

$$A_{nn} - A_{\ell\ell} - A_{ss} = 1 \quad (19)$$

In many models the double helicity flip amplitude vanishes. In the Cartesian basis this gives

$$N = S \quad (20a)$$

Thus

$$A_{nn} = -A_{ss} \quad (20b)$$

and the sum rule (19) can also be written

$$2A_{nn} - A_{\ell\ell} = 1 \quad (20c)$$

In models like the constituent interchange model where H spin is conserved

$$L = N = S \quad (21a)$$

and

$$A_{nn} = -A_{\ell\ell} = -A_{ss} = 1/3. \quad (21b)$$

Note that the constituent interchange model is also described by a variation of Fig.3, shown in Fig.7. Thus any change in the description of the proton wave function introduced to obtain a better fit to the 90° scattering data has implications for a large number of other phenomena.

The results (21) are easily derived in the constituent interchange model by examining the symmetry properties of the diagram of Fig.7. We first note that the diagram of Fig.3 involves the replacement of one

quark in a baryon by another. If the transition is between two baryon states having the same spatial wave function, the quark transition can involve only changes in flavor and spin orientation. Such a change is described by an SU(6) generator which is a step operator changing one of the six flavor-spin states to another.

Fig.7: Constituent Interchange Model for Nucleon-Nucleon Scattering

The diagram of Fig.7 describes two single-quark transitions, one in each nucleon. The transition matrix element is therefore proportional to the product of two SU(6) generators, one for each nucleon. Thus the matrix element for the contribution of a diagram like Fig.7 to a transition from an initial state AB to a final state A'B' is

$$\langle A'B' | T_{\alpha i \beta k}^{\beta j \alpha m} | AB \rangle = T(s, t) \langle A' | G_{\alpha i}^{\beta j} | A \rangle \langle B' | G_{\beta k}^{\alpha m} | B \rangle \quad (22)$$

where $T(s, t)$ is a reduced matrix element depending upon the kinematic variables but independent of spin and flavor, and $G_{\alpha i}^{\beta j}$ is the SU(6) generator describing a transition from a quark state with flavor α and spin i to a state with flavor β and spin j . The same flavors α and β occur in reverse order in the two matrix elements in (22) because the quark flavor is conserved in the transition described by Fig.7. However, the spin indices i and k are allowed to change to new values j and m , because there can be spin flip in the transition. Furthermore, the basis for spin states has not been specified and conservation in one basis (e.g. helicity) may not be equivalent to conservation in another (e.g. transversity).

Let us now assume that there is one basis in which the spin quantum number is conserved and work in this basis. For example, if helicity is conserved in the center-of-mass-system, as is conventionally assumed in the CIM, then i and k denote helicity states and helicity conservation means that $i=m$ and $j=k$. If we furthermore assume equal contributions from all diagrams like Fig.7 independent of spin and flavor, the total transition matrix element is given by

$$\langle A'B' | T | AB \rangle = \sum_{\alpha, \beta, i, k} T(s, t) \langle A' | G_{\alpha i}^{\beta k} | A \rangle \langle B' | G_{\beta k}^{\alpha i} | B \rangle. \quad (23)$$

This expression is seen to be a scalar in the SU(6) flavor-spin

space, since its dependence upon spin and flavor is only in the scalar product of the matrix elements of two generators. The $SU(6)$ group has an $SU(2)$ spin subgroup which differs from ordinary spin because the basis chosen for each quark is the helicity, which depends upon the momentum of the individual quark state and which changes in the transition from the initial to the final state. This $SU(2)$ group is the H spin, defined in Ref.5, and its generators for each quark are the helicity and the two helicity-flip (raising and lowering) operators. Since Eq.(23) is a scalar under $SU(6)$, it is also a scalar under the $SU(2)$ H -spin subgroup. Thus the transition amplitude is invariant under H -spin rotations. This immediately gives the results (21) since the quantities L , N and S are seen from Eqs.(17) to go into one another under 90° H -spin rotations. The occurrence of the negative signs in Eqs.(18) and (19) are also simply seen as the difference between ordinary spin and H spin or helicity. Two particles moving with opposite momenta have antiparallel spins if they have the same helicity, but their longitudinal components of H spin, defined by helicity are parallel. The normal components of H spin and ordinary spin are defined to be the same, so that transversity is simply defined in both bases. Then sideways H spin must also be defined as opposite to ordinary spin to preserve the angular momentum commutation relations for H spin.

This derivation has used only the $SU(6)$ properties of the transition operators and not of the wave functions. The results (21) therefore cannot be changed by introducing $SU(6)$ breaking into the wave functions. The $SU(6)$ group defined here is $SU(6)_H$ which uses H spin rather than ordinary spin or W spin. Only the non-strange subgroup $SU(4)_H$ is relevant for nucleon-nucleon scattering.

8. Conclusions : The Future of Polarization

We conclude with the resolution of Wien's paradox by Planck. The incident light from the right in Fig.2 is unable to pass through the polarizer on the left after the 45° Faraday rotation. However, if it is reflected back and undergoes another 45° Faraday rotation, it cannot exit back through the analyzer at the right and is reflected again. After a third 45° Faraday rotation it can now pass through the polarizer and exit at the left. The second law of thermodynamics is saved!

The moral of this story is that polarization and spin effects have traditionally brought surprises to physicists, particularly to those who thought that such effects were unimportant. In hadron physics, large unexplained effects keep turning up and are still unresolved puzzles. A good measurement of the uninteresting beta ray polarization could have discovered parity nonconservation many years before its prediction by Lee and Yang. Nobody knows whether there are further exciting discoveries of this kind waiting for polarization experiments. The only way to find out is by trying them.

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