UCRL-10897

# University of California

# Ernest O. Lawrence Radiation Laboratory

## BARYON SPECTROSCOPY

TWO-WEEK LOAN COPY

*This is a Library Circulating Copy which may be borrowed for two weeks. For a personal retention copy, call Tech. Info. Division, Ext. 5545*

## DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

Rept. submitted for meeting of the International Conf. on Nucleon Structure — Stanford, June 24-27, 1963. Rept. submitted also for pub. in the Proceedings.

UCRL-10897

UNIVERSITY OF CALIFORNIA
Lawrence Radiation Laboratory
Berkeley, California

Contract No. W-7405-eng-48

# BARYON SPECTROSCOPY

Arthur H. Rosenfeld

July 9, 1963

# BARYON SPECTROSCOPY

Arthur H. Rosenfeld

Department of Physics and Lawrence Radiation Laboratory
University of California, Berkeley, California

July 9, 1963

## ABSTRACT

Current experimental knowledge of the quantum numbers of baryons is surveyed, and an attempt is made to systematize this information.

# BARYON SPECTROSCOPY*+

Arthur H. Rosenfeld

Department of Physics and Lawrence Radiation Laboratory
University of California, Berkeley, California

July 9, 1963

## I. INTRODUCTION

At a conference on the structure of the nucleon some of you may question the relevence of this talk, or of the next one by D. H. Miller on meson spectroscopy. However, Chew pointed out earlier that nucleons are merely the most accessible of many strongly interacting states, and in fact I shall spend some time on the question of which of the pion-nucleon resonances may be simply excited rotational "recurrences" of the nucleon. To justify surveying the mesons I need only point out that nucleon form factors are often parameterized in terms of the masses of the nonstrange mesons.

Current knowledge about baryons has been thoroughly covered at the Topical Conference on Recently Discovered Resonant Particles, held at Ohio University, Athens, Ohio, in April 1963. In particular, R. H. Dalitz delivered a paper on the Systematics of Baryon and Meson States [1], which it is pointless for me to reproduce here (also impossible in 25 minutes). Since April, the most significant results seem to be negative -- failure so far to find $\Omega^-(167?)$ or $\Xi^*_{1/2}(1600)$, or to establish the parity of $Y_1^*(1660)$, so I shall try to emphasize these points, particularly in paragraphs 4.2.

This talk is divided into two parts: a short comment on the new masses for $\Sigma^-$ and $\Sigma^0$ and their relation to the masses of the other eight stable baryons, followed by a longer part surveying the resonances.

## II. MASSES OF THE STABLE BARYONS; NEW MASSES FOR $\Sigma^-$ AND $\Sigma^0$

The mass of the $\Sigma^+$ is obtained by observing the protonic decay of $\Sigma^+$'s stopped in emulsion, and thankfully has not changed. The $\Sigma^- - \Sigma^+$ mass difference is then established by comparing the ranges of $\Sigma^\pm$ produced by the following two reactions resulting from capture of stopped $K^-$ mesons by protons in nuclear emulsion:

$$K^- p \Rightarrow \Sigma^- \pi^+ \quad \text{or} \quad \Sigma^+ \pi^- . \tag{1}$$

For years, W. Barkas and I have issued wallet cards in which this difference is given as 6.56 MeV. As long as emulsion stacks were too small to permit one to measure the range of the pions produced in reactions (1), there was no easy check on this mass difference. But, with larger stacks, the pion ranges started to suggest a larger mass difference, and in all fairness to us, footnote (n) of the recent editions of our Table points out this anomaly. By now Barkas has convinced himself that the trouble is with the range-energy relation for intermediate-velocity, negatively-charged particles [v/c for the $\Sigma$ in reactions (1) is about 0.15] [2]. He thinks that, as a slow charged particle passes an atom, there is time for the atom to be polarized. Thus a negatively charged ionizing particle has time to repel the orbit of the atomic electrons, and hence will lose less energy than a positively charged ionizing particle. All of this complication has of course been empirically calibrated into the range-energy relation for positive particles, so a correction must now be applied to negative particles. If we believe the mass difference as calculated from the ranges of the pions, which are relativistic so that this effect is unimportant, we find a mass difference of 8.25 MeV, i.e., 1.6 MeV higher than previously.

The mass of $\Sigma^0$ must also be raised 1.6 MeV, since it is calculated from the $\Sigma^-$ mass via a measurement of the $\Sigma^- - \Sigma^0$ mass difference from the capture of $\Sigma^-$'s in hydrogen:

$$\Sigma^- p \Rightarrow \Sigma^0 n, \qquad \Sigma^0 \rightarrow \gamma\Lambda .$$

The present situation is summarized in Fig. 1, which also shows that when the mass of $\Xi^0$ becomes known, there will be another test of SU(3) using the relation of Coleman and Glashow [3],

$$\Xi^- - \Xi^0 = (\Sigma^- - \Sigma^+) - (n - p), \tag{2}$$

where the symbols stand for the masses of each baryon.

With respect to the masses of cascades, several groups have reported values for the mass of the $\Xi^-$ (see Table I). But since the number of cascades of both charges is by now large, systematic errors in the mass are much larger than statistical errors. For example, at the Christmas 1962 American Physical Society Meeting, F. T. Solmitz reported that, on a carefully selected sample of 450 $\Xi^-$'s, the statistical error was only 0.1 MeV, but the systematic error, as yet unstudied, might be several MeV. For a sample of ~100 $\Xi^0$'s, the statistical error was 0.8 and again he could not quote a realistic overall uncertainty. So, for the present, prediction (2) stands at

$$5 \pm ? \stackrel{?}{=} (8.3 \pm 0.5) - (1.3) = 7 \pm 0.5 . \tag{3}$$

We shall not know if it is really satisfied until we have the results of the careful study of systematic errors now under way.

Figure 1 illustrates a useful mnemonic, namely that within all the baryon charge-multiplets the more negative the charge, the larger the mass. The same rule also applies to the $K^0 - K^+$ meson doublet; it cannot, of course, apply to the pion, since $\pi^+$ and $\pi^-$ must have the same mass.

## III. GENERAL PROPERTIES OF RESONANT STATES

### 3.1. Natural Units for the Widths of Resonances

If we have an exponentially decaying state, $|\psi|^2 \propto e^{-t/\tau}$, then its Fourier transform is a Gaussian with a full width at half maximum $\Gamma$ given by

$$\Gamma = \frac{\hbar}{\tau} = \frac{2/3 \times 10^{-21} \text{ MeV sec}}{\tau} . \tag{4}$$

If this state is moving with a velocity $v$, it will on the average go a distance $v\tau$ before decaying; taking into account time dilation, $v$ becomes $\gamma v = \eta c = \frac{p}{mc} c$, and using (4) for $\tau$ we have

$$d = \frac{p}{mc} \frac{\hbar c}{\Gamma} = \frac{p}{mc} \frac{197 \text{ MeV Fermi}}{\Gamma} . \tag{5}$$

Thus when we read that the $\rho$ meson has a $\Gamma$ of about 100 MeV, we see that if its momentum is a few hundred MeV/c, it has gone on the average only 1 Fermi before it decayed. Therefore the $\rho$ generally decays in the presence of other particles whose amplitudes interfere either constructively or destructively (depending on the production reaction). Hence, we should not be surprised that the $\rho$ peak position and width appear to vary from experiment to experiment and has been likened by

Steinberger to a wobbly lump of jelly. One can, of course, improve the situation experimentally by using the Brookhaven alternating-gradient synchrotron or the CERN proton synchrotron to produce such resonant states with very high momenta, i.e., moving away very fast. By contrast, the UCLA group is just mailing a preprint which states that the width of $\Xi^*(1530)$ is $7 \pm 2$ MeV [4]. On the average, then, it travels pc/1530 times 25 Fermi, so that it really decays in "outer space" and should behave reproducibly.

### 3.2. Notation: The Symbol-Minded Approach

The figures and Table VI are the real meat of this talk, but before we can read them I must introduce the notation, which has been concocted by Chew, Gell-Mann, and me. In addition to having atomic mass number $A = 1$, baryons can be specified by a mass and four other quantum numbers: hypercharge Y (or strangeness S), isotopic spin I, and spin and parity $J^P$. Since suggestive symbols ($N$, $\Lambda$, $\Sigma$, $\Xi$) already exist for the baryons with $I < 3/2$, we suggest using these four symbols to specify A, Y, and I. Thus in this "symbol-minded" approach, N(938) stands for the nucleon, and N(1512) stands for the 600-MeV pion-nucleon resonance which is normally written $N^*_{1/2}(1512)$. For $I = 3/2$ (e.g. the original $p_{3/2}$ $\pi N$ isobar $N^*_{3/2}(1238, 3/2^+)$, we must then invent a new symbol; we choose $\Delta$. The isobar then becomes $\Delta(1238)$, and if the $\pi^+p$ 1920-MeV resonance (found at $T_{\pi^+} = 1350$ MeV) really has $J^P = 7/2^+$, then it can be called a "recurrence" of the isobar, and written $\Delta^{II}(1920)$. Note that the symbols do not include the spin and parity, which are usually the last-determined quantum numbers of a new state. For that reason a newly discovered resonance can usually be assigned a symbol almost as soon as it is discovered. When $J^P$ are finally determined, we suggest specifying

them with a subscript. These subscripts are listed in footnote 1 to Table VI (it is called Table VI instead of Table II because it is Table VI from the most recent Barkas and Rosenfeld compilation of data for particle physics [5].

Next a few comments on how spins and parities for some of the baryons have been established.

### 3.3. Spins from Angular Distributions

Most of you are probably familiar with Yang's theorem of maximum complexity of angular distributions [6]; here I want to generalize it a little bit. First let me define the complexity $n$ of an angular distribution as the highest power of $\cos\theta$ present. Then if we are dealing with a single partial wave $\psi(J)$, the theorem states that the maximum complexity in $|\psi|^2$ is given by $n \leq 2J$, qualified of course by the condition that $n$ must be even, since the square of a single partial wave cannot yield terms odd in $\cos\theta$.

But in dealing with experimental resonances, we often find ourselves dealing with a situation

$$\psi_R(J_1) + \psi_{NR}(J_2),$$

where $\psi_R$ is a small resonant term which varies rapidly as the energy passes through its resonance value, and $\psi_{NR}$ is a large slowly varying "background" which generally has a smaller value of $J$ than the resonance under study.

In this case we cannot observe $|\psi_R|^2$, but we can often see the rapidly varying cross term $\psi_R\psi_{NR}$. A useful generalization is that the maximum complexity of this cross term is [7]

$$n \leq J_1 + J_2, \tag{6}$$

qualified of course by the condition that n must be even or odd depending on whether the parities of the two interfering states are alike or opposite.

Relation (6) illustrates that there are always two possible interferences that give the same value of n. Thus an odd value of n can come from $J_1^+$ and $J_2^-$ or $J_1^-$ and $J_2^+$. This is of course a consequence of the Minami ambiguity, which states that such competing pairs of interferences yield identical angular distributions (but, thankfully, different polarizations).

Often, of course, we do know something about the background. Thus as Cence has already pointed out, at the 600-MeV $\pi^- p$ resonance N(1512), there is a sizeable coefficient $a_2$ of $\cos^2\theta$, implying $J = 3/2$. There is also a rapid variation of $a_3$, implying opposite-parity interference with the lower isobar $\Delta_\delta(1238, 3/2^+)$, so we guess an assignment $N_\gamma(1512, 3/2^-)$. In fact, the favored $J^P$ assignments for the whole sequence of $\pi p$ resonances have been arrived at by keeping track of the interferences between each resonance and that immediately above and below. This is discussed further in 4.1.

Perhaps the cleanest example of the determination of $J^P$ via interference between $\psi_R$ and $\psi_{NR}$ is the case of $\Lambda_\gamma(1520)$. Here Ferro-Luzzi, Tripp, and Watson [8] were easily able to show that the $K^- p$ and $\bar{K}^0 n$ channels resonated in a $3/2^-(d_{3/2})$ state. The question of whether the $\Sigma\pi$ channel also was $d_{3/2}$ or $p_{3/2}$ brings us next to the general problem of parity determinations.

### 3.4. Parities from Polarizations

Unless one is lucky enough to observe interference with a known background, one cannot determine the parity of a resonant state unless one

can produce it polarized (or at least aligned) and then observe the polarization (or at least anisotropies) of its decay products. The analyses have been quite different for the two possible cases of "formation" experiments vs "production" experiments.

By "formation" I mean just the experiments that we have been discussing so far: i.e., one can supply the ingredients of $\Delta(1238)$ and "form" it by giving the pion the correct kinetic energy, or one can form $\Lambda(1520)$ by shooting 395-MeV/c $K^-$'s at protons.

As an example of "production" let me choose $\Sigma(1385)$. Since 1385 MeV is below the mass of a proton plus a K meson, one could form $\Sigma(1385)$ only by shooting $\Lambda$ at $\pi$, or vice versa (neither of these experiments is feasible). So instead one must "produce" it in reactions like $K^- p \rightarrow \Sigma(1385) + \pi$.

A successful parity analysis in a formation experiment is the work of Tripp, Watson, and Ferro-Luzzi [9]. As we just mentioned, they formed $\Lambda_\gamma(1520)$ with 395-MeV/c $K^-$'s on p and observed that its decay $\Sigma^+$'s were polarized. By observing the energy-dependence of this polarization, they were able to show that the $\Sigma\pi$ state was also $d_{3/2}$ and not $p_{3/2}$, thus proving to the satisfaction of most people that the $\Sigma\Lambda$ relative parity is even. (By convention, the $\Lambda p$ relative parity is defined as even.)

Recently there have been two successful parity analyses in production experiments, showing that $\Sigma(1385) \rightarrow \Lambda\pi$ and $\Xi(1530) \rightarrow \Xi\pi$ are both $p_{3/2}$ decays. [If we then assume that the parity of the $\Xi$ is positive, we can say that $\Sigma_\delta(1385)$ and $\Xi_\delta(1530)$ are both $3/2^+$ resonances.]

For $\Sigma(1385)$, there had been mounting evidence for a $\cos^2\theta$ term in its decay angular distribution, showing that it had $J \geq 3/2$. Then

Shafer et al. [10] were able to produce nearly 1000 highly polarized $\Sigma(1385)$ events, and showed that although a $p_{3/2}$ decay fit the data very well, $d_{3/2}$ was ruled out. Of course it may still be that $J^P \geq 5/2^{\pm}$, but it has turned out to be useful in this game of classifying states always to give them tentatively the simplest possible assignment until that is shown to be wrong.

For $\Xi(1530)$, the U.C.L.A. group [4] studied its decay $\Xi^* \rightarrow \Xi\pi$ and find that the only acceptable assignments are $p_{3/2}$ or $d_{5/2}$ or values of $J \geq 7/2$.

I should point out that both these experiments yielding $J^P = 3/2^+$ took place <u>after</u> the speculation by Gell-Mann and others that they both belonged to the same SU(3) decuplet as $\Delta_\delta(1238)$ because of the equal-mass-spacing rule. [11]

In concluding my comments on parity assignments, I should comment on the very nice recent work of Byers and Fenster [12], who have derived very general and comprehensible test functions for all values of J and P.

## IV. BARYON SYSTEMATICS

### 4.1. Pion-Nucleon States

At a conference on the nucleon, it seems appropriate to emphasize nonstrange baryons. Here the most recent development is the discovery by Diddens et al. [13] of two more resonances, one in each isospin state, N(2190) and $\Delta(2360)$. They are shown, along with the four lower resonances, in Fig. 2.

To classify these six resonances it is useful to invoke an old phenomenological observation [14], which is illustrated in Table IIa, for

those baryons for which there is some evidence as to their spin and parity. For a given orbital angular momentum there are of course two possible values of J. The useful observation, first pointed out to me by J. Helland, is that the lower J seems to resonate in the lower value of I, i.e. 1/2, while the higher J seems to resonate as a $\Delta$, i.e. with $I = 3/2$. As Cence mentioned this morning, even the $J^P$ values of Table IIa are not yet certain, but they seem to be the simplest possible consistent set. This rule has been interpreted recently by Kycia and Riley as an isospin-dependent spin-orbit coupling [15]; and in a recent Phys. Rev. Letters, Carruthers states that he can support this rule with dynamical calculations [16].

Now comes the question of where to put the new bumps of Diddens et al. There are as yet no data on even the angular distribution of elastic scattering, although Gerald Smith tomorrow will present some data on the $\Sigma K$ channel of N(2190), which could perhaps be optimistically interpreted as suggesting a J of 9/2. The simplest argument is that <u>only</u> <u>one</u> series of $\Delta$ resonance exists, namely $\Delta_\delta(1238)$, $\Delta_\delta^{II}(1920)$, and hence the best home for the new $\Delta(2360)$ is as $\Delta_\delta^{III}$, the third occurrence of this $\delta$ series with a $J^P$ of $11/2^+$. We have plotted it at $11/2^+$ in Fig. 3a. Notice that this makes the Regge trajectory a surprisingly straight line. If one then takes the point of view that third occurrences <u>are</u> found (and that they lie on surprisingly straight trajectories), then one is tempted to assign N(2190) the title $N_a^{III}$, with $J^P = 9/2^+$. This is also shown on Fig. 3a.

Two other pairs of alternative assignments have been suggested for N(2190) and $\Delta(2360)$; they both involve inventing a new lower-energy resonance. The most obvious candidate for this is the "shoulder" in the $\pi^+p$ cross section at a pion kinetic energy of about 850 MeV (invariant

mass of about 1640 MeV). I personally doubt that this is a resonance, since there is no shoulder at all in the elastic-scattering cross section, and the whole effect is easily explained away as a rapid rise in the cross section for the production of an additional pion. Further, the elastic angular distribution at 1640 has a complexity of $n = 3$, which makes it hard to call it a resonance with a spin of greater than 3/2. Having said all these qualifications, I can illustrate in Table IIb the two simplest possible alternate assignment schemes. The column labeled "Regge-choice" is my reluctant second choice if Table IIa turns out to hinge on a wrong guess; it simply crowds states into the lowest possible vacancies of Table IIa. The trajectories corresponding to this "Regge-choice" are drawn in Fig. 3b. The column of Table IIb labeled "Kycia-Riley" is motivated by their isospin-dependent spin-orbit coupling. It is unpleasant to extreme Regge-ists, because the trajectory would have to start "above sea-level" at $J = 5/2$ rather than at $J = 1/2$.

## 4.2. General Baryon Systematics

We saw in the last section that even the systematics of nonstrange baryons is poorly understood. But now things are going to get worse. We have come to the part of this talk that is the most difficult to give, and will have the most transient time value; this is to try to survey a large number of experimental facts (many of which are not well established) in terms of some ideas about Regge trajectories and unitary symmetry (both of which are also not established). If I could wait a year, crucial developments (both experimental and theoretical) would surely change any conclusions of this survey, but since the conference is taking place now, I must proceed to gather up what <u>is</u> known and present it in Fig. 3a, which

is a scatter diagram of masses of the known baryons vs the simplest possible $J^P$ assignments. The axes are reversed from those of the conventional Chew-Frautschi diagram, so that the masses may be plotted vertically, as in a conventional energy-level diagram. In fact, we see nestled in the lower left corner the same diagram for the eight stable baryons that was presented in Fig. 1. Here they are called the $\alpha$ octet to signify that they all probably have $J^P = 1/2^+$. The vertical scale is actually linear in $m^2$ instead of m. I drew it that way at a time when I thought wrongly that there was some reason to prefer $m^2$, however the lines joining the various excited states (that seem to recur with their angular momentum increased modulo two) are so strikingly straight that I shall continue to use an $m^2$ scale.

In Section 4.1 we discussed the fact that the two positive-parity pion-nucleon states may recur twice or even three times. In addition we see that $\Lambda$ may well recur as the $\Lambda_\alpha(1815)$ resonance. No other recurrence are yet known, but we have drawn in hopeful open circles for $\Sigma_\alpha^{II}$ and $\Xi_\alpha^{II}$ at $J^P = 5/2^+$.

The negative-parity states are surrounded with a line which distinguishes them, and perhaps keeps them in quarantine, since their $J^P$ assignments are mainly guesses. No anisotropy in the decay of $\Lambda(1405)$ has yet been reported, so our rule of simplest available assignments suggest $J^P = 1/2^-$; this would correspond to the S-wave $\bar{K}N$ bound state suggested long ago by Dalitz and Tuan.

We now comment on Fig. 3a from the point of view of SU(3). To the right of the $\alpha$ octet we see three $\delta$ charge-multiplets, constituting 9/10 of the proposed decuplet. There has been a hydrogen bubble chamber run at CERN with $K^-$'s of energy high enough (3.5 BeV/c) to produce the

missing $\Omega^-$ stable baryon needed to complete the decuplet. No event has yet been found, meaning that the production cross section is not greater than about 1 μb. I want to point out that this is not a reason to be concerned; in fact one recent estimate of the cross section at this momentum gives less than 1 μb [17]; perhaps we are going to have to start measuring cross sections in nanobarns! Note that the production reaction sought is

$$K^- p \Rightarrow \Omega_\delta^- K^+ K^0 .$$

We can establish a scale for the expected cross section by examining the most nearly equivalent known reaction

$$K^- p \Rightarrow \Xi_\delta (1530) K\pi .$$

We find that, based on two reported events and normalized to the same phase space, the average cross section is only 4 μb. Further it seems unlikely that it will be as easy to produce an $\Omega^-$ (with strangeness $S = -3$) as a $\Xi^*$ (with $S = -2$). So until there are either longer runs, or runs at higher momenta, or runs with high-energy antiprotons, SU(3) enthusiasts need not worry too much about the nondiscovery of $\Omega_\delta^-$.

However, if we transfer our attention to the negative parity "octet," we have some cause for worry. Glashow and Rosenfeld have pointed out that, if the $J^P = 3/2^- = \gamma$ guess for $\Sigma(1660)$ is correct, then there should be another $\Xi_\gamma$ at mass (1600) [18]. At Athens, Leitner [1] reported that its production cross section by 2.3-BeV/c $K^-$'s is at least 20 times less than the cross section for $\Xi_\delta(1530)$. Probably a factor of twenty in a single experiment is not a decisive blow, but $\Xi_\gamma$ should show up pretty soon if things are to work out. Actually my personal guess is that it is not

so much SU(3) that is shaky as the $\gamma = 3/2^- J^P$ assignments. It is crucially important to do a latter-day Tripp-Watson-Ferro-Luzzi experiment-and-analysis on $\Sigma(1660)$, which can be formed by 715-MeV/c $K^-$'s on protons. Ticho et al. at UCLA have been trying to do this experiment. Unfortunately they do not have film with 715-MeV/c $K^-$'s on protons, but they do have 750-MeV/c $K^-$'s on deuterium, and the Fermi momentum of the proton may give them enough energy spread to do the experiment, if they also have enough events. But it should be done in hydrogen.

Finally, two remarks in favor of SU(3). When, about 1960, resonances started appearing everywhere, there was no reason not to expect $\Sigma\pi$ resonances in all isospin states — — 2, 1, and 0. But they have not appeared in $I = 2$ at least up to about 2 BeV. Nor are there any resonances below 2 BeV in the Kp system (as opposed to the $\bar{K}p$ system). Now SU(3) does not say anything about whether or not systems resonate, but it does say that if there is a resonant $\Sigma\pi$ isospin quintet, then it must be part of a unitary 27-plet. Therefore, one is not at all likely to stumble into an isolated $I = 2$ $\Sigma\pi$ resonance. And if $K^+p$ resonates, then it is part of a $Y = 2$ isospin triplet which in turn must be part of at least a unitary 27-plet. Even a $K^+n$ $I = 0$ resonance must belong to at least a decuplet [19]. At one time a CERN counter experiment by Dowell et al. [20] gave circumstantial evidence for a $Y_2(1550)$ but Kalbfleisch et al. have since done a similar experiment in a bubble chamber and cannot corroborate the effect [21]. There are often clues [22] that there may be something interesting with $S = -1$ at about 1550, but it is almost surely not in $I = 2$. Recently, Alston et al. using 1 to 2 BeV/c $K^-$ have also failed to find any $\Sigma\pi$ resonances in $I = 2$ below 2 BeV [23]. In summary, I think it is

rather striking that below 2 BeV there are now known N(1512) and (1688); $\Delta$(1238) and (1920); $\Lambda$(1405), (1520), and (1815); $\Sigma$(1385) and (1660), and $\Xi$(1530), but nothing in $Y_2$ or Kp.

A final attempt to summarize baryon systematics is presented in Fig. 4. Here we have drawn each charge multiplet as a single bar, and organized the figure like an energy-level diagram. One advantage of Fig. 4 over Fig. 3 is that there is room to label each bar with its established quantum numbers, and even to display the competing assignments of Table IIa and IIb for the two highest pion-nucleon resonances. The dotted line meandering horizontally across the picture separates the occurrences from their recurrences.

## FOOTNOTES AND REFERENCES

* This work was done under the auspices of the U. S. Atomic Energy Commission.

† Presented at the International Conference on Nucleon Structure, Stanford University, June 24-27, 1963.

1. Proceedings of the Conference on Recently Discovered Resonant Particles, Ohio University, Athens, Ohio, April 1963 (The University of Ohio Press, 1963).
2. W. H. Barkas, J. N. Dyer, and H. H. Heckman, Resolution of the $\Sigma$ Mass Anomaly, Phys. Rev. Letters 11, 26 (1963).
3. S. Coleman and S. L. Glashow, Phys. Rev. Letters 6, 423 (1961).
4. P. E. Schlein, D. D. Carmony, G. M. Pjerrou, W. E. Slater, D. H. Stork, and H. K. Ticho, $J^P$ Determination of the $\Xi\pi$ Resonance (1.530 GeV)* (UCLA preprint); this result is in conflict with the larger $\Gamma$ reported by J. Leitner on behalf of P. L. Connolly et al. (BNL/Syracuse) in reference 1.
5. W. H. Barkas and A. H. Rosenfeld, Data for Particle Physics, UCRL-8030 Rev., April 1963.
6. See, for example, J. M. Blatt and V. F. Weisskopf, Theoretical Nuclear Physics (John Wiley & Sons, Co., New York, 1952), p. 535.
7. Robert Huff, A Theorem of Maximum Complexity for the Angular Distribution of Decay Products, Alvarez Physics Note, Memo No. 449, April 1963 (unpublished).
8. M. Ferro-Luzzi, R. D. Tripp, and M. B. Watson, Phys. Rev. Letters 8, 28 (1962).

9. R. D. Tripp, M. B. Watson, and M. Ferro-Luzzi, Phys. Rev. Letters 8, 175 (1962); M. B. Watson, M. Ferro-Luzzi, and R. D. Tripp, Analysis of $Y_0^*(1520)$ and Determination of the $\Sigma$ Parity, UCRL-10542, January 15, 1963 (to be published in Phys. Rev.)

10. J. Shafer, D. Huwe, and J. Murray, Phys. Rev. Letters 10, 179 (1963).

11. M. Gell-Mann, in Proceedings of the International Conference on High Energy Physics (CERN, Geneva, 1962), p. 805.

12. N. Byers and S. Fenster, Phys. Rev. Letters 11, 52 (1963).

13. A. N. Diddens, E. W. Jenkins, T. F. Kycia, and K. F. Riley, Phys. Rev. Letters 10, 262 (1963).

14. A. H. Rosenfeld, Proceedings of the 1962 Varenna Summer School, in Nuovo Cimento (supplement to be published, 1963) and Strongly Interacting Particles and Resonances, UCRL-10492, August 1962.

15. T. F. Kycia and K. F. Riley, Phys. Rev. Letters 10, 266 (1963).

16. P. Carruthers, Phys. Rev. Letters 10, 538 and 540 (1963).

17. A. H. Rosenfeld and S. G. Wojcicki, Alvarez Physics Note, Memo 448, April 23, 1963 (unpublished).

18. S. L. Glashow and A. H. Rosenfeld, Phys. Rev. Letters 10, 192 (1963).

19. S. L. Glashow and J. J. Sakuri, Nuovo Cimento 25, 337 (1962).

20. J. D. Dowell, W. Koch, B. Leontic, A. Lundby, R. Meunier, J. P. Stroot, and M. Szeptycka, Phys. Letters 1, 53 (1963).

21. G. R. Kalbfleisch, G. Alexander, O. I. Dahl, D. H. Miller, A. Rittenberg, and G. A. Smith, Phys. Letters 4, 225 (1963).

22. See for example the work of C. Baltay et al., on $\bar{p}p \Rightarrow \Sigma_\delta \bar{\Sigma}_\delta$, Phys. Rev. Letters 11, 32 (1963).

23. M. H. Alston, A. Barbaro-Galtieri, A. H. Rosenfeld, and S. G. Wojcicki, Bull. Am. Phys. Soc. 8, 348 (1963).

Table I. Reported values of the $\Xi^-$ mass

| Mass (MeV) | Reference |
|---|---|
| 1318.4 ± 1.2 | W. H. Barkas and A. H. Rosenfeld, reference 5 |
| 1321.0 ± 0.5 | L. P. Bertanza et al., Phys. Rev. Letters 9, 229 (1962). |
| 1322 ± ? | F. T. Solmitz, J. P. Berge, J. R. Hubbard, M. L. Stevenson, and S. G. Wojcicki, Lawrence Radiation Laboratory, private communication. |
| 1321.1 ± 0.65 | H. Scheider, Phys. Letters 4, 360 (1963). |

Table IIa. The five best established nonstrange baryons, plus simplest guesses for the new resonances reported by Diddens et al.

| State | $J^P = (\ell - 1/2)^P$ | Angular momentum and parity | $J^P = (\ell + 1/2)^P$ | State |
|---|---|---|---|---|
| None | | S-wave = $0^-$ | $1/2^-$ | None |
| $N_\alpha(938)$ | $1/2^+$ | P-wave = $1^+$ | $3/2^+$ | $\Delta_\delta(1238)$ |
| $N_\gamma(1512)$ | $3/2^-$ | D-wave = $2^-$ | $5/2^-$ | None |
| $N_\alpha^{II}(1688)$ | $5/2^+$ | F-wave = $3^+$ | $7/2^+$ | $\Delta_\delta^{II}(1920)$ |
| None | $7/2^-$ | G-wave = $4^-$ | $9/2^-$ | None |
| $[N_\alpha^{III}(2160)\ ?\ ]$ | $9/2^+$ | H-wave = $5^+$ | $11/2^+$ | $[\Delta_\delta^{III}(2360)\ ?\ ]$ |

Table IIb. Alternative assignments of the nonstrange baryons. Here $\Delta(1640)$ represents the $\pi^+p$ shoulder at $T_\pi = 850$ MeV.

| State | $J^P = (-1/2)^P$ | Angular momentum and parity | $J^P = (+1/2)^P$ | State: Regge choice displayed in Fig. 2b. | State: Kycia-Riley choice, Ref. [15] |
|---|---|---|---|---|---|
| None | — | S-wave = $0^-$ | $1/2^-$ | $\Delta_\beta(1640)$ | None |
| $N_\alpha(938)$ | $1/2^+$ | P-wave = $1^+$ | $3/2^+$ | $\longleftarrow$ $\Delta_\delta(1238)$ | $\longrightarrow$ |
| $N_\gamma(1512)$ | $3/2^-$ | D-wave = $2^-$ | $5/2^-$ | $\Delta_\beta^{II}(2360)$ | $\Delta_{\beta+2}(1640)$ |
| $N_\alpha^{II}(1688)$ | $5/2^+$ | F-wave = $3^+$ | $7/2^+$ | $\longleftarrow$ $\Delta_\delta^{II}(1920)$ | $\longrightarrow$ |
| $N_\alpha^{II}(2160)$ | $7/2^-$ | G-wave = $4^-$ | $9/2^-$ | — | $\Delta_{\beta+4}(2360)$ |

Table VI.
TENTATIVE DATA ON STRONGLY INTERACTING STATES (April 1963, A. H. Rosenfeld)

| Particle | Established quantum No. $I(J^{PG})$ | Possible assignment: Quantum No. $I(J^{PG})$ | Possible assignment: Regge[1] trajectory | Mass (MeV) | $\Gamma$[2] (MeV) | Mass$^2$ (BeV)$^2$ | Dominant decays: Mode | % | Q[4] (MeV) | p or $p_{max}$ (MeV/c) |
|---|---|---|---|---|---|---|---|---|---|---|
| $K_1K_1$ | $0(J_{even}^{++})$ | $0(0^{++})$ | $+\omega_\alpha$ | $\sim 2m_K$ | ? | | Even number of pions $K\bar{K}(K_1K_1, K_2K_2$, not $K_1K_2)$ | | <0 | <0 |
| f = Vacuum ? | $0(\geq 2^{++})$ | $0(2^{++})$ | $+\omega_\alpha$ | 1250 | 75 | 1.56 | $2\pi$ | large | 980 | 690 |
| | | | | | | | $4\pi$ | < 30 | 710 | 550 |
| | | | | | | | $K\bar{K}(K_1K_1, K_2K_2$, not $K_1K_2)$ | ? | 256 | 380 |
| $\eta$ | $0(0^{-+})$ | | $+\omega_\beta$ | 548 | < 10 | .30 | $\pi^+\pi^-\pi^0$ | 23 | 134 | 174 |
| | | | | | | | $\pi^0\pi^0\pi^0$[3] | 39 | 143 | 182 |
| | | | | | | | $\pi^+\pi^-\gamma$ | 7 | 269 | 235 |
| | | | | | | | $\gamma\gamma$ | 31 | 548 | 274 |
| $\omega$ | $0(1^{--})$ | | $-\omega_\gamma$ | 782 | < 15 | .62 | $\pi^+\pi^-\pi^0$[3,5] | 84 | 368 | 326 |
| | | | | | | | $\pi^0\gamma$ | 12±4 | 647 | 379 |
| | | | | | | | $\pi^+\pi^-$ | 4 | 503 | 364 |
| $\phi$ | $0(J_{odd}^{--})$ | $0(1^{--})$ | $-\omega_\gamma$ | 1020 | < 5 | 1.04 | $K\bar{K}(K_1K_2$, not $K_1K_1$, $K_2K_2)$ | | 24 | 111 |
| | | | | | | | Odd number of pions | | | |
| $\pi$ $\pi^0$ | $1(0^{--})$ | | $-\pi_\beta$ | $\pi^0$ 135 | 0 | 0.018 | $\pi^0 \to \gamma\gamma$[6] | 100 | 135 | 67 |
| $\pi$ $\pi^\pm$ | | | | $\pi^\pm$ 140 | 0 | .02 | $\pi^\pm \to \mu\nu$ | 58 | 34 | 30 |
| $\rho$ | $1(1^{-+})$ | | $+\pi_\gamma$ | 750 | 100 | .56 | $\pi\pi$[3] (p-wave) | 100 | 471 | 348 |
| K $K^0$ | $\frac{1}{2}(0^-)$ | | $\kappa_\beta$ | $K^0$ 498 | 0 | .24 | $K_1^0 \to \pi^+\pi^-$[6] | $2/3K_1$ | 219 | 206 |
| K $K^\pm$ | | | | $K^\pm$ 494 | 0 | | $K^\pm \to \mu\nu$ | 58 | 388 | 236 |
| $K^*_{1/2}$(888) | $\frac{1}{2}(1^-)$ | | $\kappa_\gamma$ | 888 | 50 | .78 | $K\pi$(p-wave) | 100 | 251($K^0\pi^-$) | 283 |
| $K^*_{1/2}$(725) | $\frac{1}{2}$(?) | ? | ? | 725 | < 15 | .53 | $K\pi$ | ? | 101($K^-\pi^0$) | 161 |
| N n | $\frac{1}{2}(\frac{1}{2}+)$ | | $N_\alpha$ | n 940 | 0 | .88 | $e^-\bar{\nu}p$[6] | 100 | .78 | 1.2 |
| N p | | | | p 938 | | | | – | – | – |
| $N^*_{1/2}$(1688)="900 MeV $\pi p$" | | $\frac{1}{2}(\frac{5}{2}+)$ | $N^{II}_\alpha$ | 1688 | 100 | 2.84 | $N\pi$(f-wave) | 80 | 610 | 572 |
| | | | | | | | $\Lambda K$(f-wave) | < 2 | 76 | 235 |
| $N^*_{1/2}$(1512)="600 MeV $\pi p$" | | $\frac{1}{2}(\frac{3}{2}-)$ | $N_\gamma$ | 1512 | 100 | 2.28 | $N\pi$(d-wave) | 80 | 434($\pi^-p$) | 450 |
| $N^*_{3/2}$(1238)="Isobar" | | $\frac{3}{2}(\frac{3}{2}+)$ | $\Delta_\delta$ | 1238 | 100 | 1.53 | $N\pi$(p-wave) | 100 | 160($\pi^-p$) | 233 |
| $N^*_{3/2}$(1920) | $\frac{3}{2}(\frac{7}{2})$ | $\frac{3}{2}(\frac{7}{2}+)$ | $\Delta^{II}_\delta$ | 1920 | ~200 | 3.69 | $N\pi$ | 30 | 842($\pi^-p$) | 722 |
| | | | | | | | $\Sigma K$ | < 4 | 233 | 425 |
| $\Lambda$ | $0(\frac{1}{2}+)$ | | $\Lambda_\alpha$ | 1115 | 0 | 1.24 | $\pi^-p$[6] | 67 | 38 | 100 |
| $Y^*_0$(1815) | $0(J\geq\frac{5}{2})$ | $0(\frac{5}{2}+)$ | $\Lambda_\alpha$ | 1815 | 120 | 3.29 | $\bar{K}N$ | 60 | 383 | 541 |
| | | | | | | | $\Sigma\pi$ | <33 | 490 | 504 |
| $Y^*_0$(1405) | 0(?) | $0(\frac{1}{2}-)$ | $\Lambda_\beta$ | 1405 | 50[5] | 1.97 | $\Sigma\pi$ | {100} | 69($\Sigma^\mp\pi^\pm$) | 144 |
| | | | | | | | $\Lambda 2\pi$ | | 10($\Lambda\pi^+\pi^-$) | 69 |
| $Y^*_0$(1520) | $0(\frac{3}{2}-)$ | | $\Lambda_\gamma$ | 1520 | 16 | 2.31 | $\Sigma\pi$(d-wave) | 55 | 194($\Sigma^0\pi^0$) | 267 |
| | | | | | | | $KN$(d-wave) | 30 | 88($K^-p$) | 244 |
| | | | | | | | $\Lambda 2\pi$ | 15 | 125($\Lambda\pi^+\pi^-$) | 253 |
| $\Sigma$ $\Sigma^+$ | $(\frac{1}{2}+)$ | | $\Sigma_\alpha$ | 1189 | 0 | 1.42 | $n\pi^+$[6] | 50 | 110 | 185 |
| $\Sigma$ $\Sigma^0$ | | | | 1193 | 0 | 1.42 | $\Lambda\gamma$ | 100 | 76 | 74 |
| $\Sigma$ $\Sigma^-$ | | | | 1197.4 | 0 | 1.42 | $n\pi^-$ | 100 | 117 | 192 |
| $Y^*_1$(1385) | $1(J\geq\frac{3}{2})$ | $1(\frac{3}{2}+)$ | $\Sigma_\delta$ | 1385 | 50 | 1.92 | $\Lambda\pi$ | 98 | 135($\Lambda\pi^0$) | 210 |
| | | | | | | | $\Sigma\pi$ | 4±4 | 49($\Sigma^-\pi^+$) | 119 |
| $Y^*_1$(1660) | $1(\frac{3}{2})$ | $1(\frac{3}{2}-)$ | $\Sigma_\gamma$ | 1660 | 40 | 2.76 | $\bar{K}N$ | ~10 | 225 | 406 |
| | | | | | | | $\Sigma\pi$ | 25 | 335 | 386 |
| | | | | | | | $\Lambda\pi$ | 30 | 410 | 441 |
| | | | | | | | $\Sigma\pi\pi$ | 20 | 200 | 328 |
| | | | | | | | $\Lambda\pi\pi$ | 15 | 275 | 394 |
| $\Xi$ $\Xi^0$ | $\frac{1}{2}(\frac{1}{2}?)$ | $\frac{1}{2}(\frac{1}{2}+)$ | $\Xi_\alpha$ | ? | 0 | 1.72 | $\Lambda\pi^0$[6] | – | | |
| $\Xi$ $\Xi^-$ | | | | 1321 | | | $\Lambda\pi^-$ | – | 66 | 138 |
| $\Xi^*$(1530) | $\frac{1}{2}(\frac{3}{2}+)$ | $\frac{1}{2}(\frac{3}{2}+)$ | $\Xi_\delta$ | 1530 | <7 | 2.34 | $\Xi\pi$ | 100 | 74($\Xi^-\pi^0$) | 148 |

MUB-1358

FOOTNOTES (Table VI.)

? Means data that either I have not seen, or of which I am not yet convinced.

[1] The reader can use the data on p. 1 without reference to this shorthand notation. The first (and perhaps the only useful) contraction comes in choosing a single symbol to denote baryon number B, strangeness S, and I-spin I. Thus for the S = 0 meson with I = 0 (like $\omega$) we chose $\omega$. For the S = 0 meson with I = 1 (like $\pi$, $\rho$) we chose $\pi$. For K and $K^*_{1/2}$ we chose a Greek $\kappa$. Suggestive names ($N, \Lambda, \Sigma, \Xi$) existed for the baryons with I = 1/2, 0, and 1. For I = 3/2 [e.g., the $N^*_{3/2}$ ($3/2^+$, 1238) and $N^*_{3/2}$ (1922) isobars], we invent symbol $\Delta$; if $\Xi^*_{3/2}$ shows up, we suggest O (omicron). One shock is that $\Lambda$ (I = 0) now stands for something that can break up into $\Sigma\pi$, but is forbidden by conservation of I to break up into $\Lambda$ and a single $\pi$.

The symbols above are useful independent of the idea of a Regge trajectory. In addition, the Regge conjecture suggests that particles (e.g., $\omega$, N, $\Delta$, etc.) having the same parity, but J-values differing by 2, can lie in the same trajectory. To emphasize this point, and to further condense the notation, we suggest the following subscripts to denote parity and a string of J's differing by 2:

| Subscript | For mesons | For baryons |
|---|---|---|
| $\alpha$ | $0^+$, $2^+ \cdots$ (e.g., vacuum or ABC) | $\frac{1}{2}+$, $\frac{5}{2}+, \cdots$ (thus p = $N_\alpha$) |
| $\beta$ | $0^-$, $2^- \cdots$ (e.g., $\pi$ meson) | $\frac{1}{2}-$, $\frac{5}{2}-, \cdots$ |
| $\gamma$ | $1^-$, $3^- \cdots$ ($\gamma$ for "vector") | $\frac{3}{2}-$, $\frac{7}{2}-, \cdots$ [e.g., $D_{3/2}Kp$ resonance $Y_0^*$ (1520)] |
| $\delta$ | $1^+$, $3^+ \cdots$ (none known) | $\frac{3}{2}+$, $\frac{7}{2}+ \cdots$ (e.g., the 3/2, 3/2 isobar $\Delta_\delta$) |

G parity is written as a prescript (this avoids confusion with the charge of a particle). In the past it has been conventional to use an asterisk to indicate an excited state; instead we use a Roman superscript to indicate a rotational recurrence. Thus the $\alpha$-baryons are written $N_\alpha$ for the proton ($J^P = \frac{1}{2}^+$), and $N_\alpha^{II}$ (1688) for the 900-MeV $\pi N$ resonance, which is known to have J = 5/2 and which we guess has positive parity and is the "second occurrence" of $N_\alpha$.

Where its properties are essentially unknown, a particle has been given the simplest possible assignment merely because it had to be listed somewhere.

This notation was evolved in conversations with G. F. Chew and M. Gell-Mann.

[2] $\Gamma$ = empirical full width at half-max with background substracted.

[3] For analysis of possible neutral decay modes, see Tables 2 and 3 in G of R. Lynch, Proc. Phys. Soc. (London) 80, 46 (1962).

[4] Q values apply to decays to neutral particles (unless that mode is forbidden).

[5] See notes below on this particle.

[6] Common electromagnetic or weak decays are listed for convenience. The masses come from Table I, except for m($\Xi^-$) for which see note on $\Xi^-$ below.

References and Notes on Individual Particles

CERN means: Proceedings of the 1962 International Conference on High-Energy Physics (Interscience Publishers, Inc., New York, 1962). (For a complete bibliography to 11-7-61, see M. Lynn Stevenson, Bibliography on Pion-Pion Interaction, Lawrence Radiation Laboratory Report UCRL-9999, November 7, 1961 (unpublished)).

---

$K_1K_1$(1020) Erwin et al., CERN, p. 333; Bigi et al., CERN, p. 247; Alexander et al., CERN, p. 336; and Phys. Rev. Letters 9, 460 (1962).

f(1250) Selove et al., Phys. Rev. Letters 9, 272 (1962); Veillet et al., Phys. Rev. Letters 10, 29 (1963).

ABC? See Abashian, Booth, and Crowe, Phys. Rev. Letters 7, 35 (1961).

$\eta$ - Pevsner et al., Phys. Rev. Letters 7, 421, (1961); Bastien et al., Phys. Rev. Letters 8, 114 (1962); Carmony, Rosenfeld, and Van de Walle, Phys. Rev. Letters 8, 117, (1962); Rosenfeld, Carmony, and Van der Walle, Phys. Rev. Letters 8, 293 (1962); Pickup, Robinson, and Salant, Phys. Rev. Letters 8, 329 (1962); Chretien et al., Phys. Rev. Letters 9, 127 (1962); Fowler et al., Phys. Rev. Letters 10, (1963) discuss the $\pi^+\pi^-\gamma$ decay mode.

$\omega$ Maglić, Alvarez, Rosenfeld, and Stevenson, Phys. Rev. Letters 7, 178 (1961); Pevsner et al., Phys. Rev. Letters 7, 421 (1961); Stevenson, Alvarez, Maglić, and Rosenfeld, Phys. Rev. 125, 687 (1962); Xuong and Lynch, Phys. Rev. Letters 7, 327 (1961); Neutral mode from CERN, p. 713. The $\pi^+\pi^-$ decay mode is a private communication from Murray et al.

$\phi$ Bertanza et al., (CERN, p. 297, and Phys. Rev. Letters 9, 180, 1962 have reported a low-energy $K_1K_2$ interaction at about 1020 MeV. Possible explanation for this effect is a second $\omega(\omega_\gamma)$ and should not be confused with the $K_1K_1$ enhancement listed above.

$K^*$(880) Alston et al., Phys. Rev. Letters 6, 300 (1961); CERN, p. 291; Chinowski et al., Phys. Rev. Letters 9, 330 (1962).

$K^*$(730) Alexander, Kalbfleisch, Miller, and Smith, Phys. Rev. Letters 8, 447 (1962), and CERN, p. 320. The width ($\Gamma < 8$) is from Wojcicki, Kalbfleisch, and Alston (Bull. Am. Phys. Soc. 8, 341 (1962) and private communications.)

$\rho$ See summary by Stevenson, UCRL-9999, and CERN (1962).

$N^*$ For reviews see Falk-Vairant and Valladas, Rev. Mod. Phys. 33, 362 (1961); B. J. Moyer, Rev. Mod. Phys. 33, 367 (1961). For recent data, see J. Helland, Phys. Rev. Letters, 10, 27 (1963), and CERN, p. 4. The $\pi p$ phase shift for $N^*_{3/2}$ (1238) goes through 90 deg at 1238 MeV, but because of a $\pi\lambda^2$ factor, the $\pi p$ cross section reaches its maximum at 1225 MeV; see de Hoffman et al., Phys. Rev. 95, 1586 (1954); and Klepikov, Mescheryakov, and Sokolev, JINR-D-584, (1960). The established quantum numbers of the 600- and 900 MeV $\pi p$ states $N_{1/2}$(1512) and $N_{1/2}$(1688) are not given for lack of space; they are 3/2? and 5/2? At 1640 MeV invariant mass in $I = 3/2$ there is another shoulder, probably not a pure resonance.

$Y^*_0$(1815) Chamberlain, Crowe, Keefe, Kerth, Lemonick, Maung, and Zipf, Phys. Rev. 125, 1696 (1962); also D. Keefe, CERN, p. 368.

$Y^*_0$(1405) Alston et al., Phys. Rev. Letters 6, 698 (1961); Bastien et al., Phys. Rev. Letters 6, 702 (1961); Alexander et al., Phys. Rev. Letters 8, 460 (1962).

$Y^*_0$(1520) Ferro-Luzzi, Tripp, and Watson, Phys. Rev. Letters 8, 28 (1962); Tripp, Watson, and Ferro-Luzzi, Phys. Rev. Letters 8, 175 (1960); Watson, Ferro-Luzzi and Tripp, UCRL-10542 (Phys. Rev. - to be published).

$Y^*_1$(1385) Alston and Ferro-Luzzi, Rev. Mod. Phys. 3, 416 (1961). The following papers establish that $J>1/2$: Ely et al., Phys. Rev. Letters 7, 461 (1961); Bertanza et al. (BNL-Syracuse), Phys. Rev. Letters (to be published); Shafer, Huwe, and Murray (Berkeley) Phys. Rev. Letters (to be published). In addition, the following papers show that if $J = 3/2$, then $d_{3/2}$ is ruled out: Colley et al., Phys. Rev. 128, 1930 (1962); Shafer, Huwe, and Murray (Berkeley) Phys. Rev. Letters (to be published).

$Y^*_1$(1660) Alvarez et al., Phys. Rev. Letters 5, 184 (1963); Bastien and Berge, Phys. Rev. Letters 5, 188 (1963); Alexander et al., CERN, p. 320.

$\Xi^-$(1321) Mass from Bertanza et al., Phys. Rev. Letters 9, 229 (1962). Spin from Donald Stork, talk at New York APS meeting, Jan. 1963.

$\Xi^0$(1316) Mass from F. T. Solmitz, talk at Stanford APS meeting, Dec. 1962.

$\Xi^*_{1/2}$(1530) Pjerrou et al., Phys. Rev. Letters 9, 114 (1962); and CERN, p. 289; Bertanza et al. Phys. Rev. Letters 9, 180 (1962); and CERN, p. 279. (The J assignment is a preliminary private communication from the UCLA group. Specifically, $J = 1/2$ ruled out. $J = 3/2^-(d_{3/2})$ has a $\chi^2$ probability of $< 2\%$, but $J = 3/2^+$ fits satisfactorily.)

## FIGURE LEGENDS

Fig. 1. Masses of the stable baryon.

Fig. 2. Pion-nucleon total cross sections as a function of energy. The solid line represents $\pi^+p$ interactions where $I = 3/2$, so the peaks are labeled $\Delta$. The dashed line gives $\pi^-p$ interactions, and reflects both N and $\Delta$ resonances.

Fig. 3a. Possible quantum numbers for the baryons. Values of J corresponding to 1/2 (modulo two) are drawn with solid vertical lines, connected by solid lines to guide the eye; these lines may correspond to Regge trajectories. Dashed lines apply to values of $J = 3/2$ (modulo two). There is reasonably good evidence for the $J^P$ assignments for all the positive parity states except the two above 2000 MeV (the two baryons of Diddens et al.). However there is very little evidence for any of the negative parity states except $\Lambda(1520)$. The $J^P$ assignments for the nonstrange baryons corresponds to that of Table Ia.

Fig. 3b. Alternative assignments for the negative parity baryons, as shown in Table Ib.

Fig. 4. Possible quantum numbers for the baryon charge multiplets. Established $J^P$ values are listed for each particle; the experimental references are given in Table VI. The known baryons are all displayed as bands written $\alpha\alpha\alpha\alpha\alpha\alpha\alpha$, $\beta\beta\beta\beta\beta\beta\beta$, etc.; the hoped-for ones are written $\alpha\ \alpha\ \alpha\ \alpha$, $\beta\ \beta\ \beta\ \beta$, etc. and stable states are underlined. For a similar display for the mesons, see the next talk by D. H. Miller.

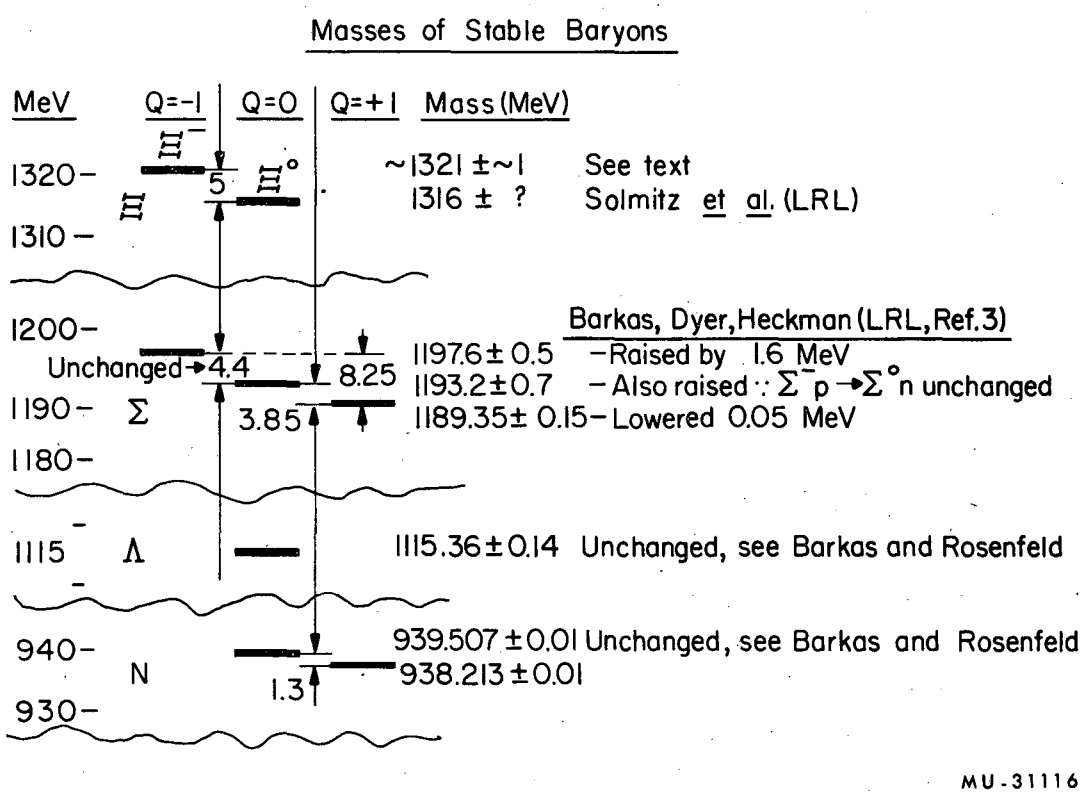
Masses of Stable Baryons
MeV
Q=-1
Q=0
Q=+1
Mass (MeV)
1320-
1310-
1200-
1190-
1180-
1115
940-
930-
Ξ
Ξ⁻
Ξ°
5
~1321 ±~1
See text
1316 ± ?
Solmitz et al. (LRL)
Barkas, Dyer, Heckman (LRL, Ref. 3)
Unchanged
4.4
8.25
3.85
Σ
1197.6 ± 0.5
-Raised by 1.6 MeV
1193.2 ± 0.7
-Also raised ∵ Σ⁻p → Σ°n unchanged
1189.35 ± 0.15
-Lowered 0.05 MeV
Λ
1115.36 ± 0.14
Unchanged, see Barkas and Rosenfeld
N
1.3
939.507 ± 0.01
Unchanged, see Barkas and Rosenfeld
938.213 ± 0.01
MU-31116

Fig. 1

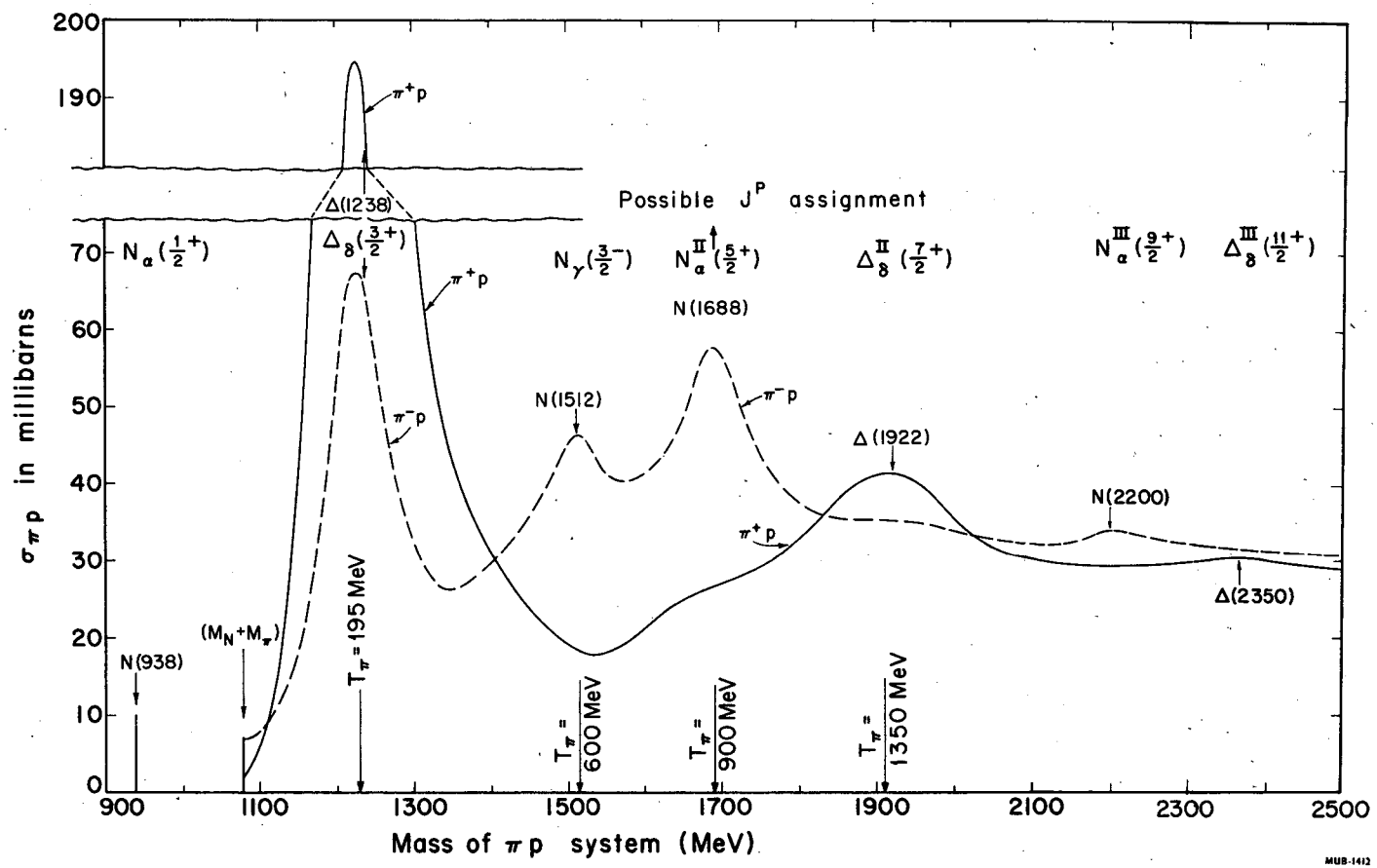
Possible $J^P$ assignment
$N_\alpha(\frac{1}{2}^+)$
$\Delta_\delta(\frac{3}{2}^+)$
$N_\gamma(\frac{3}{2}^-)$
$N_\alpha^{II}(\frac{5}{2}^+)$
$\Delta_\delta^{II}(\frac{7}{2}^+)$
$N_\alpha^{III}(\frac{9}{2}^+)$
$\Delta_\delta^{III}(\frac{11}{2}^+)$
$\Delta(1238)$
N(1688)
N(1512)
$\Delta(1922)$
N(2200)
$\Delta(2350)$
N(938)
$(M_N+M_\pi)$
$T_\pi = 195$ MeV
$T_\pi = 600$ MeV
$T_\pi = 900$ MeV
$T_\pi = 1350$ MeV
$\pi^+p$
$\pi^-p$
$\sigma_{\pi p}$ in millibarns
Mass of $\pi p$ system (MeV)
MUB-1412

Fig. 2

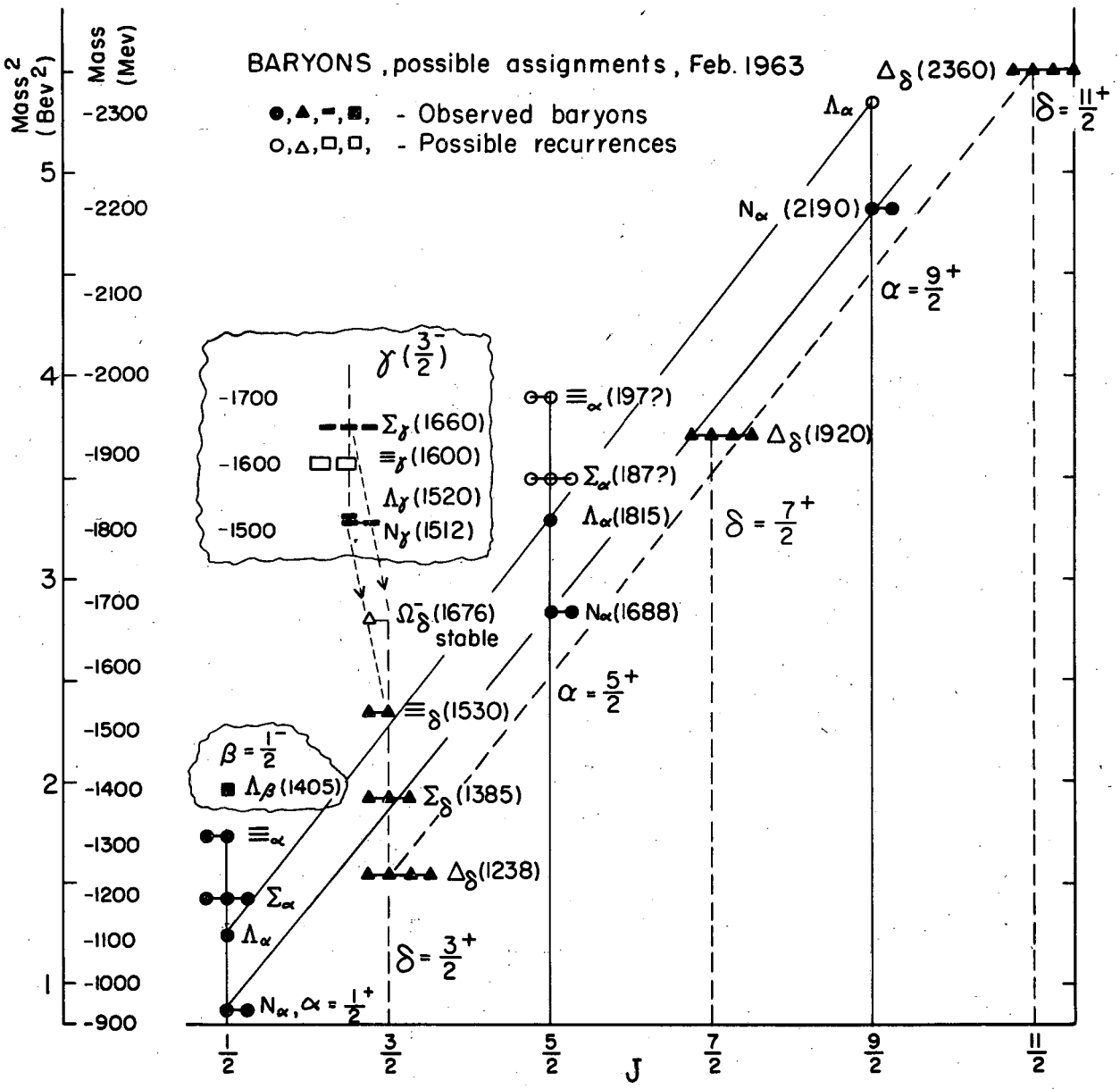
BARYONS, possible assignments, Feb. 1963
●,▲,▬,■, - Observed baryons
○,△,□,□, - Possible recurrences
Mass² (Bev²)
Mass (Mev)
J
$\Delta_\delta(2360)$
$\delta = \frac{11}{2}^+$
$\Lambda_\alpha$
$N_\alpha$ (2190)
$\alpha = \frac{9}{2}^+$
$\gamma(\frac{3}{2}^-)$
$\Sigma_\gamma(1660)$
$\Xi_\gamma(1600)$
$\Lambda_\gamma(1520)$
$N_\gamma(1512)$
$\Xi_\alpha$(197?)
$\Delta_\delta(1920)$
$\Sigma_\alpha$(187?)
$\Lambda_\alpha(1815)$
$\delta = \frac{7}{2}^+$
$\Omega^-_\delta(1676)$ stable
$N_\alpha(1688)$
$\alpha = \frac{5}{2}^+$
$\Xi_\delta(1530)$
$\beta = \frac{1}{2}^-$
$\Lambda_\beta(1405)$
$\Sigma_\delta(1385)$
$\Xi_\alpha$
$\Sigma_\alpha$
$\Delta_\delta(1238)$
$\Lambda_\alpha$
$\delta = \frac{3}{2}^+$
$N_\alpha, \alpha = \frac{1}{2}^+$
MUB-1632

Fig. 3a

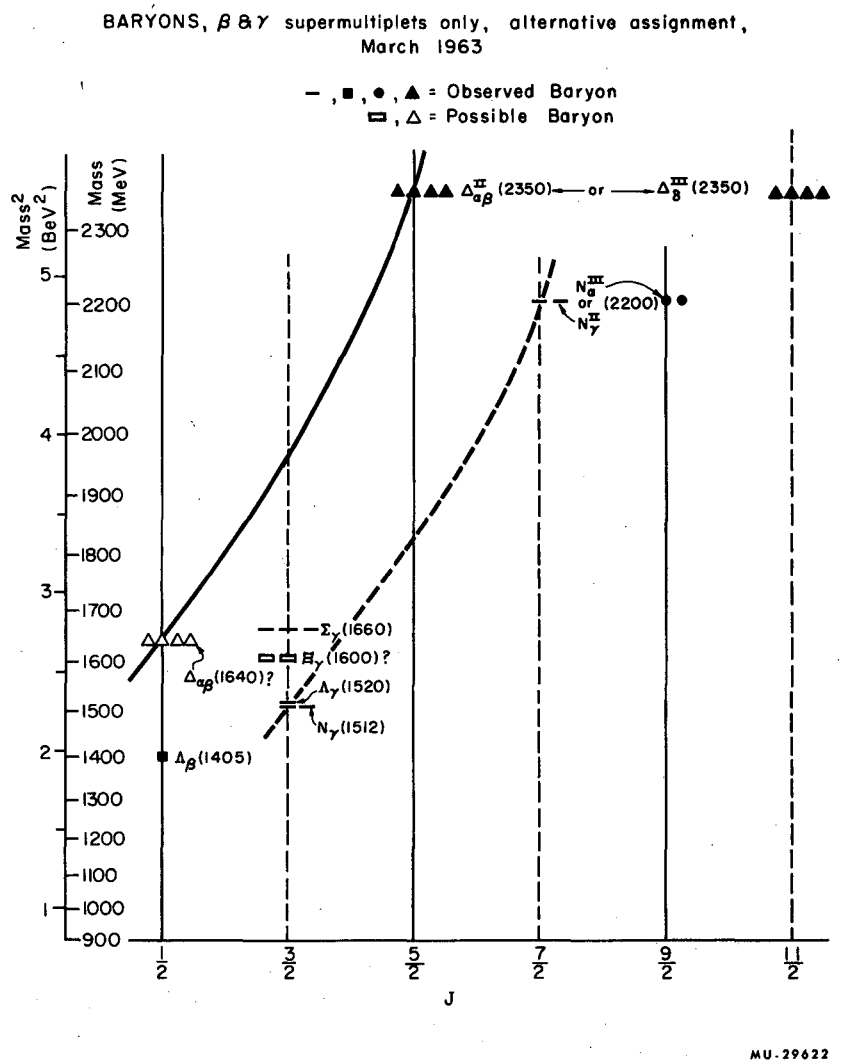
BARYONS, β & γ supermultiplets only, alternative assignment,
March 1963
— , ■ , ● , ▲ = Observed Baryon
▭ , △ = Possible Baryon
Mass² (BeV²)
Mass (MeV)
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
5
4
3
2
1
Δ^II_αβ (2350) or Δ^III_δ (2350)
N^III_α or (2200)
N^II_γ
Σ_γ (1660)
Ξ_γ (1600)?
Λ_γ (1520)
N_γ (1512)
Δ_αβ (1640)?
Δ_β (1405)
1/2
3/2
5/2
7/2
9/2
11/2
J
MU-29622

Fig. 3b

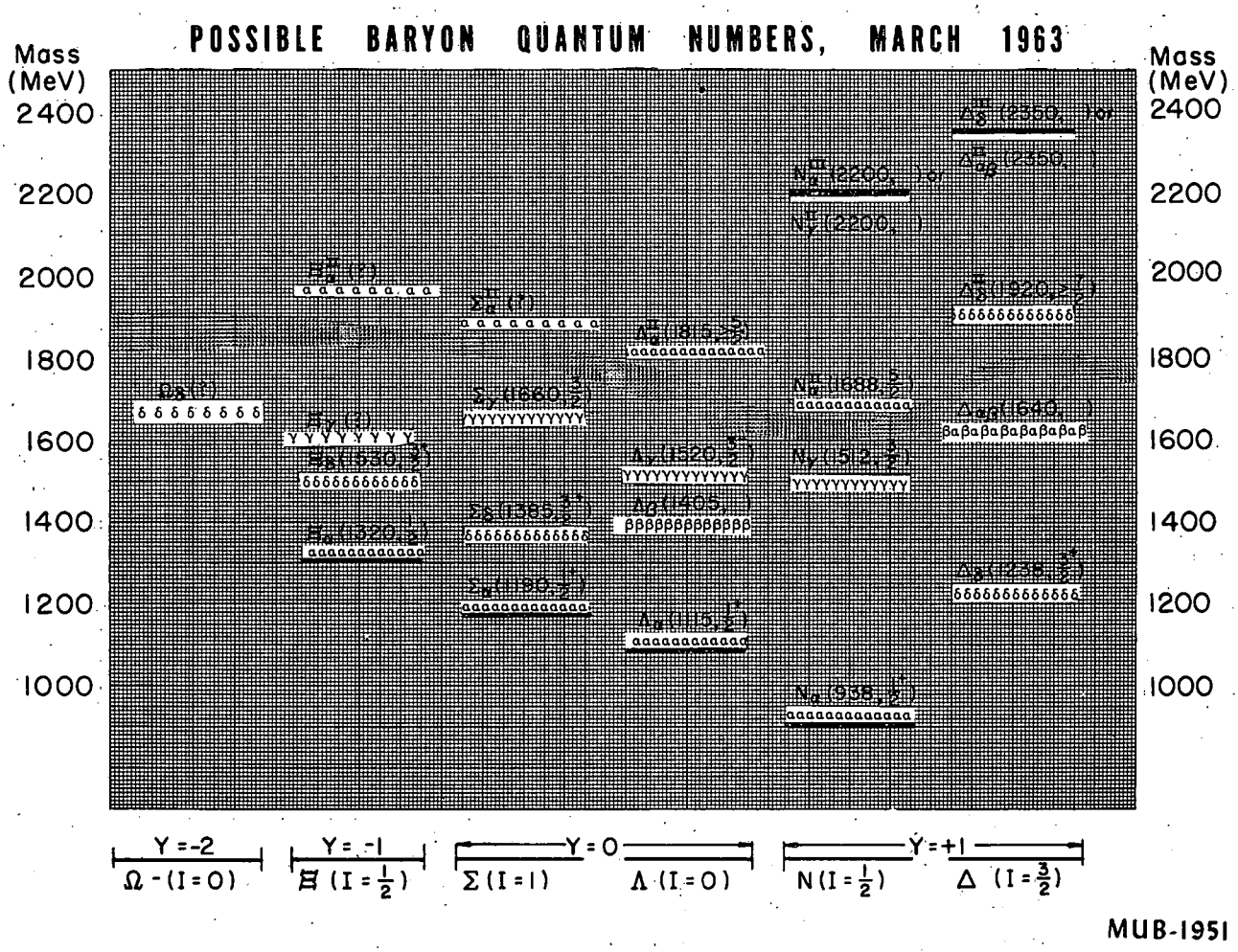
POSSIBLE BARYON QUANTUM NUMBERS, MARCH 1963
Mass (MeV)
2400
2200
2000
1800
1600
1400
1200
1000
Y = -2
Ω - (I = 0)
Y = -1
Ξ (I = 1/2)
Y = 0
Σ (I = 1)
Λ (I = 0)
Y = +1
N (I = 1/2)
Δ (I = 3/2)
MUB-1951

Fig. 4

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.