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NEW DIRECTIONS FOR NUCLEAR PHYSICS - A PERSONAL VIEW*

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I have been asked to talk about the future, but this is easier if we first remind ourselves of the past. Let me do so in a largely qualitative way.

It is now widely believed that the cosmos in which we live originated some 15 billion years ago with a so-called "big bang". In this big bang relativistic energies were presumably available because the large red shifts found for some objects in the sky indicate that they recede with relativistic energies. All the particles we know and those we still hope to discover were probably created in the very beginning; nowadays we hardly find enough letters in the Latin and Greek alphabets, including some superscripts and subscripts, to describe them all. We, who are the metastable descendants of this super-alphabet-soup, clearly have a natural interest in the particles which form our prehistory! A selection of these particles is shown in Fig. 1, which some of you may have seen before. It is interesting that practically all these particles now play a role in the context of this conference, starting with the widest state represented here, the Δ, down to the sharpest decaying state we know, the neutron. Of course, the longer the particles live the more we can "manipulate" them.

You have probably all heard of the evidence for new particle families, J/Ψ etc.; "charmed" particles may also exist with lifetimes expected to be intermediate between those of the π^0 and the K^0_S, as I have indicated in Fig. 1. If I were to continue the lifetime axis indefinitely, I would finally come to lower limits for the lifetime of the proton. (See, e.g., M. Goldhaber, Proc. Am. Phil. Soc. 119, 24 (1975).) The proton lives more than 10^{23} years no matter how it decays, and for specific decay modes much larger partial lifetime limits have been obtained. For the decay mode $p \to \mu + X$, Reines and Crouch (Phys. Rev. Lett. 32, 493 (1974)) have found a partial lifetime $\gtrsim 10^{30}$ years. Now of course as soon as experimentalists find such limits, theoreticians come along to tease us and predict that the proton ought to decay with just about this lifetime or maybe ten times more slowly. Pati and Salam (Phys. Rev. Lett. 31, 661 (1973)) have published such an idea. With such lifetimes, observation of even one event per year requires a very large detector, and this is one of our problems for the future: how can we build huge detectors that will not be swamped by backgrounds?

Even if the proton were absolutely stable, the nuclei we are built of would not necessarily live forever. You know of course that radioactive nuclei will disappear after a sufficiently long time, but there are many nuclei you normally don't think of as disappearing which will also disappear, e.g., all those for which we haven't yet found double beta decay no matter how hard we have looked because our detectors are not sufficiently sensitive. All

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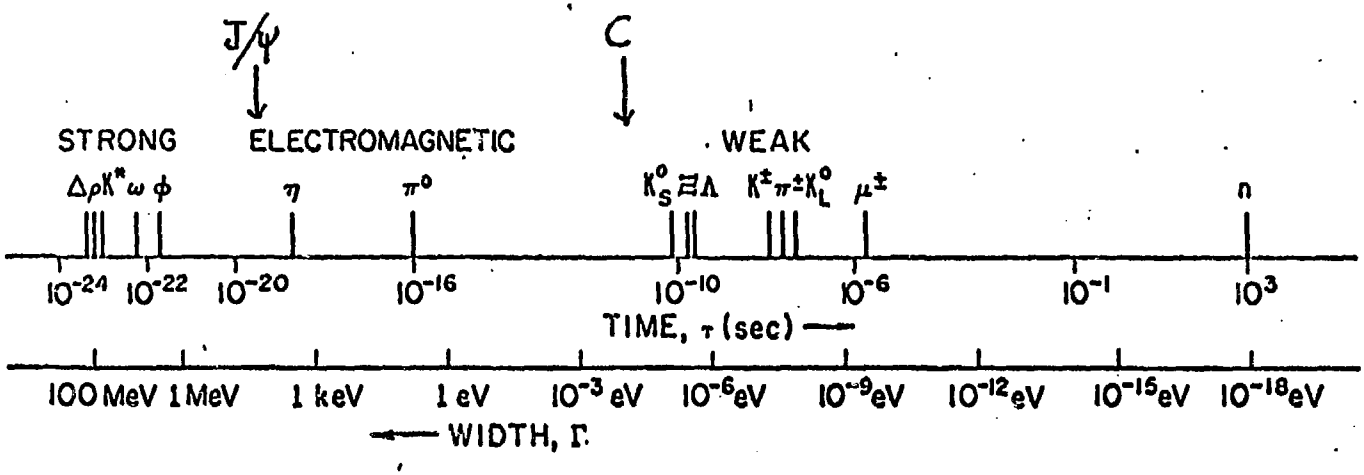

FIGURE 1

Lifetime (τ) for some of the "fundamental" particles and corresponding width (Γ). The interactions governing the decay of particles are strong, electromagnetic or weak, as indicated.

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the isobars removed by two in charge between which double beta decay is energetically possible, one way or the other, would be reduced, if you wait long enough, to a single one of that pair. We need better methods for measuring these very rare decays, searches involving very large quantities of material; maybe we should develop further the method we once used by building, e.g., huge calcium fluoride crystals. For other materials, too, attempts of this type might lead to results in this field. Where double beta decay results in a noble gas, the gas can be extracted from a very old mineral, and this has worked well because of negligible gas impurities. With more courage we could extract also non-gases and show that they have grown in the sample if we find either a) that the amounts of original impurities are negligible or b) that the chemical state of the decay end-product differs from that of the impurity; this depends on finding ways of distinguishing between decay product and impurity. Since modern mass spectrographs and other methods could, in principle, detect single atoms, extremely long lifetimes could, conceivably, be found. I believe that so far no one has had the courage to do this; it is probably a problem for the long-range future.

As I said, most of the particles represented in Fig. 1 play a role in the kind of physics that was discussed at this conference. Starting on the left with the delta, we heard in the talk by Weber that the original euphoria of three years ago concerning evidence for spectator Δ's did give rise to critical emphasis on backgrounds, and he is now optimistic that we know how to correct for some important backgrounds, especially in inclusive production. He also quoted some work in progress by A. S. Goldhaber and L. Kisslinger in which they try to come to grips with the important theoretical question, raised so often at this conference, of the transition from virtual to real particles.

It was perhaps naive of us to think that we could add up in one experiment results for $\pi^- + \Delta^{++}$ and $\pi^+ + \Delta^{++}$. We added these because of poor statistics, but, while $\pi^- + \Delta^{++}$ might form a reasonable vertex, we don't know anything about a triple-charge vertex and therefore perhaps should have treated these reactions separately. In fact the data had a very slight hint of a real effect for $\pi^- + \Delta^{++}$, which may have been washed out by averaging over other reactions, and this would be worth pursuing further. One might also try to find a possible choice of energies for the incoming particles at which they might be in resonance with the deltas. This might emphasize delta production if the incoming particles were not simultaneously in resonance with nucleons; since most of these resonances are rather wide, it will not be easy to choose useful resonances, but perhaps this is an approach worth pursuing.

We heard from Moniz that the mean free path of deltas is of the order of 1 fm; it might be interesting to study the production of deltas in nuclei (e.g., at Los Alamos proton energies) as a function of mass number because, if the delta cannot come out from very far, this will show up in the dependence of the production cross section on mass number; as far as I know such a study has not yet been made.

Some subjects we have heard about and will hear more about in the future are the many new kinds of spectroscopy that are emerging.

We heard about hyperfragments from Feshbach; there has also been a suggestion by A. A. Tyapkin (Dubna preprint) that, if charmed particles exist, then there might be nuclei corresponding to the hypernuclei but containing a charmed baryon instead of a hyperon, and these would have a much larger energy release. This would of course illustrate most explicitly that we have here a new quantum number which is conserved in strong interactions. Feshbach emphasized that we should look for hypernuclei in which a Σ^- or Σ^+ was formed instead of a Λ, but one problem is that in a nucleus with Z protons and N neutrons a Σ^- will very quickly be absorbed on a proton (making Λn), or correspondingly a Σ^+ on a neutron (making Λp). Therefore these states will be very wide, although still of considerable interest. The question arises whether there is a chance for the existence of sharp states containing a Σ^-. One possible state discussed in earlier conferences is $nn\Sigma^-$. There is still no good evidence for or against its existence. We might perhaps look at a reaction—this is a dream reaction—like $^3H + K^- \rightarrow nn\Sigma^- + \pi^+$, which would have a well-defined energy release if $nn\Sigma^-$ is a sharp state. Or, if a stable target is preferred, then $^4He + K^- \rightarrow nn\Sigma^- + p + \pi^+$ could be looked for, a more complicated reaction.

C. Dover, T. Londergan, and A. Gal are interested in trying to estimate the binding energy of the $nn\Sigma^-$ and other states, since something is known about these interactions if SU(3) arguments are used. But whether or not this state is bound, the chance that the more complicated $nn\Sigma^-\Sigma^-$ is bound is much larger. Here we have an α-particle-like structure which would clearly be bound more strongly. Still another super-α structure is $nn\Lambda\Lambda\Sigma^-\Sigma^-$, and you can go further. You can add two Ξ^-. By having chosen these charges correctly we have stabilized this super hypernucleus as far as strong interactions are concerned. Correspondingly you could have $pp\Sigma^+\Sigma^+\Lambda\Lambda\Xi^0\Xi^0$, and in this case you might go on adding charmed baryons, C^+C^+, and so on. So here are super alpha particles where you put everything into one pot, all with an S-wave function, and it is possible that these configurations would be strongly bound. Whether we can learn to calculate such things will be interesting to look into because for a while it will be very hard to produce anything of this kind. Maybe a fraction of the chain, e.g., $nn\Sigma^-\Sigma^-$, could be created by Ξ^- on neon in a bubble chamber, since Ξ^- beams have been produced. It could also be that in extremely high energy collisions, where we have already found that we can make antideuterons and anti-^3H, we might make such complex structures too. The mechanism for production of $\bar{D}$'s made in very high energy collisions is still incompletely understood. How are they formed dynamically? It could be that they are formed partly from $\bar{\Delta}$'s or other $\bar{N}^*$'s; if they are formed from such excited nucleons we can allow much higher relative momenta to form the deuterons. Maybe that would make it less astounding than the low momenta needed to form antideuterons from normal antiparticles. But that is still very much an open question and worth investigating further.

Another new spectroscopy still in its infancy is $\bar{B}B$ spectroscopy, in which an antibaryon and a baryon form states that are short-lived but still sufficiently well-defined for resonances to be seen. This idea was pioneered by I. S. Shapiro and his collaborators, and a

number of experiments have confirmed the existence of sharp states near the nucleon-antinucleon threshold, the first being those by Kycia and collaborators and by Kalogeropoulos and collaborators, which give fairly good proof that near the $\bar{N}N$ threshold there are states of this sort which are fairly sharp, only a few MeV wide. Recently Kalogeropoulos and collaborators have developed a technique at Brookhaven which involves recording the time of flight of antineutrons, and they hope to measure the position of such states very accurately. Since Shapiro's calculations still made a number of simplifying assumptions, more detailed calculations have recently been carried out at Brookhaven (C. Dover and M. Goldhaber, submitted to Phys. Rev. D). These calculations must be considered as only illustrative of what we ultimately hope to achieve as experiments and theory improve.

The main idea of these calculations, which treat not only $\bar{N}N$ but also $\bar{\Lambda}\Lambda$, $\bar{\Sigma}\Sigma$, and $\bar{\Xi}\Xi$ (the whole SU(3) baryon octet), is to take the one-boson exchange potentials that have been fitted to nucleon-nucleon scattering and change the sign of those terms ascribed to mesons of odd G-parity (like the ω). In this way we get strong attractive forces where for nucleons there is a repulsive core. In the absence of a proper relativistic field theory, the potential approach still remains a useful tool of some predictive value. With the strong attractive forces you get binding, and of course for very strong binding you do not trust the calculation at all, but near thresholds they are perhaps a good guide to what might exist. You shouldn't take the predictions too literally. The results shown in Fig. 2 should be considered only illustrative; probably the energies are good only to 100 or 200 MeV. Close to the threshold for $\bar{N} + N$, states are predicted that have perhaps already been observed. In going away from the threshold, the knowledge is less definite, and the calculation becomes less reliable the further one goes. The width also increases, and this gives rise to less well-defined states. These are, incidentally, estimated widths; in the spirit of these illustrative calculations further assumptions must be made about the annihilation region, and so on. Wide resonances are known in this general region, but whether they have anything to do with the calculated states remains to be shown; they would be expected to have a large partial width into $\bar{B} + B$ breakup. This gives an impetus to more experiments. If some time in the far future we shall have good data on both position and width of these resonances, we would have a very interesting check of the whole idea.

Just to keep you from being too optimistic, Fig. 3 shows a comparison of some nucleon-antinucleon states calculated from the potential of Nagels, Rijken, and deSwart with some states calculated from the potential of Bryan and Phillips. You see that with two different potentials, both taken seriously in the literature, the states predicted move around considerably; thus, a few hundred MeV is about the best you can have as a guide. If one day we were to have experimental confirmation of these states, that would be of great importance to the ultimate understanding of the origins of the nucleon-nucleon force.

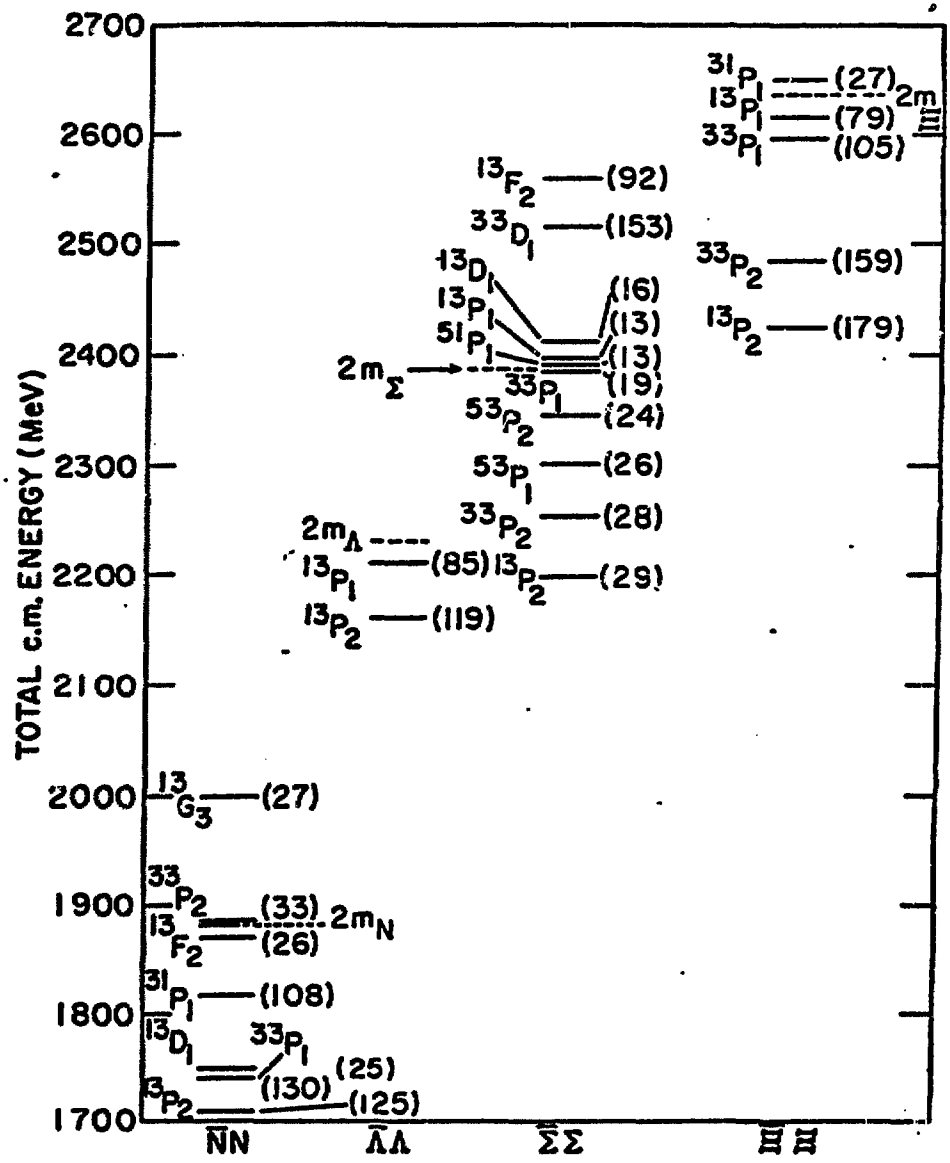

Fig. 2. Calculated energy spectra of $\bar{B}$-B states, using a potential obtained by the G-parity transformation from the BB potential of Nagels, Rijken and deSwart (Nijmegen preprint). The mesons corresponding to the states $^{2I+1,2S+1}L_J$ have parity $\pi = (-1)^{L+1}$, charge parity $C = (-1)^{L+S}$ and G-parity $G = C(-1)^{I}$. Bound L=0 states and the deeply bound $^{13}P_0$ states are omitted. The numbers in parentheses are very crude estimates of the total width of each state (in MeV).

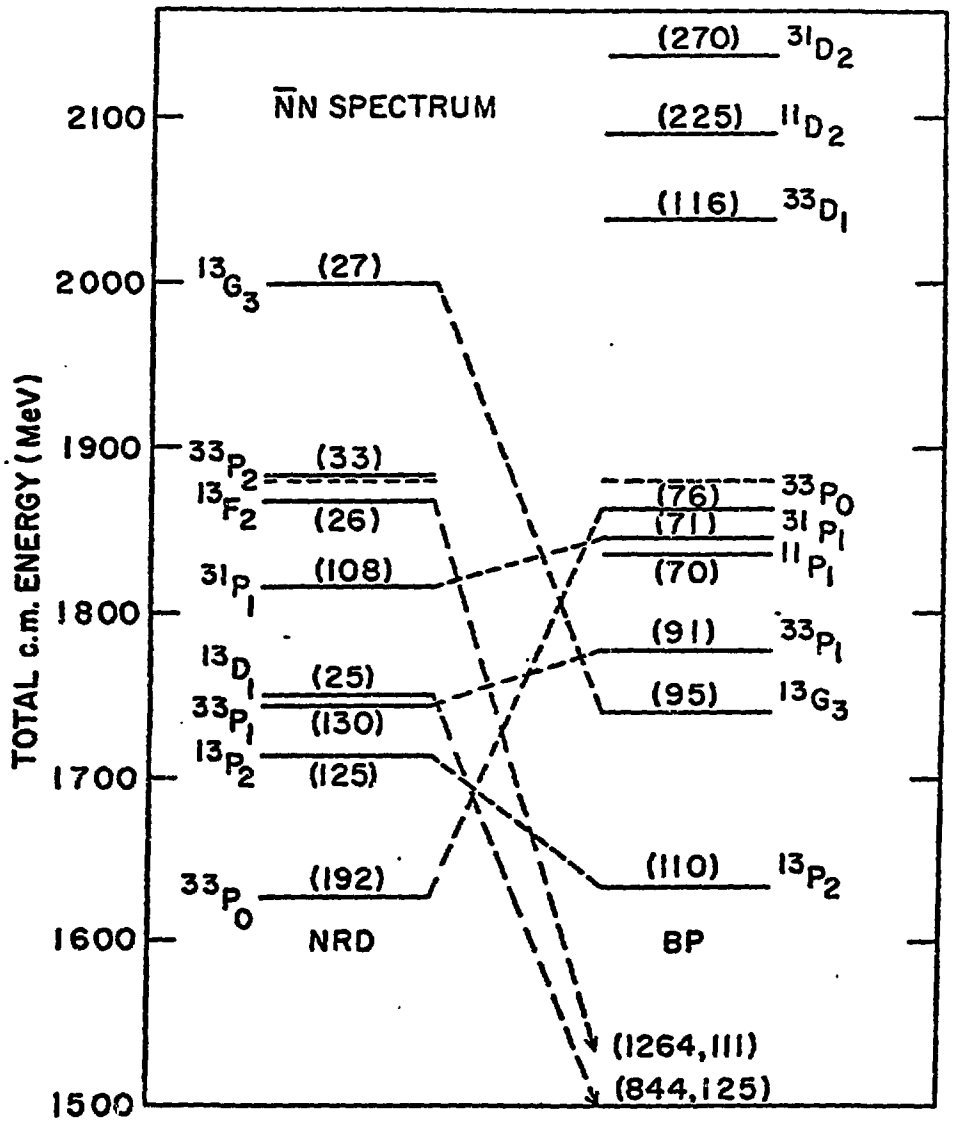

Fig. 3. Comparison of two different $\bar{N}N$ potential models. The right-hand spectrum [BP] follows from the Bryan-Phillips potential (see C. B. Dover, Proceedings of the Fourth International Symposium on $\bar{N}N$ Interactions, Syracuse, May 2-4, 1975, Vol. II Chap. VIII, pp. 37-91).

The dynamics of the formation of $\bar{B}B$ states in high energy collisions may have features in common with the dynamics of the formation of $\bar{D}$. The two "spectroscopies" can probably learn from each other. $\bar{B}B$ states would have played an important role in the big bang if it had been originally symmetrical in B and $\bar{B}$. G. Steigman has recently reviewed the evidence against such an initial symmetry between matter and antimatter in our cosmos (to appear in Am. Rev. of Astron. and Astrophys., Vol. 14).

One thing we have become aware of at this conference is a great increase in precision in reactions involving pions, either pion absorption giving very exact gamma energies or production of pions very close to threshold. We have heard from Tzara, and also G. T. Emery (Phys. Lett. 60, 351 (1976)) has published ideas, on how you might dream of doing precision work in the future. At the Indiana cyclotron, for example, with a resolution that Emery puts at 30 keV, one could study the production of negative pions in bound states, in S states, and sometimes in states not yet reached because the π^- mesons get absorbed from higher states. In this way we could also reach states around a nucleus that is normally not stable. Similarly, there are plans at the Bates Electron Linac to study e,e' reactions leading to bound states of π^-.

In past conferences you have often heard the cliché that not only can elementary particles be used to study nuclei but also that the nucleus is a laboratory for elementary particles. There are many examples of this. A thought that might be worth pursuing is the following: Let us expose a highly deformed odd-A nucleus aligned in some crystal (at low temperature) with the long axis alternatively parallel or at right angles to the direction of a beam of protons or pions, etc. This might be a very interesting way to study A-dependent effects because in considering such effects we are still often puzzled as to whether we are dealing with a complicated process, where simultaneous interactions with closely neighboring nucleons take place, or with multiple successive processes; in this way we might see a difference between such effects, but as far as I know such a search has not yet been started. Nuclear chemists might even be interested in studying fragments coming out of differently aligned nuclei. This might serve as a further check on their Monte Carlo calculations.

Let me finish by saying a few words about other far-out matters. Nuclear physicists have long accepted that neutron stars are in some way big nuclei and that these big nuclei may contain besides π-meson condensates Λ's and Σ's, because all the levels for neutrons are so highly filled that it pays to make new Fermi-particles, even considerably heavier ones. Now if charm is confirmed, we may also have to take into account a "charmed sea" of particles in neutron stars. This will deserve a closer look if and when charmed particles become a reality.

Another question concerns the existence of very heavy nuclei. By now many people have considered this question from a theoretical and experimental point of view. There is a possibility of a track of a very heavy nucleus: the "magnetic monopole" track reported by Price and his collaborators has an alternative interpretation.

In a recent talk at the New York meeting of the American Physical Society Price reported that a nucleus with $Z \approx 50-80$ and $A > 2000$ could be compatible with their data. If this interpretation remains viable, it will be up to us nuclear physicists to see whether we can in any way explain how a nucleus that heavy lives long enough to get to us from outer space, either directly or as a fragment produced in the atmosphere from a nucleus of still larger Z and A. I have no very good idea to offer on this, and I leave it with you as a little exercise for the future.

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