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TRENDS IN NUCLEAR PHYSICS — WHAT CAN WE LEARN FROM HIGH ENERGY INTERACTIONS?*

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It is useful for scientists to pause from time to time, to look back at past achievements, to take note of the direction in which their field of research is going and to ask the perhaps elusive question: What are our goals? The interconnection of different fields of research may lead through unforeseen progress in one field to a redefinition of goals in another field, or to a more realistic restatement of those goals, which may turn out to be more complex and more ambitious than we had at first imagined. Thus nuclear physicists cannot ignore progress in the field of elementary particles, usually connected with high energy physics. High energy interactions with nuclei can help in the understanding of nuclear structure and in return help with the solution of problems in the elementary particle field. The walls which have been created between the low and high energy fields should be made as permeable as possible.

For practical reasons the low energy interactions of those new short-lived particles which are produced by high energy interactions, such as μ, π, K mesons, etc., may be considered as part of the high energy field. Like other high energy physics experimentation it implies, as a rule, that one first has to convince a committee of the value of an experiment before one can do it. Some think this is a little like going to confession before one has sinned.

When Rutherford first postulated the existence of a nucleus of the atom in 1911, he had in mind a massive, positively charged, point particle. Later it was realized that the nucleus must have finite extension, a shape that is not necessarily spherical, variable density of charge and matter, and, underlying all this, a complicated internal structure.

When a high energy particle interacts with a nucleus, it can produce, because of its rapid motion, an "instantaneous" picture of its constituents. High energy electrons and protons have been used to study the details of the distribution of charge and matter, or more specifically proton and neutron distribution, in the nucleus. Electrons, which measure the charge distribution, have the advantage that they do not interact strongly with nucleons, and there is therefore no need for higher-order corrections for multiple interactions. On the other hand, strongly interacting particles, e.g., protons or pions, give us information about the nucleon distribution. These are very complex and active fields of research, in which an important goal is comparison of the experimentally obtained distributions with those calculated from the nuclear shell model.

The charged particles produced by accelerators often show interesting interactions if they live long enough to come to rest in matter. In particular, if they are negatively charged, they may end up in atomic orbits of nuclei whose charge and mass number, Z^A, the experimenter can choose. The known negative particles that live long enough, because they do not decay by a strong or electromagnetic interaction, are, in order of increasing mass, μ^-, π^-, K^-, $\bar{p}$, Σ^-, Ξ^-, Ω^-. (Fig. 1) Exotic atoms formed by the first five have been studied and have yielded information about the charge and matter distribution in nuclei. The μ meson is the only one of these particles that does not interact strongly with nucleons. It therefore can reach the K-shell of an atom. From the exact energies of μ-orbits we have learned much about the charge distribution of nuclei.

*Introductory Talk, International Conference on Nuclear Physics, Munich, 1973

At a recent conference held at Brookhaven* the fate of some of the strongly interacting particles in atomic orbits and inside nuclei was discussed.

Nucleons can exist in excited states which can be naturally grouped together. The best known are the octet of spin 1/2 and the decuplet (decimet) of spin 3/2.

I = 1/2; J = 1/2	p n (N)	Λ	Σ^+ Σ^o Σ^- (Σ)	Ξ^o Ξ^- (Ξ)	Octet
Mean mass (MeV)	939	1116	1193	1318	
I = 3/2; J = 3/2	Δ^{++} Δ^+ Δ^o Δ^- (Δ)	- - - - - -		Ω^-	Decuplet
Mean mass (MeV)	1236			1673	

The Δ resonance, also known as the (3,3) resonance, has a width $\Gamma \sim 100$ MeV, corresponding to a lifetime $\sim 10^{-23}$ sec.

Just like the proton and neutron some of these excited nucleons, and perhaps all, can be bound to nuclei, and thus form what I should like to call paranuclei. The best known examples are the weakly decaying hypernuclei containing a Λ, discovered by Danysz and Pniewski 20 years ago. Most other paranuclei can decay by strong interaction. Their energy is therefore usually ill defined; they form rather wide states.

There is an attractive short-range force between lambdas and nucleons. Because Λ's have I = 0 they cannot exchange single pions with nucleons. Two-pion or K exchange leads, because of the larger masses involved, to a short-range force. The force is not strong enough to give a bound state for either pΛ or nΛ, but, for any existing heavier nucleus, from the deuteron up, the Λ will be bound, and the result will be a hypernucleus e.g., $D + \Lambda \rightarrow {}^3_\Lambda H$. We can generalize this by saying that to any particle-stable nucleus we can add a Λ and get a hypernucleus which should again be particle stable. Even some particle-unstable nuclei may on addition of a Λ become particle stable; for instance, ${}^5He$, which we know to be particle unstable, forms the core of ${}^6_\Lambda He$, which is particle stable. We may also expect that particle-stable excited nuclei will bind Λ's, and the Λ may also be in an excited state. Recently the strangeness analogue state was discovered at CERN.

Thus we can expect a great variety of phenomena and this field is worth pursuing in considerable detail, at least until it reaches sufficient maturity that we can test fundamental ideas.

The binding energy of a Λ, the energy necessary to remove a Λ from a hypernucleus, is now well known up to about ${}^{16}_\Lambda O$. It starts with the very low binding energy of ${}^3_\Lambda H$, which is ~ 100 keV. With increasing mass number the binding energy increases at first linearly and appears to saturate for large A, at around 30 MeV. For ${}^{16}_\Lambda O$ it is about halfway up to the saturation point. The saturation value is approximately known from emulsion data on heavy fragments. With the

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*Nuclear and Hypernuclear Physics with Kaon Beams, BNL Report, Edited by H. Palevsky (to be published). See talks by Dalitz, Povh, Bressani, and others; summary by M. Goldhaber.

availability of K beams, it will be possible to determine in well-defined heavy nuclei the binding energy of a Λ, and this will yield the depth of the potential, which can then be extrapolated to an infinitely large nucleus.

How does a Λ move in the nuclear potential? Will the fact that the Pauli principle holds for the nucleons sufficiently limit the possible Λ-N scatterings so that the Λ effectively behaves as an independent particle? Bodmer has considered this question. The relatively shorter range of the Λ-N interaction indicates that only fast virtual excitations will occur. In our nuclear experience, correlations may be strong but shell model orbitals are still excellent first approximations for all practical purposes. Thus here also, while the relative Λ-N wave functions will be strongly correlated at short distances, at large distances an independent orbital picture should be valid. Theory accounts well for the binding energies found for Λ's.

Hypernuclei containing two Λ's have been discovered, and there is no reason why they shouldn't bind more; but of course as soon as there are more than two Λ's, assuming that the Pauli principle holds among the Λ's, which most of us believe, they will have to fill higher states. For a given mass number, Λ's can be expected to be bound up to some subshell. A very rich but difficult field is awaiting us here. The name "hypernucleus" may be redefined as having a meaning more general than the original one; instead of hypernuclei with only Λ's we could consider hypernuclei with Σ's or other strange particles. But, as soon as we have, e.g., a Σ^- in a nucleus that contains a proton, there will be a strong interaction, $\Sigma^- + p \rightarrow \Lambda + n$, with an energy release of 80 MeV. Thus a Σ^- will not survive long in a nucleus containing protons; similarly, a Σ^+ will not survive long in one containing neutrons; a Σ^0 will not survive long in any nucleus. Therefore, we can expect only wide states, with the possible exception of an α-type combination like $\Sigma^-\Sigma^-nn$, which has no strong decay mode. A probably more stable combination is $\Sigma^-\Sigma^-\Lambda^0\Lambda^0nn$, a super α-type structure with six s-shell baryons. Theoreticians can probably predict whether these combinations are particle stable, and if so, experimenters might like to chase these unusual hypernuclei.

There is evidence for a Λ-nucleon spin-spin interaction. Unlike the case of the proton-neutron interaction, the singlet state is the lowest. This is fairly well established from the study of ${}^4_\Lambda H$ and ${}^4_\Lambda He$. The existence of spin-orbit coupling for the Λ, though theoretically very likely, is not yet established.

The interaction of Λ's with nuclei can in principle be deduced if the behavior of a nucleus and that of fundamental particles governed by SU(3) are known; thus our understanding of these fields is tested in a new way.

From the capture of strongly interacting negative particles (e.g., π^-, K^-, $\bar{p}$, etc.) from high atomic orbits, a great deal can be learned about the nuclear surface. One can hope that these efforts will lead to an answer to the old question of whether neutrons prevail on the surface, as recent results again indicate.*

As the various beams get better we can ask finer and finer questions, both about the nucleus and about elementary particles. We can study their magnetic moments, their polarizability, and for the Ω^- we may even think of searching for a quadrupole moment since it has a spin 3/2. One can expect a very interesting spectrum** if the quadrupole moment is sufficiently large, but this is somewhat futuristic until better Ω^- intensities become available.

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*Bugg et al. Phys. Rev. Letters 31, 475 (1973)

**See R. M. Sternheimer and M. Goldhaber, Phys. Rev. A, 8, (Nov. 1973)

Another field of interest, considered by Kerman, Kisslinger, and others in the last few years, is the virtual existence of Δ's in nuclei, in particular in the deuteron. The existence of Δ's has been used to explain magnetic moment anomalies, a discrepancy found in the n-p capture cross section, etc., though some theoreticians have remained skeptical. While preparing this talk I thought it worth while to ask whether the existence of Δ's in the deuteron could be more directly demonstrated. Since the deuteron has $I = 0$ and the Δ has $I = 3/2$, the deuteron must change into two Δ's: $\Delta^{++}\Delta^{-}$ and $\Delta^{+}\Delta^{o}$ of equal probability. If one of the two Δ's were suddenly hit by a high energy particle, the other, "spectator," Δ would go off in the direction it happened to be moving when its partner was hit. Half of these spectator Δ's should therefore be expected to be emitted into the backward hemisphere in the laboratory system, not only in the center-of-mass system in which high energy physicists are more accustomed to dwell. I asked some of my high energy friends who had bubble chamber pictures of deuterium exposed to high energy particles to look for this phenomenon. A group* from Florida State University and the University of Pennsylvania analyzed an exposure of D to 15 GeV/c π^{+} mesons. Their preliminary results are shown in Figs. 2 and 3. Figure 2 shows a plot of the decay mass of a p (slow) — π^{-} combination vs. cos θ, where θ is the laboratory angle of the p_s-π^{-} system with respect to the incoming π^{+}. There is evidence for a fairly clean Δ peak uniformly distributed in the backward hemisphere. It is unlikely that such a distribution is a kinematic accident. Figure 3 is the momentum distribution of the p_s- π system for events with $\cos\theta \le 0$. These data, preliminary though they are, seem best explained by assuming that a Δ^{o} is emitted isotropically in this reaction. This can be tentatively considered as confirmation that the deuteron exists part of the time as ΔΔ. From this sample one can obtain a rough estimate of ~1% for the fraction of ΔΔ in the deuteron, if the $\pi\Delta^{+}$ interaction is assumed to be the same as the πp interaction.

A coupled-channel treatment of the Δ resonances in deuterium, presented to this Conference by S. Jena and L. Kisslinger (662), predicts an expected momentum distribution for the Δ's which is not too far off from that observed, though better statistics are needed. Thus we may say that about 10^{21} times per second the deuteron changes into two Δ's which then revert back in about 10^{-23} sec into a proton and neutron.

It is important to test these ideas with other energetic particles. Analyses are now under way, in many places, of bubble chamber pictures of deuterium exposed to various particles ($\pi^{\pm}$, $K^{\pm}$, p) of momenta ranging from 7 to 28 GeV/c. If the backward Δ's are correctly interpreted, the nature of the projectile should not matter, provided it is energetic enough.

The high energy physicists can use this phenomenon to study particle interaction with an effective Δ target by requiring a slow backward Δ as an indicator that a Δ was very probably hit. The theoreticians will have to take the ΔΔ component of the deuteron more seriously and consider how much it, for instance, affects the quadrupole moment of the deuteron, etc. The existence of virtual Δ's in heavier nuclei with isotopic spin I > 0 where single Δ's could exist deserves further theoretical and experimental investigation.

After these observations were made, I learned of an excellent review on "Nuclear Isobar Configurations" by Arenhövel and Weber**, which contains much of the background for what I have discussed here. I suppose the high energy experimenters have not paid enough attention to this review because the words "laboratory system" do not appear in it explicitly.

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*S. Hagopian, C. Horne, D. Pewitt, B. Wind, and V. Hagopian (Florida State) and J. Bensinger (Pennsylvania).

**H. Arenhövel and H. J. Weber, Springer Tracts 65, 58-91 (1972).

There are many other areas of research where high and low energy physics interact, often to their mutual benefit. Let me mention a few. The scattering of pions by nuclei, especially of pions in the (3,3) resonance region, is the subject of intense experimental and theoretical investigation. The effective pion-nucleus potential and the role of the Δ in the nucleus are not yet established.*

The availability of relativistic heavy ions at the Bevatron accelerator in Berkeley promises many interesting investigations. One result, by Heckmann and his colleagues, is rather intriguing: The slow fragments into which a fast moving nucleus breaks up have momenta independent of their mass, $\sim m_{\pi}c$, in the system of the moving nucleus.

The nucleus has many uses in the study of high energy phénomena. Let me mention one recent result by Piccioni and his collaborators: Multi-GeV deuterons break up in the Coulomb field of a heavy nucleus in a manner predictable from their low energy photo-dissociation cross section. Thus, by detecting the protons, homogeneous "tagged" neutrons of known momenta become available for high energy experimentation.

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*See Summer Study at the Los Alamos Meson Facility (to be published).

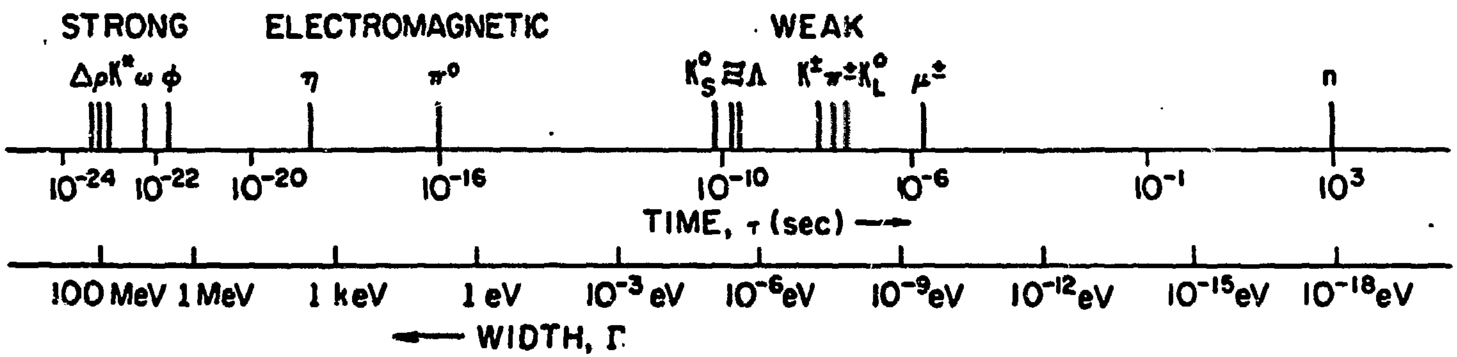

FIGURE 1

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.

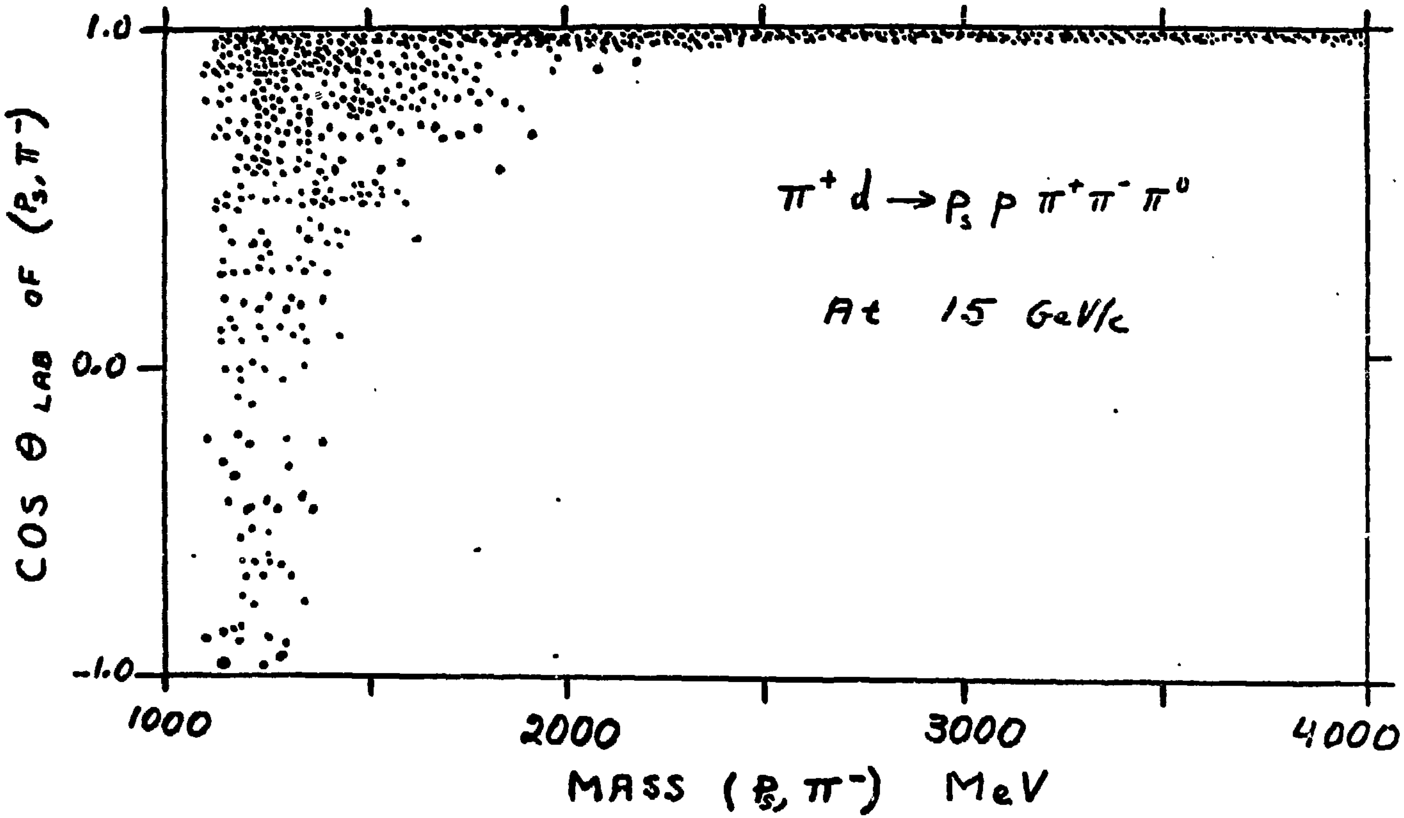

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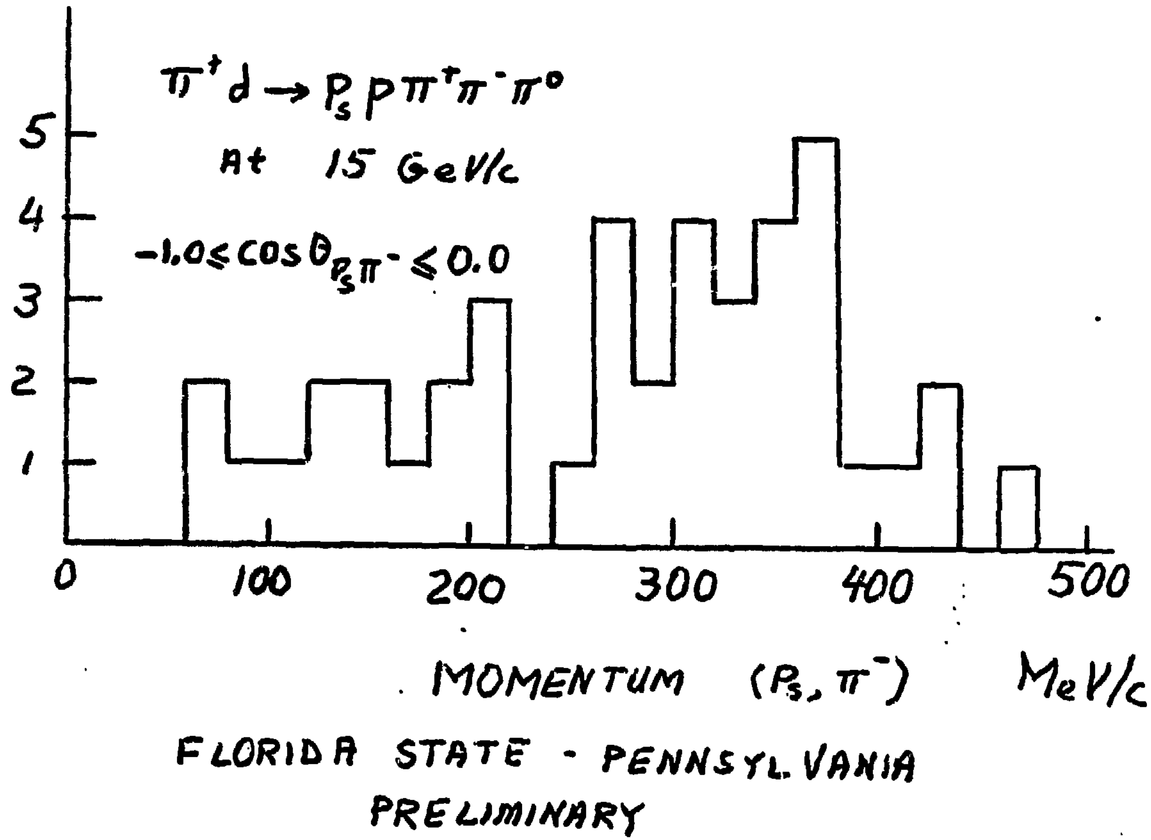
FIGURE 2



$\pi^+ d \rightarrow P_s p \pi^+ \pi^- \pi^0$
At 15 GeV/c
$-1.0 \leq \cos\theta_{P_s\pi^-} \leq 0.0$
5
4
3
2
1
0
100
200
300
400
500
MOMENTUM (P_s, π^-) MeV/c
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FIGURE 3