NUCLEAR PHYSICS —
AT THE FRONTIERS OF KNOWLEDGE

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Nuclear physics has been and will be a major factor in science and technology. It makes unique and important contributions to medicine, to industry and to other sciences. Interaction with other physics has been strong. Astrophysics and mesoscopic physics are notable examples. This is illustrated by Figure 1. But what I shall talk about today are labeled “universals”. This refers to results which transcend the limits of a given subject providing fundamental principles which inform not only nuclear physics but all of science. It is the universals which take nuclear physics research from the parochial albeit fascinating studies of nuclear reactions and structure to the development and formulation of concepts of significance for all of the physical sciences.

Fundamentally nuclear physics research is concerned with the physics of systems consisting of a small number of interacting particles. By small number we mean much less than the $10^{23}$ particles of condensed matter but greater than one. What have we discovered about such systems in the last fifty years? When I look back over that period, I am struck by the advances that were made, and this in spite of the fact that certainly at the beginning and for some time longer we only knew that the nucleon-nucleon force was strong, short range, spin and isospin dependent. It was in nuclear physics that the concept of internal symmetry, e.g. isospin was introduced. Some of the results which were uncovered include most importantly the existence of collective motion. This includes the existence of a mean field which leads to the shell model, the deformed nucleus leading to rotational bands and most recently to superdeformed nuclei (Figure 2), the doorway states such as the giant electromagnetic resonances, the isobar analog states, the Gamow-Teller resonances all which seem to be connected with a symmetry of the nuclear Hamiltonian fission isomers and nuclear molecules reflecting the properties of highly deformed nuclei. The whole panorama of nuclear reactions has been observed, ranging from direct reactions, to compound nuclear formation and including, in the case of heavy ions, fusion and fission and deep inelastic scattering. Theoretically, descriptions of nuclear structure and the giant resonances have been formulated and importantly it has been possible to obtain the properties of nuclei starting from the nucleon-nucleon force. And a formalism has been developed which permit the interpretation of nuclear reactions.
The concept of nuclear temperature is a part of that description. Statistical methods were introduced in response to the “chaotic” neutron and proton spectra revealed in various reactions. (Of course the term chaos had not been introduced when these methods were developed.) Very importantly it was found that energy averaging over the chaotic spectrum leads to the optical model. An illustration of the effect of energy averaging to yield an isobar analog resonance is shown in Figure 3. Finally we come to the weak interactions. It was in $\beta$ decay that parity non-conservation was observed and the description of $\beta$ decay in terms of V-A interaction was determined. Tests of the standard model have been made; others are in progress. Undoubtedly each of you would have items which you would add to this list.

We emphasize that the above phenomena and concepts apply to a small system with a maximum number of a few hundred particles. Do these show up in other small systems? The answer is yes, and a most striking example is given by mesoscopic physics - Consider metallic clusters for example. These are stable combinations of metallic atoms (Na, (the most deeply bound systems) K, Pb) whose number can range from tens to thousands. It is found that the number of atoms in the most abundantly produced clusters form a set of magic numbers, (see Figure 4) which are conveniently understood as the bound states of electrons in a mean field, called jellium, which can be taken to have the Woods-Saxon shape. A deformed potential leads to better agreement with experiment.(see Figure 5) Giant resonances are seen. (see Figure 6) And a number of phenomena exist which can be readily understood when references is made to nuclear analogs. Of course the nature of the clusters do change when the number of atoms is relatively large. A second example is provided by quantum dots and by very small conductors. The phenomena in these cases is very similar to that exhibited by “chaotic” nuclear spectra (see Figure 7) and have been treated in an identical fashion making use of the appropriate nuclear theoretical developments. Further examples can be cited. The point to be emphasized is that small systems exhibit common phenomena – moreover these occur in spite of the fact that the interparticle forces are very different in character. Thus the researches in Nuclear Physics leads to results which can be characterized as universal in that with suitable modifications they apply to small systems generally.

We turn now to the future. It should be emphasized that there is continuing research in all the areas mentioned above as you can see by simply looking at the conference program. But what we shall devote most of the talk to is the very exciting prospect presented by the three new systems now under study by nuclear physicists. There is the study of radioactive beam nuclei which are far from the stable valley. What are the properties of nuclei which have an excessive number of neutrons (e.g. $^{11}$Li) or an excessive number of protons? The next two systems I will mention involve properties of QCD, (quantum chromodynamics). The first is the study of the structure of the hadrons. The nucleon for example is now seen to be a many body system; the particles involved are up and down quarks, sea quarks, that is strange quarks and anti quarks of the up, down and strange variety and gluons. The interactions are
strong and the kinematics are relativistic. A matter of great interest is the effect of
the nuclear medium on the internal structure of the nucleon. It raises the general
question of how to incorporate the complex internal structure of a particle into a
description of a bound system of such particles. Or if one considers the nucleus to be
a collection of quarks and gluons how do these condense into the nucleons forming
the usual description of the nucleus? Still a third aspect of this same problem is
how to reconcile the boson exchange models of nuclear forces with the quark-gluon
models. There is the question of how strange particles behave in nuclei. What are
the baryon-lyperon interactions?

We turn next to the quark-gluon plasma. This is short hand for the state of nu-
clear matter under high density and/or high temperature (i.e. highly excited). We
will be able to trace the behavior of nuclear matter as density and/or temperature
are increased from low to high values. This will be accomplished by the study of
the collision of heavy ions from low to ultra-relativistic energy. The major issues at
the ultra relativistic end are: Under conditions of high density and temperature will
we form a region in which quarks and gluons are deconfined? Will chiral symmetry
be restored? These are the three or four essentially new areas which provide op-
portunities for productive and significant research by nuclear physicists. In addition
one should also consider the more established sub-fields which continue to expose
new phenomena and new puzzles and importantly provide the intellectual support
needed for the exploitation of the newer initiatives. New concepts, new structure of
“universal” importance will be developed within these sub-fields.

1. The Nucleon

Let us now discuss these “new” scientific opportunities. We begin with the nu-
cleon. The model of the nucleon as consisting of three constituent quarks, in spite
of its many successes turns out to be too simplistic. It was hoped that this model
was a mean field model which involved an average over the quark-quark, quark-gluon
and gluon-gluon interactions. That hope in some approximation may be correct but
is now clear that it is not capable of fully describing the hadron. One must take into
explicit account the degrees of freedom represented by gluons and quark-antiquarks,
the so called sea quarks.

The principal experimental tools involve electron, or more generally lepton-nucleon
scattering, and proton-proton scattering. Importantly both projectiles and targets
can be polarized. The results are expressed in terms of structure functions includ-
ing spin structure functions, from which a description of the hadron will eventually
emerge. The simplest of these are the form factors obtained by the scattering, elastic
and inelastic, of unpolarized electrons (or leptons) by an unpolarized nucleon. Con-
siderable progress has been made although further experiments on the determination
of the neutron form factor are desirable for a precision result. Spin structure functions
(see Figure 8, 9, 10) have provided the startling result that 30% of the nucleon spin
resides in the quarks, -10% in the strange sea quarks while the remainder must reside in the gluons which must be polarized or in angular momentum contributions which have not been included in the calculations. Another experiment which will bear on this issue are parity violating electron scattering which can yield the strange quark contributions to the magnetic moment of the proton. Another startling result is the indication that the population of anti up sea quarks differs substantially from that of the anti down sea quark. Finally one should mention the evidence that the nucleon is deformed so that the effective quark-quark interaction must contain a tensor component.

Investigation of the gluon distribution will be one of the goals of the ($\vec{p}, \vec{p}$) collisions. The protons bring in gluons so that the reactions like $g + \vec{q} \rightarrow q + \gamma$ and $g + g \rightarrow q + g$. The first of these yields a direct photon production while the second will manifest itself in two jets. The production of $W^+$ and $W^-$ reflects the presence of anti down and anti up quarks respectively.

Internal structure generally guarantees the existence of excited states and vice versa the properties of excited states and their excitation can inform us with respect to the internal structure. Thus a second phase of the study of the nucleon is the study of excited state – hadron spectroscopy. QCD leads one to expect the existence of exotic states, e.g. mesons whose dominant configuration contains only gluons and/or more than a single $\bar{q}q$ pair. From $\bar{p}p$ annihilation at rest one obtains a rich spectrum of scalar states including the $f_0(1520)$ meson, a glueball candidate. Great progress has been made in identifying numerous conventional $\bar{q}q$ systems. But the search continues for the predicted glueball and hybrid states.

At low energies, an effective Lagrangian with consequent chiral perturbation theory ($\chi$PT) has been derived. Relevant experimental issues include $\gamma + p \rightarrow \pi^0 + p$ reaction, the electric polarizability of charged pions, the spectral shape of the $\eta \rightarrow 3\pi$ decay.

The next level of study is the hadronic interactions. The main issue is the connection of the meson exchange description of nucleon forces with the quark-gluon degree of freedom. Or how do the quark-gluon degrees of freedom manifest themselves in baryon-baryon scattering? The nucleon-nucleon sector has been thoroughly studied but we need information on the hyperon-nucleon interaction and on the hyperon-hyperon interaction. What for example are the properties of the dibaryon system? Is there a 6 quark system like the one suggested by Jaffe? The data is very sparse. As can be seen from Figure 11, very little is known regarding the hyperon-nucleon interaction.? The best information so far is obtained from the properties of hypernuclei.

Finally we turn to hadrons in nuclear matter. Experiments involving the EMC effect continue. Beyond that I shall mention only (1) the suspected phenomenon of color transparency in which very small color singlet objects which interact weakly with nuclear matter are formed in hard collisions and (2) the approach to chiral
symmetry with increasing density. Of course the nuclear gluon distribution as well as that of the anti-quark distribution have not been adequately studied.

2. Heavy Ions and the Quark-Gluon Plasma

There are many fundamental issues connected with heavy ion collisions. I will pick on one: namely can concepts which have been developed to understand the behavior of macroscopic systems be used to understand phenomena encountered in heavy ion collisions? For example is the concept of temperature valid for these relatively small systems? And if so what characterizes thermal equilibrium? Can one expect to see change of phase change as the experimental parameters are changed? Is classical hydrodynamics valid? Can transport theory be used? And what is the impact of collective forms of motion? Remember we are dealing with relatively few constituent particles. A caveat here. In Au + Au collisions at the AGS 1600 particles were produced. Are macroscopic concepts applicable?

A great new frontier is now being opened with the use of relativistic heavy ion reactions which create systems with high energy and/or matter density. Will the consequences be deconfinement so that a new form of matter is generated – the quark-gluon plasma? What are the appropriate degrees of freedom? What will be the collective forms of motion? And the most important question, how will the change from hadronic matter to the quark-gluon plasma matter takes under the regime of high energy and high density? For example it is thought that baryon free matter is generated when two heavy ions pass through each other as illustrated in Figure 12. It is of better to look at the whole picture as shown in Figure 13. Here we can see the possible changes which can occur as the density and/or temperature (≡ energy density) change.

Parenthetically, these phases of nuclear matter play a role in the history of our universe, another significant contribution of nuclear to astrophysics.

On this diagram the various paths which might be explored by experiments located at the AGS at Brookhaven, the SPS at CERN and RHIC at Brookhaven are sketched. The AGS provides beams with energies of (11.6A) GeV, the SPS heavy ion energies are (160A)GeV while at RHIC the colliding beams have energies of (100A x 100A)GeV. The first two of these involve fixed target energies so that the CM energies ar relatively low. RHIC will be ready for experiment by 1999.

From experiments now being conducted at the AGS and SPS one learns of the existence of a regime in which 1/2 of the nucleons are in excited states. Thus has been called “Baryon Resonance Matter”. Another and surprising result is the high stopping power - greater than predicted. At the AGS the two colliding nuclei Au + Au stop each other leading to baryon densities thought to be as high as 10\(\rho_0\) where \(\rho_0\) is the normal nucleon density. Strangeness production is enhanced, multiply strange baryons as well as anti-strange baryons are produced. The suppression of \(J/\psi\) and \(\psi'\) increases with increasing transverse energy. An excess in the production of dilepton
pairs of low and intermediate mass is reported for the collision of protons and light ion collisions at the SPs. These results are provocative. Further experiments are needed. It will be fascinating to follow their behavior as the center of mass energy increases to the RHIC maximum of 200A GeV. Will there be visible indications of the change from nuclear matter to the quark-gluon plasma (see Figure 14)?.

Relatistic heavy ion physics presents a very exciting prospect with many opportunities for discoveries of a fundamental-universal importance.

3. Radioactive Nuclei

This research area is concerned with nuclei which are neutron (or proton) rich. They are radioactive and approach the neutron (proton) dripline. The nuclei in the stable valley number a few hundred whereas the radioactive nuclei number a few thousands. As can be seen in Figure 14, in the case of the stable nuclei the spatial distribution of the neutrons and protons are substantially identical, the neutron and proton radius are equal to within roughly 0.1 fm. For the neutron rich nuclei (e.g. $^{11}$Li, $^{8}$He) outside of the stable valley this is no longer the case (see Figure 16). The surplus neutrons are found just outside core when the two neutron separation energy is of the few MeV. One then speaks of a neutron skin. When that energy is very small certainly less than 1 MeV one finds a spatial neutron distribution with a very long tail of low density. This is confirmed by the momentum distribution which a corresponding narrow peak. These nuclei are said to possess neutron halos (see Figure 17). All halo nuclei except $^{11}$B, have two neutrons in the last orbital. This indicates that the binding of these nuclei is a consequence of the interaction of these two neutrons implying a strong two neutron correlation maximizing their attractive potential energy.

One can ask can the properties of these nuclei be obtained from what we know about the nucleon-nucleon interaction from the properties of the stable nuclei? What collective forms of motion will they exhibit? It is already surmised that they are deformed so that there should be the corresponding rotational levels. Super and hyper deformation are anticipated (see Figure 18). It will also be possible to probe the super-heavy region. In the case of the halo nuclei crudely one expects an oscillation of the two halo neutrons against the core nucleus as illustrated in Figure 19. This it is believed has been observed by in photo disintegration where one finds a “soft” El mode which can be described as a resonance. The radioactive nuclei are polarized permitting the measurement of their magnetic moments.

Research in sub-field is just beginning. Only the surface has been scratched. What shall we find when we dig deeper?

4. Weak Interactions

The study of the weak interactions at the present time has several facets. One is the study of the properties of the various neutrinos $\nu_e$, $\nu_\mu$, $\nu_\tau$. Do they have mass?
Can an oscillation among them be induced? Is there a Majorana type neutrino? Experiments which hear on that question include double $\beta$ decay, the $\beta$ decay of $^3$H, the solar neutrino problem, and elastic neutrino scattering. Long baseline experiments are planned in which neutrinos are observed after having traveled a large distance to see whether or not the neutrinos have changed character.

A second front is testing the standard model. $K$ decay is an important example. Another possibility for studying CP and CPT violations lies in the decay of the $\phi$ meson. The study of the CKM matrix continues.

In a third front the weak matrix elements in the baryon-baryon sector are revealed in the decay of the $\Lambda$ in a hypernucleus via $\Lambda + N \to N + N$. Another possible process is $\Lambda + N \to N + N + N$. Recently it was found that parity non conservation could be detected by the scattering of low energy neutrons by nuclei (see Figure 21). The present experiments clearly reveal the existence of doorway states which were postulated some thirty years ago to explain the dependence of the neutron strength function on the mass number. Finally and most importantly the electron accelerator facilities provide a means for studying the standard model and in addition provides a probe which through the parity non conserving interaction can yield information on the weak matrix elements at the quark level.

5. Nuclear Theory

Nuclear theory’s function is to act as a guide, as an interpretator and finally as a synthesizer. As new areas are investigated, theory needs to study and suggest the incisive experimental signals which provide probes of the system under investigation. On the other hand it must attempt to characterize the systems by calculations from first principles. These are of course not independent endeavors. Of course experiment is a collaborator and often an instigator.

The computer has become an important tool for theory. Using statistical methods, and such formalisms as the Fadeev theory, the ground state energies of the light nuclei have been successfully calculated as illustrated by the table below. This provides unique information on the nucleon-nucleon potential. Only the two body potential is used as the effect of the many-body nuclear forms can be shown to be small as a consequence of chiral symmetry. There is hope that statistical methods can be extended in such a fashion as to make calculation of the states of heavy nuclei possible. Clearly as we go more completely into the computer age, highly sophisticated methods will be developed and problems now regarded as totally intransigent will be routinely solved.

| Nucleus ($J^\pi$) | $^2$H ($1^+$) | $^3$H ($\frac{1}{2}^+$) | $^4$He ($0^+$) | $^5$He ($\frac{5}{2}^-$) | $^6$Li ($1^+$) |
|-------------------|-------------|----------------|-------------|----------------|-------------|
| Expt (MeV)        | -2.22       | -8.48          | -28.3       | -27.2          | -32.0       |
| Theory (MeV)      | -2.22       | -8.47(2)       | -28.31      | -26.5(2)       | -32.4(9)    |

Another example of the use of computers is QCD. QCD is a non-linear theory
which makes it a fortiori difficult. Progress has been made on a number of fronts. One is lattice gauge theory used to study nucleon and meson structure. It from such calculations that we have learned of the importance of instantons. A second is the use of sum rules, generally derived from QCD, which permit the extraction of the contributions of quarks, sea quarks, strange quarks and gluons from experimental data. A third approach is know as chiral perturbation theory. It is an effective theory consistent with QCD which is presumed to apply at low energies. It makes use of the fact that the Goldstone bosons decouple at zero energy so that an expansion in powers of the energy.

In the case of heavy ion physics the computer makes it possible to calculate hadronic and partonic cascades. The former has been successfully used to understand the collision of heavy ions at the AGS and the SPS. At intermediate energies a one body transport equation (LBUU) is very successful. At relativistic energies lattice-gauge calculations have been used to explore the properties of the quark-gluon plasma.

The quantative consequences of QCD remains unsolved, although the approaches described above have made some progress toward this goal. A fully relativistic theory which can simultaneously describe structure and reactions is still a considerable distance away. It is the major problem certainly of nuclear physics, but beyond that, of theoretical physics generally. But with the coming of age of computers, and the construction of high energy accelerators it may become possible with the combined efforts of experimentalists and theorists to find a solution.

Symmetry continues to be of great interest. We have already noted the effective use of chiral symmetry. Symmetry is the underlying motif of the interacting boson model and other algebraic formulisms. SU(3) symmetry is used in the derivation of the nucleon sum rules mentioned above. It is used for the coupling constants in deSwart’s et.al’s description of the baryon-baryon interaction. A neglected field in my opinion in spite of its long history, is the study of SU(3) symmetry and its violations.

It is not possible to finish this address without pointing to the extraordinary increase in technical capability which has occurred in recent years. Accelerator physicists have designed and built facilities which provide nuclear researchers with beams of high quality with a great range in energy and in particle species – and importantly these beams can be polarized. CW beams make coincidence experiments feasible. Accompanying these developments are improvements in detector efficiency and solid angle coverage permitting a full description of the reaction under study.
FIGURE CAPTIONS

Figure 1. Contributions of Nuclear Physics.

Figure 2. Gamma-ray spectra in $^{152}$Dy obtained by summation of gates set on most members of the superdeformed band.

Figure 3. The top figure is a high resolution cross section for the reaction $^{92}$Mo$(p,p)$. The lower curve is a poor resolution cross section.

Figure 4. Sodium cluster abundance spectrum: (a) experimental (after Knight et al., 1984); (b) dashed line, using Woods-Saxon potential (after Knight et al., 1984); solid line, using the ellipsoidal shell (Clemenger-Nilsson) model (after de Heer, Knight, Chou, and Cohen, 1987).

Figure 5. Fission dissociation energies, $\Delta_{26,P}$ for the doubly cationic $K_{26}^+$ cluster as a function of the fission channels $P$. Solid dots: Theoretical results derived from the SE-SCM method. Open squares: Experimental measurements. Top panel: The spherical model compared to experimental data. Middle panel: The spheroidal model compared to experimental data. Lower panel: The ellipsoidal model compared to experimental data.

Figure 6. Photoelectron spectra of small alkali cluster anions.

Figure 7. Comparison of magnetoresistance structure from simulation and experiment. The experimental system is a Au-Pd wire of length 7900 Å and width 500 Å. The simulated wire is 400 by 40 sites, with $W=0.6$ and $E=0.2$.

Figure 8. Structure Functions.

Figure 9. The spin structure function $g_1^p(x)$ for the proton.

Figure 10. The ordinate represents increasing orders of approximation.

Figure 11. Total cross-sections for baryon-baryon scattering.

Figure 12. The collision of relativistic heavy ions.

Figure 13. Phase Diagram.

Figure 14. Signatures of Quark-Gluon Plasma.

Figure 15. Chart of the Nuclei.

Figure 16. HF potential for $^{16}$O isotopes.

Figure 17. The ratio of the proton and the neutron density is almost constant everywhere in a stable nucleus. However the neutron skins develops when more neutrons are added on unstable neutron rich nuclei. Then neutron halos are formed in nuclei near and on the dripline. The proton skin may also be formed in proton rich unstable nuclei.

Figure 18. Various exotic shapes of nuclei. Exotic orbitals appears in the region far from the stability line provides many types of deformations.

Figure 19. The soft modes of various multi polarities are expected in nuclei with neutron skin and/or neutron halo. The resonances provide us a mean to study the compressibility or other properties of asymmetric nuclear matter.

Figure 20. Magnetic and Quadrupole moments for radioactive nuclei.

Figure 21. The parity nonconserving longitudinal asymmetries $P$ for $^{232}$Th.

Figure 22. The parity nonconserving longitudinal asymmetries $P$ for $^{232}$Th.
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