NUCLEAR PHYSICS RESEARCH REQUIREMENTS FOR ELECTRON AND HEAVY ION MACHINES

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Summary

There has been a great deal of interest in a variety of new machines intended to probe atomic nuclei for hadronic and quark aspects which lie beyond the familiar shell model view of nuclei. This paper gives the physics perspective within which the proposals for such machines have arisen and discusses the two classes of tools - high energy cw electron machines and relativistic heavy ion machines - which lie at opposite ends of the arsenal being gathered for the pursuit of QCD in nuclei. The electron machines present a reasoned analytic approach to the simplest systems and the heavy ion machines a major thrust for startling new physics in the quark-gluon sea.

1. Introduction

Around the world there is an intense new interest in new kinds of accelerators for nuclear physics because of a quite remarkable and sudden change in the direction of nuclear physics. Nuclear physicists have come to believe that quark structure of nucleons must play a role in nuclei and, further, that the nuclear arena may be the best place to unravel the long distance aspects of quantum chromodynamics (QCD). In this paper I want to give a brief overview of the science perspective within which that conviction has been attained, the long list of questions which have suddenly become urgent and the accelerators which appear to be needed to answer the questions.

The passions of the debate about new accelerators are sufficiently great that the organizers invited me, a spectator, to speak on the subject rather than one of the active participants. The whole gamut of nuclear subfields is involved in the change in direction. At the far right one has the careful conservative approach based on the best understood probe, the electron. At the far left one has the radical faction proposing relativistic heavy ion machines in a headlong rush toward quark-gluon matter. In the centre are the meson factories (TRIUMF and LAMPF) now proposing to boost their energies twentyfold or more. As a confirmed centrist I am asked here to report on both extremist factions. Next, the debate rages around the world but has been approached most critically and articulately in the national context of the United States. Over the past few years a number of panels of the American Nuclear Science Advisory Committee - particularly the Paul Report¹ on Heavy Ion Facilities (1982), the Barnes Report² on the Role of Electromagnetic Interactions in Nuclear Science (1982), as well as the recent proposals for GeV electron accelerators³ and for relativistic heavy ion machines⁴ presented to NSAC - have provided very valuable critiques of the field of science and the requisite accelerators. As a foreign member of NSAC, whose emotions are not pushed beyond all operational levels by the vagaries of U.S. nuclear science funding, I plan to base much of my discussion on the United States context and to freely plagiarize the appropriate panel reports. My position is clearly that of the dispassionate, non-expert spectator.

2. The QCD Nucleus

For the past four decades particle physics and nuclear physics drifted apart. With the recent advent of QCD from particle physics and with the new central interest of nuclear physics in the dynamical aspects of QCD one has the very welcome prospect that the two fields may again be converging.

The interest of nuclear physics in QCD dynamics has not been heralded by any major single discovery. In fact, as we shall report below, the effects of QCD in nuclei are, so far, proving rather elusive. Rather, the interest has been aroused by the basic physical fact that the size⁵ of the nucleon bag (~ 0.8 fm) is only a little smaller than the internucleon spacings⁶ (~ 2.2 fm) in the centre of a nucleus. In spite of short-range repulsion, or the correlations imposed on identical fermions by the Pauli principle, it then becomes likely that occasionally the quark bags will coalesce in a normal nucleus. How does this affect nuclear properties?

Figure 1(a) shows the familiar view of a nucleus in which neutrons and protons move in single-particle orbits but interact through meson exchange (π 's, ρ 's, etc.). This shell model view has been remarkably successful in describing the properties of nuclear energy levels. It predicts, correctly, an astonishing variety of single particle and collective phenomena which will no doubt continue to challenge a number of nuclear physicists for many years. The pursuit of the phenomena associated with this picture will continue to be carried out, in part, with the system of several dozen very fine tandem accelerators and low energy cyclotrons which remain active in the world.

Going beyond the nucleon picture one can enquire about hadron aspects which involve mesons, isobars, meson exchange currents, etc. Extending the familiar picture in this way requires medium energy accelerators.

The new view of a nucleus is given, in very qualitative and tentative terms, by Fig. 1(b) in which each nucleon is viewed as a colour-neutral bag of three quarks. Some of the quark bags may touch or coalesce leading to freer motion - or "percolation" of the valence quarks. Does this happen? Should it happen? How can phenomena related to quark percolation be discovered? What would such phenomena tell us about QCD?

There is a great deal of room for the possibility of startling physics, and this is the engine which is driving the current interest. QCD, with its asymptotic freedom, tells us about the very short range interactions of the quarks inside the bag. It is not very vocal about the confinement mechanism or any detailed properties of dynamics relating to quark separations comparable to the bag radius or to typical internucleon spacings. There are suggestions from detailed calculations with lattice gauge theories that QCD (in contradistinction to QED) is confined. However, the very concept of a "bag" - a sharp separation between inside and outside - reveals the lack of sophistication in the physics treatment. Pions are believed to be excluded from the bag but to condense out of the vacuum when two bags are in close proximity. The conservation of chiral symmetry at the bag surface is known to be important. But many open questions remain. Does the bag surface breathe? Is the bag distorted? What is the polarization of the surrounding vacuum? The answers to such questions may, on the one hand, tell us about long distance quark dynamics. On the other hand such effects may manifest themselves in new physics of the nucleus. That is the hope and expectation.

Is there any present evidence for quark effects in nuclei? At low and intermediate energies the present evidence is only flimsy, though amusing. Figure 2 shows, qualitatively, the Gamow-Teller collective giant resonance seen in the forward-angle ($q \approx 0$) p,n reactions measured by Goodman *et al.*⁷ at Indiana over the past

Fig. 1. (a) The familiar single-particle picture of the nucleus in which protons (large solid circles) and neutrons (open circles) interact through meson (small closed circles) exchange; (b) the quark model nucleus in very qualitative terms; nucleons are considered as colour-neutral bags of quarks with some of the quark bags overlapping.

few years. Neither the width nor the energy of this resonance is very surprising - they are garden-variety collective resonances - but the area under the resonance is less than that expected from the appropriate sum rule. The reaction, measured with 200 MeV incident protons, enables the strength to be measured over a considerable energy interval. Throughout the periodic table the integrated strength in each nucleus appears to be quenched by about a factor of two. Much of the strength dispersal appears to be due to Δ -hole interactions where $\Delta(1232)$ differs from the nucleon by having one of its quark-spins flipped. This is then a manifestation of hadron aspects of the nucleus. The strength quenching is predicted to be a direct consequence of the nuclear medium modification of the pion cloud surrounding the nucleon bag.

The quenching of the Gamow-Teller strength function has aroused considerable interest because it was predicted by Magda Ericson⁸ and others. Rho⁹ and others have also shown that if one analyses the nucleon-nucleus response function into various multipoles and spin-isospin pieces certain components (such as the MI spin-flip, or Gamow-Teller, piece) are especially sensitive to QCD effects. In essence they may act like filters for the desired physics. Still one might have hoped for something more dramatic than the diminution of an area. At present there is a clear need to sort out the various pieces of the nuclear response functions with high

Fig. 3. European Muon Collaboration data on $\Delta(x) = F_2^{\text{IRON}} - F_2^{\text{D}}$. x is equal to $Q^2/2Mq^0$ where q^0 is the energy transfer in the laboratory.

Fig. 2. A qualitative description of the collective GT resonance observed in σ_{pn} at 0° . The primary interest here is neither in the level energy, E_{GT} , nor in its width, Γ_{GT} , but rather in the wings of the resonance.

quality beams of protons and electrons at intermediate energy.

At ultrahigh energies one can probe the distribution functions of quarks in the nucleus directly and there may be important clues here. Figure 3 shows the data - as reported a few weeks ago in the analysis of Jaffe¹⁰ - obtained at CERN from the scattering of muons from ^2H and ^{56}Fe at 50 (GeV/c)² momentum transfer squared. At high momentum transfer such muons should be sensitive only to quarks: the nucleons are irrelevant. At fixed high momentum transfer the structure function is a function of the momentum of the struck quarks. The difference between the structure functions for ^{56}Fe and ^2H is significant. The former is a nucleus and the latter is not. In Jaffe's interpretation the valence quarks of ^{56}Fe wander more freely than those of ^2H . If confirmed by further such measurements and analyses one may obtain direct confirmation of the percolating quark picture. Such high energy measurements can provide an instantaneous snapshot of the nucleus. The question will remain how such percolations affect the properties of normal nuclei but it would be surprising if there were not important effects.

Among the tantalizing prospects for startling nuclear physics one is inclined to include the anomalous observed in emulsion work¹¹ at the Bevalac. Figure 4 shows the distribution of measured mean free paths, about the average for the second collision of very energetic heavy ions (~ 1 GeV/nucleon) which have experienced a primary collision. The data suggest that a small fraction ($\sim 6\%$) of the secondary particles have ten times shorter mean free paths than the others. The suggestion is that the ion, in its primary collision, attains a state which is ten times more interactive than that of a normal nucleus and that this highly unusual state persists through 10^{-10} s or more and,

Fig. 4. The mean free path parameter of secondaries compared to that of the primary beam. The solid curve represents 6% of the fragments having $\Lambda^* = 2.5$ cm rather than $\Lambda^* = 30.4$ cm for the primary beam.

possibly, through violent tertiary collisions. Is this some evidence, at these modest energies, of quark-gluon matter? It is very frustrating that the elucidation and verification of the anomalous by counter experiments has not yet occurred.

There are also some interesting suggestions of quark effects in the high q^2 form factors for electron scattering from few-nucleon systems. But there is not much else at present.

One might be tempted to ask whether or not the remarkable success of the shell model does not by itself make unlikely any strong manifestation of quark effects in normal nuclei. The answer is, not really. Low-lying levels of nuclei involve the arrangement of nucleons in the outer shells whose orbits occur in that half of the nuclear volume which is significantly below central density. The quark effects are likely to be strongly density dependent and therefore to occur predominantly in the centre of the nucleus. Further, in the phenomenological shell model one employs effective interactions and effective operators. Some of the initial effects of quark and hadron degrees of freedom may possibly be simulated by the modifications of interactions and operators. Again one hopes for more. Yet the interest in quark effects has given new urgency to sorting out the limits of validity of the current shell model. As Arima¹² has urged one needs to be sure that the tensor force - for example, in M1 moments and transition probabilities - cannot mimic most of the effects of Δ -hole interactions before one leaps to conclusions about the role of the latter. Clearly needed are careful calculations - in reasonable configuration spaces and with reasonable interactions and operators - which include mesonic exchange currents and all of the appropriate props of the conventional shell model.

The compelling picture of the QCD nucleon embedded in a nuclear medium and the few pieces of present evidence pointing toward hadron and quark effects have raised many new questions. What is the role of pions in the nucleus? How do Δ 's propagate in the nucleus? What happens to the nucleus when one introduces hadrons containing strange (and other) quarks? It is the search for the answers to such and many similar questions which has led to the new electron and heavy ion proposals.

3. The Requirements for a cw Electron Accelerator

Beginning with electron accelerators we follow the physics arguments which led the Barnes Committee² to recommend that a high priority be given in the United States to the construction of a 4 GeV cw electron accelerator. The effect of this recommendation - and of the concomitant physics - has been felt at this conference where at least three independent proposals³ with this aim have been presented. The leap from present low duty factor accelerators below 1 GeV to cw machines at 4 GeV does not lack technical challenge.

Existing electron accelerators have provided much of the truly quantitative information about charge distributions, transition densities and many other nuclear properties. What is now needed to sort out hadron and quark aspects of the nucleus is data with much better spatial resolution (~ 0.2 fm) and at much higher energy and momentum transfers.

Consideration of the physics requirements leads to determination of the principal characteristics of the electron accelerator, especially its energy and duty factor. Most of the physics requirements outlined below involve, at least in part, coincidence experiments so that a high duty factor is imperative. The factors which determine the beam energy are predominantly kinematical: maximum three-momentum transfer q_m (or

four-momentum transfer Q_m), maximum energy transfer ω_m , and the angular range of the scattered electron. From the form factor - which is the Fourier-Bessel transform of the transition density - one can establish empirically that

$$q_m = 1.5/\Delta r,$$

where Δr is the desired spatial resolution. For $\Delta r \sim 0.2$ fm this requires $q_m = 8 \text{ fm}^{-1}$. The maximum energy transfer ω_m - for example in an $(e, e'X)$ reaction - is determined by the excitation energy of X and of the residual nucleus, and by the recoil energy of X . The range of angles required is determined by the Rosenbluth formula and the need to separate longitudinal (σ_L) and transverse (σ_T) components of the cross section. Usually 150° is sufficient to determine σ_T while small angles determine σ_L (50° is sufficient).

As an example of the importance of the kinematical factors in defining the beam energy, Fig. 5 shows a plot of the kinematic regions available with $E_0 = 2$ GeV and $E_0 = 4$ GeV. The ordinate is the square of the four-momentum transfer ($Q^2 = q^2 - \omega^2$) while the abscissa is the square of the missing mass, W_p^2 , assuming a proton target:

$$W_p^2 = M_p^2 - Q^2 + 2M_p\omega.$$

Figure 5, from the Barnes report, also includes ten classes of experiments which are:

- (1) Single-arm measurements of few-nucleon targets for elastic form factors and inelastic structure functions
- (2) Coincidence measurements of few-nucleon targets including formation of isobars
- (3) Production of short-lived vector mesons identified by their decay products in few-nucleon systems
- (4) The spectroscopy of kaons and hypernuclei
- (5) Production of the Δ resonance in complex nuclei
- (6) Nucleon knockout in complex nuclei
- (7) Deep inelastic studies in complex nuclei to momentum transfers revealing quark-gluon processes

Fig. 5. Kinematic region accessible with (a) 2 GeV and (b) 4 GeV electron energy and targets of p, d and ^3He .

Fig. 6. The proton inelastic structure function νW_2 as a function of Q^2 and the scaling variable w' .

- (8) Giant resonance excitation (10-50 MeV) to extract transverse and longitudinal transition densities
- (9) Discrete states of complex nuclei and the transition densities for charge, current and spin
- 10) Exploration of symmetries (electroweak parity violation) with polarized electrons

Almost all of these experiments [(1) and (9) are the exceptions] require high duty factor. However, only the most important of them [(1), (2) and (7)] require 4 GeV rather than 2 GeV.

Table I gives some of the other beam parameters required by the experiments.

To demonstrate how double- and triple-arm coincidence experiments may provide information about the transition from nucleon to quark degrees of freedom, Fig. 6 shows a three-dimensional plot of the proton inelastic structure function in terms of two kinematic variables. At small Q^2 and low missing mass the indicated nucleon resonances stand out above the background contributed by scattering from quarks. For large W^2 and Q^2 the resonances fade away suggesting that the transition primarily takes place in the region $W < 2$ GeV, $Q^2 < 3-4$ (GeV/c) 2 . Again, 4 GeV beams are required.

The push toward a 4 GeV cw electron accelerator will clearly open the way toward other cw accelerators at lower energy. A 4 GeV accelerator is not likely to operate below 1 GeV. Much important nuclear physics, especially that associated with experiments (3), (8) and (9), can be pursued with such a lower energy facility.

4. The Requirements for Heavy Ion Accelerators

Heavy ion accelerators for nuclear physics include re-vitalized low energy machines as well as several proposals for relativistic heavy ions. Although we focus here on the new plans for relativistic machines we should not forget the physics of those at lower energy.

There are several regimes of physics interest at lower energies. At energies (5-10 MeV/nucleon) sufficient for nuclei to penetrate through the Coulomb barrier one studies a host of classical liquid drop effects as well as molecular resonances, high spins, electromagnetic properties and transitions, etc. Here the Pauli principle greatly affects the physics. At energies between 10 MeV/nucleon and the Fermi energy (~40 MeV/nucleon) deeply inelastic collisions occur and the study of dissipation processes is important. At energies above the Fermi energy spectator processes begin to play a role and the Pauli principle is no longer all-important.

Table I. Beam parameters required by experiment. "Minimal" means most experiments can be performed if all parameter values are obtained simultaneously. "Special" means certain important measurements require one or more specific parameters to meet this specification, at the expense of other parameters. The numbers given are derived from the physics requirements, with some consideration of present technical feasibility.

Beam parameter	"Minimal"	"Special"
Step size ($\Delta E/E$)	2×10^{-2}	3×10^{-4}
Energy uncertainty ($\Delta E/E$)	1×10^{-3}	5×10^{-4}
Emittance ^a	-	0.01π mm-mrad near 1 GeV
Maximum current	50 μ A	150 μ A
Current stability	$\pm 20\%$	$\pm 20\%$
Duty factor	80%	80%
Micro structure	10^{-9} s	chopped or bunched
Polarization	0	40%

^aThe "minimal" value required for the emittance must be assessed in the context of the coincidence spectrometer system design.

The community of heavy ion physicists, world-wide, has been shifting toward user facilities of moderate size in which cyclotrons or linacs boost the energy of tandems or cyclotrons. The main interest is the transition from classical to hydrodynamical phenomena. Between 100 MeV/nucleon and 1 GeV/nucleon the current interest in physics appears to diminish. Does it leap up again at relativistic energies?

The science interest for relativistic heavy ion physics covers a range of topics including (1) the physics of deconfinement and the attainment of a quark-gluon plasma, (2) nuclear matter at high density and temperature, (3) strange particle production, (4) multiple pion production, (5) the fragmentation process, and (6) a variety of possible exotic states (anomalons, Lee-Wick matter, etc.). Of these the second is a general one covering much of the motivation. We focus here on the first topic to illustrate the interest.

The search for the quark-gluon plasma epitomizes the condition of much of relativistic heavy ion physics. It is a fishing expedition into waters which appear deep, carried out by inadequately equipped fishermen fond of fishing stories and possibly capable of landing some primordial creatures. During its first second our universe consisted of a quark-gluon sea whose conditions we may be able to replicate in the laboratory for 10^{-22} s. The fossil remnants of that early quark-gluon state, and the nuclear formation in the next three minutes, are the nucleons and elements of our world as manifest in the element abundance curve. It is, perhaps, a cosmic irony that we are now trying to recreate that state by banging together the largest fossil pieces.

The vision of what lies beyond ordinary hadronic matter is given by Fig. 7. On a temperature density plot there is believed to be a region in which the quarks become deconfined until, at still higher temperatures or densities, one attains the quark-gluon plasma.

The figure also shows one possible trajectory, in density and temperature, when a stationary heavy nucleus is struck, head-on, by a heavy nucleus of 10 GeV/nucleon.

It is possible that in this trajectory the quark-gluon plasma is attained for 10^{-22} s. Some simple properties of the phase diagram, the trajectory and the physics of the quark-gluon plasma can be speculated on but much uncertainty remains.

Quark deconfinement is postulated to occur when the quark bags touch (low temperature, high density) so that the quarks roam freely. Because there is some uncertainty about model parameters such as the bag size there is also some uncertainty (error bars in Fig. 7) about the critical density. Even at low density the quarks can become deconfined (this may occur in neutron stars). High temperature nucleon collisions create pions (and other hadrons) so eventually the space between the nucleon bags fills up again allowing the quarks to wander. The energy density of a hot gas of pions increases as T^4 above the pion rest mass energy of 140 MeV. Thus one expects the critical temperature to exceed 140 MeV by only a moderate amount as indicated.

The density-temperature history of a system in which a stationary heavy ion is struck, head-on, by a relativistic projectile heavy ion depends on the energy of the projectile. For heavy nuclei present evidence on the linearity of secondary particle production with incident total energy suggests that in the energy regime up to 10 GeV/nucleon or so the energy of the projectile is shared rather completely with the target while the two are in contact. It is on such a basis that trajectories such as that of Fig. 7 are predicted. Beyond 10 GeV/nucleon time dilation and length contraction give rise to a phenomenon called "longitudinal growth" in which much of the secondary production takes place in the wake of the collision and therefore does not contribute to the attainment of high temperatures in the overlap region. Both the Brookhaven proposal for injection of heavy ions into the AGS and the Berkeley letter of intent for a Tevalac - a successor to the present Bevalac - span the energy region up to 10 GeV/nucleon in which there appears to be a good chance for production of a quark-gluon plasma and for which maximum baryon densities can be achieved.

Speculations about the signature of a quark-gluon plasma have focused on photon, dilepton and strange particle production. For example, the shape of the dilepton low-mass spectrum is expected to vary greatly with temperature of the source, with quark-antiquark annihilation assumed to dominate the low-mass portion while $\pi^+\pi^-$ annihilation dominates the high-mass portion. Both the processes which constitute the signature for quark-gluon matter and the detection apparatus for the processes appear, at present, not to have received as much attention as they deserve.

The present plans for relativistic heavy ion physics count a great deal on the existing Bevalac experience. The Bevalac has, for years, produced a variety of heavy ions up to 2 GeV/nucleon and has recently been able to produce even uranium beams in this regime. In addition to the anomalous a large variety of processes have been studied pertaining to nuclear hydrodynamics, projectile and target fragmentation, pion and strange particle production, etc. A very good recent account of this work has been given by Nagamiya and Gyulassy.¹³ The pursuit of these processes can, perhaps, be characterized as highly tantalizing glimpses of somewhat elusive physics accompanied by imaginative ideas and jargon, driven by the desire to create extreme conditions of density and temperature. To an outsider like myself there is also an overwhelming impression that the

Fig. 7. A possible nuclear matter phase diagram with a possible trajectory for a central high-energy nucleus-nucleus collision (dashed line).

instrumentation for heavy ion physics has lagged far behind the capabilities of the accelerators or the needs of the physics. The history of the anomalous is perhaps the best touchstone on which to base such an impression. One is tempted to say that before any major new expedition toward the quark-gluon sea is mounted our very clever community of heavy ion physicists should demonstrate that a proper experiment for the anomalous can be carried out.

There is thus romance and challenge and a great deal of excitement about what can be learned with relativistic heavy ions, both about quark-gluon matter and about the hot hadronic matter which lies between this ultimate state and the physics of normal nuclei.

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