Frontiers of nuclear physics (new isotopes, rapidly rotating nuclei, reactions induced by heavy ions, giant resonances, nuclear forces)[1)]

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Areas of nuclear physics which have seen important developments recently are reviewed: (1) the discovery and study of new unstable isotopes, (2) rapidly rotating nuclei, (3) heavy-ion collisions and the distinctive features of reactions induced by heavy ions, (4) giant multipole resonances, and (5) the nature of nuclear forces and the effective interactions between particles within a nucleus. Many examples are cited to illustrate the progress in these areas.

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In nuclear physics, as in every other science, we are continuously seeing progress in established areas and the development of new areas. Extending our knowledge is a complicated and difficult process, and any breakthrough comes only after many facts have been acquired, interpreted, and subjected to a detailed theoretical analysis.

A nucleus is a complicated entity: a system consisting of a finite number of particles which are interacting strongly with each other. Each nucleus comes with its own particular variety of properties, shapes, and states. Much experience has been gained in research on such entities in nuclear physics; a variety of analysis methods and approximate approaches have been worked out. In this regard we may say that nuclear physics is a laboratory in which the fundamental laws and symmetries of such complicated systems are being studied at the microscopic level. The knowledge which has been acquired is important not only to nuclear physics but also to all natural sciences—from astrophysics to the physics of condensed matter.

In this review we will discuss the most promising directions in nuclear physics which have developed in the 1970s but for which further development is expected over the next decade. The progress which has been achieved in most of these areas has resulted from the construction of heavy-ion accelerators, which have substantially extended the scope of experimental nuclear physics.

NEW ISOTOPES

In the early days of nuclear physics, the bombardment of nuclei with nucleons significantly increased the number of isotopes available for study. Everything which we learned about the nucleus over the past 50 years came from research on about 1600 isotopes, of which only 300 are stable. Today we are being armed with some much more powerful projectiles for bombarding nuclei: ^{238}U ions at an energy of 8 MeV/A and ^{20}Ne ions at 2.1 GeV/A. In the Soviet Union we have seen the start-up of the U-400 accelerator with its intense ion beam; it is being operated at 5 GeV/A (^{12}C). The bombardment U + U can produce about 6000 different isotopes[1] (Fig. 1): four times the number studied to date. Modern spectroscopic methods, which combine an on-line capability with a variety of instruments, including lasers, are making it possible to study an ever-increasing number of isotopes. Experimental apparatus today is simultaneously determining not only M, N, and Z but also the nuclear spin I, the magnetic and quadrupole moments μ and Q, the rms radii of the neutron $\langle r_n\rangle$ and proton $\langle r_p\rangle$ distributions, the deformation parameter, β-spectra, and information on the α, β, and γ transitions.

What can we learn from these new isotopes? At this point it would be impossible to answer this question completely, but we can give several examples. The most important results in research on the neutron and proton distributions in nuclei have been obtained from the isotopes ^{40}Ca and ^{48}Ca. It has been shown that while the neutron and proton radii r_n and r_p are equal in the case of ^{40}Ca they are different in ^{48}Ca: $r_n - r_p \approx 0.2$ F.

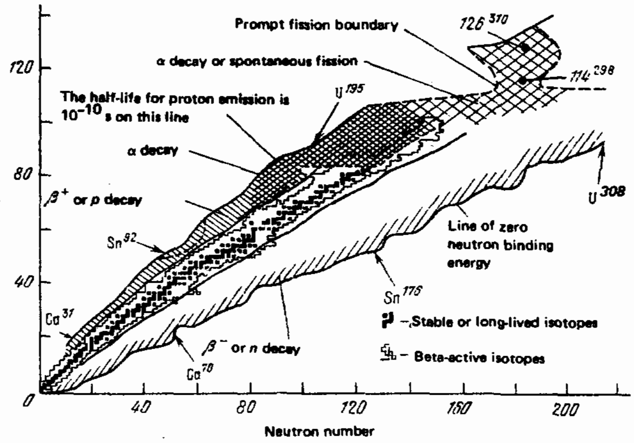

FIG. 1. Nuclear stability diagram. About 6000 different isotopes can presently be produced in nuclear reactions.

[1)] Lecture read to the Fifteenth Winter School of the B. P. Konstantinov Leningrad Institute of Nuclear Physics, Leningrad, 1980.

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But just think how much more we could learn if we were able to study all possible isotopes from ^{31}Ca to ^{70}Ca. We know of ten stable and 18 radioactive isotopes of Sn, but there could be a total of 84, with from 42 to 126 neutrons. Three neutron shells, with $N=50$, 82, and 126, are being filled at the particular number of protons involved here, $Z=50$. How much more could we learn about the symmetry term in the mass formula, the nuclear surface, and the changes in the nuclear shape if we had all these Sn isotopes available? In the case of uranium, there may be 107 isotopes, but at present we know of no more than 15. With these other isotopes available we would be able to study the changes in the fission barrier with increasing N, the relationships among the various decay branches, and other important questions.

Let us look at some of the results which have already been obtained on exotic nuclei. After the isotope ^{32}Ar was produced in reactions, and measurements were carried out on the β^+ decay $^{32}\mathrm{Ar} \rightarrow {}^{32}\mathrm{Cl}$, it became possible to study the isobar multiplet $A=32$, $T=2$ (Table I; Ref. 2). The formula $M(T_z)=a+bT_z+cT_z^2+dT_z^3$ was used to calculate the coefficients a, b, c, and d. If the nuclear forces were charge-independent, the value $d=0$ should have been found; the value actually found was $d=0.5\pm2.5$ keV. Here we may also study the superallowed β^+ decay $^{32}\mathrm{Ar} \rightarrow {}^{32}\mathrm{Cl}^*$ ($I=0^+$; $T=2$; excitation energy 5.033 MeV).

In the mercury isotope ^{185}Hg the $I=1/2^-$ ground state was found to be deformed, while the $I=13/2^+$ isomer state (176 keV) was spherical. These results mean that the potential well in this case is a complex well with two minima. The proton stability boundary is being approached very closely in many places, despite the drastic decreases in the cross sections. For example, the following isotopes have been found: $^{110}_{53}\mathrm{I}_{57}$ ($\Delta N=17$), $^{114}_{53}$Cs ($\Delta N=19$), $^{155}_{71}$Lu ($\Delta N=20$), $^{157}_{73}$Ta ($\Delta N=23$), $^{161}_{75}$Re ($\Delta N=24$), $^{169}_{77}$Ir ($\Delta N=25$) and $^{175}_{79}$Au ($\Delta N=22$). These isotopes are very close to the proton stability boundary and are separated from stable nuclei by the specified number of neutrons ΔN. The nucleus $^{74}_{37}\mathrm{Rb}_{37}$ is also at the stability boundary; its decay half-life is $T_{1/2}=64.9\pm0.5$ ms. This is the heaviest nucleus with $N=Z$ which is known today, and it is even more interesting in that the isospin of the ^{74}Rb ground state is $T=1$, while a state with $T=0$ lies above the ground state and decays by γ emission.

Some important results have been obtained in research on regions of α decay, especially in nuclei with $Z>50$ and in the rare earth region. Study of α-decay cascades can reveal the masses of unstable nuclides within ≤ 100 keV, and the half-lives found can be used to refine the theory for α decay.

TABLE I. Properties of the isoberic quintet with $A=32$.

Nucleus	T_z	Mass excess, keV	E_x, keV
32	+2	-24092.0 ± 7.0	0.0
32	+1	-19231.6 ± 1.2	5073.1 ± 0.9
32	0	-13965.1 ± 4.0	12050.0 ± 4.0
32	−1	-8295.6 ± 5.2	5033.0 ± 10.0
32	−2	-2232.2 ± 33.1	0.0

$M(T_z)=a+bT_z+cT_z^2+dT_z^3$

$a=-13965.1\pm4.0$
$b=+5468.5\pm3.1$
$c=+201.5\pm4.8$
$d=+0.5\pm2.5$

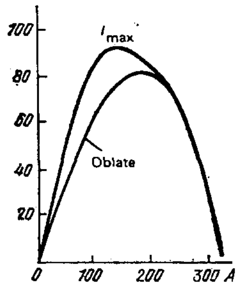

FIG. 2. Maximum orbital angular momentum $I_{\max}$ which a nucleus can acquire, as a function of the mass number A.

The question of the existence of ultraheavy elements remains an intriguing one. Despite a heroic effort, these elements have not yet been observed experimentally, although the theory definitely indicates the possible existence of long-lived elements with filled shells in the region $Z=110-114$.

RAPIDLY ROTATING NUCLEI

Another direction which has developed recently and which has expanded our knowledge of the nucleus is research on high-spin and rapidly rotating nuclear states.[3] Heavy ions can cause nuclei to rotate at angular momenta up to $I\approx100$ (in units of $\hbar$), with a rotational energy reaching $E_{\mathrm{rot}}\approx80$ MeV. A nucleus cannot acquire just any arbitrary value of I. For light nuclei the basic restriction is that the centrifugal energy satisfy $I^2/2MR^2 \leq V_0$, where V_0 is the depth of the potential well, and R is the nuclear radius. For heavy nuclei the limitation on I comes from the decrease in the fission barrier to $B_f=8$ MeV and then to $B_f=0$. The result is the curve in Fig. 2 (Ref. 4). Shell effects increase $I_{\max}$ to 100. If the nucleus is now heated, it will cool through neutron, α, and γ emission and reach yrast band2) at some I. The γ decay of the cold rotating nucleus is observed beginning at $I\approx60$.

Let us assume a spherical nucleus. In this case the orbital angular momentum of the nucleus is determined by the states of the valence nucleons. At a certain value of I, however, the core, polarized by the outer nucleons, begins to take up the motion of these outer nucleons, and the spherical nucleus transforms into a deformed (oblate) nucleus. This phase transition usually occurs at $I=10-20$. This interpretation has been verified experimentally for the nucleus[5] $^{147}_{64}\mathrm{Gd}_{83}$. In its ground state, ^{147}Gd is spherical. The quadrupole moment Q of the isomer state $I=49/2^+$ has been measured (excitation energy of 9 MeV, $T_{1/2}=510$ ns). The result, $Q_{\mathrm{exp}}=3.14$ b, implies an oblate deformation with $\beta=-0.2$. Analysis shows that the valence particles could not be responsible for more than 1.5 b, even with an effective charge.

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2) The yrast levels are the system of levels with the lowest energies for the given spin I.

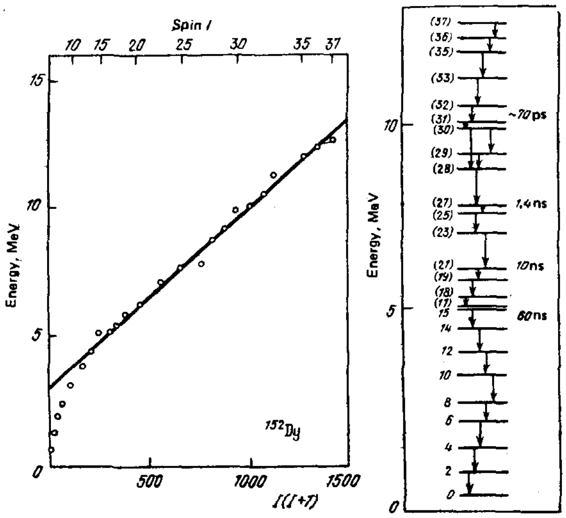

FIG. 3. The yrast spectrum of dysprosium–152. The lower levels correspond to quadrupole vibrations with respect to a spherically equilibrium state. For the upper levels there are irregularities associated with the alignment of the individual particles. The straight line corresponds to an oblate moment of inertia *J*.

Thus the entire nucleus is deformed, and its moment of inertia is approximately that of a rigid body.[3)]

A rotating nucleus has some distinctive characteristics. Now the particles of the nucleus are moving in a self-consistent rotating potential, found from a Hamiltonian of the type

$$H\omega = H - \omega \mathbf{I},$$

where ω is the rotation frequency.

The single-particle states are filled in such a manner that each particle causes the maximum possible increment in the nuclear spin *I*. The higher *I*, the greater the number of particles in the aligned state. Single-particle transitions, frequently extremely hindered, will be predominant along the yrast line[6] (Fig. 3). It is important to note that, despite the pronounced rotation, quantum shell effects remain important; they lead to irregularities in the moment of inertia *J* and to the appearance of isomer states, the so-called yrast traps. All this can be seen well in the spectrum of ^{154}Er (Fig. 4; Ref. 7); there is a sharp change in slope between $I = 10$ and $I = 12$, and there are irregularities further up the spectrum (shown for comparison is the spectrum of the deformed nucleus ^{158}Dy). What happens as *I* is increased further? Calculations show quite convincingly that another phase transition will occur at $I = 40–60$, where the oblate nucleus will become prolate or triaxial, rotating around a symmetry axis or around all three axes.

If a nucleus is prolate in its initial state ($I = 0$) and is rotating around an axis perpendicular to the symmetry axis, then collective rotational states with short lifetimes are known to form (cf. Fig. 4b). When the Coriolis energy becomes greater than the deformation energy, pairs of nucleons having a high single-particle spin *j* rotate in such a manner that the spin **j** precesses around the rotation axis **R**. The moment of inertia of the nucleus increases, and a new yrast band arises. As a result of several pairs rotating, the shape of the nucleus changes from prolate to oblate, and the nucleus itself transforms from a superfluid state to an ordinary state. In certain nuclei this phase transition occurs rapidly. Figure 5 shows results calculated for the ^{180}Hf spectrum by the Hartree–Fock–Bogolyubov method in the cranking model.[8] At small values of *I* there is an ordinary collective rotational spectrum, and the experimental points conform well to the theoretical curve. At $I = 26$, however, the main band, *A*, intersects a new band, *B*, whose internal structure is sharply different from that of the first band. The symmetry axis, which had previously been along the *z* axis, is now along the rotation axis (*y*). The gap Δ is much smaller; the nucleus has become oblate; and the moment of inertia *J* has more than doubled. Further study of the phase transition in ^{180}Hf and other nuclei will reveal new details of the behavior of nuclei under critical conditions. Experimentalists and theoreticians have devoted much effort to rapidly rotating nuclei over the past six years. They have studied several dozen nuclei in an effort to determine how the aligning of particles along the rotation axis and the increase in *I* change the balance between the single-particle and collection properties in the nucleus and how the nuclear shape changes. Interesting

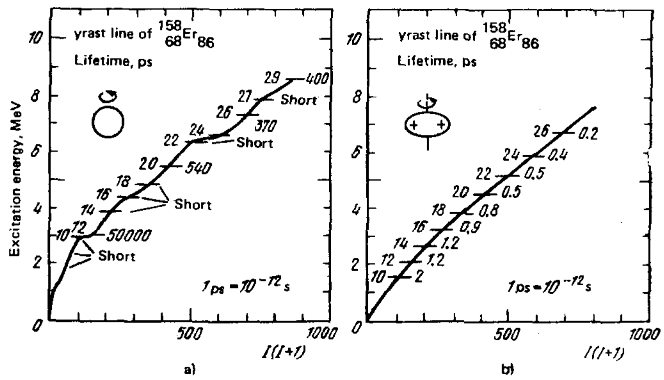

FIG. 4. Nuclear lifetimes. a: The nucleus ^{154}Er, which is spherical in its ground state and which exhibits pronounced changes in shape at $I > 10$. b: Prolate rotating nucleus ^{158}Dy.

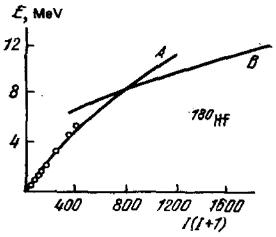

FIG. 5. Excitation energies of bands *A* and *B* as functions of $I(I+1)$. The experimentally known levels of ^{180}Hf are shown by the open circles. The effective moments of inertia near the intersection point are 66.7 and 153 MeV^{-1} for bands *A* and *B*, respectively.

[3)] The values of *Q* have also been measured for ^{147}Gd isomers with $I = 13/2^+$ ($Q = 0.73$ *b*), $I = 27/2$ (1.26 *b*), and $I = 59/2$ (3.8 *b*).

results have also been obtained from an analysis of the rich level spectrum at energies above the yrast band. It has been found that there is an isomerism region with large I including nuclei with $61 \leq Z \leq 71$ and $82 \leq N \leq 88$. Most of theoretical work has been based on the liquid-drop model with shell corrections by the Strutinsky method. For several nuclei, calculations have been carried out by the Hartree–Fock–Bogolyubov method in the cranking model (HFBC), and calculations have been started using the formalism in which the motion of the particles is described in a time-dependent self-consistent field with a Coriolis interaction (TDMFC).[9]

The possibilities for studying nuclear states with spin $I < 20$ have improved substantially. Figure 6 shows the spectrum of ^{164}Er, which is one of the richest spectra known and a good illustration of the modern experimental possibilities for studying γ spectra. In addition to the main band there are superbands—even and odd, a γ band, and two more yrare superbands. Analysis of Coulomb excitation has yielded the values of $B(E2)$ for the main and γ bands. A theoretical analysis of the ^{164}Er spectrum has been carried out on the basis of the rotational-alignment model, and the results have been entirely satisfactory.

Research on rapidly rotating and high-spin states has revealed far more than could have been expected. A great variety of transformations and transitions has been found, and research in this area of nuclear structure is just beginning to pick up speed.

REACTIONS INDUCED BY HEAVY IONS

We turn now to the actual reactions induced by heavy ions. The events which occur when an ion strikes a nucleus can be described schematically as follows (Fig. 7): At large values of l the ion is scattered elastically and collective levels undergo Coulomb excitation. At grazing values, l_{gr}, nuclear forces come into play, and inelastic reactions occur. Giant resonances are excited, and exchange, pickup, and other "direct" reactions occur. In such collisions one can observe an interference of Coulomb and nuclear forces. As a result, the maximum in the elastic cross section occurs near the "rainbow angle," which corresponds to a smaller impact parameter b than in a purely Coulomb collision. With a further decrease in b, the contact time increases, the losses of energy and particles increase, and we enter the region of deep inelastic reactions. Finally, at $l < l_{crit}$, fusion occurs, accompanied by the formation of compound states with a high spin I.

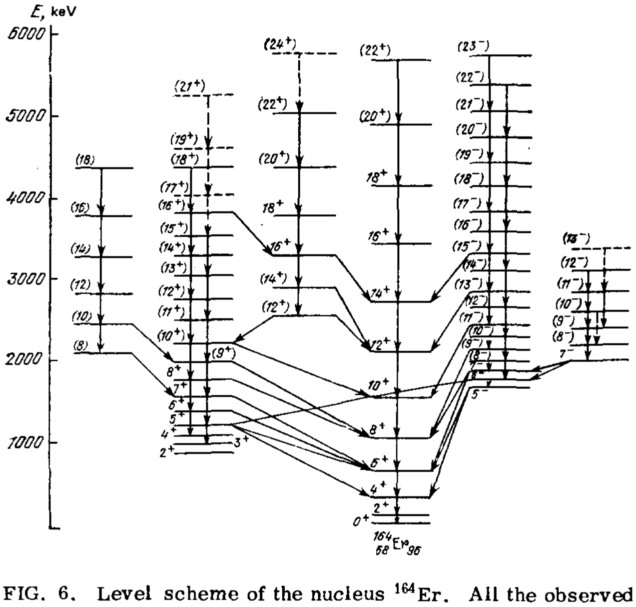

FIG. 6. Level scheme of the nucleus ^{164}Er. All the observed bands other than the ground band are shown.

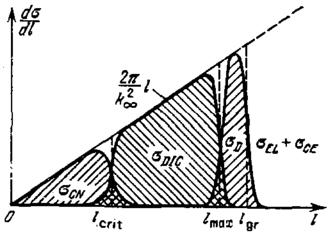

FIG. 7. Schematic picture of the reactions which occur in the collision of ions as a function of the relative orbital angular momentum l.

The theoretical approaches which have been taken to describe these reactions are quite varied. Many classical and semiclassical approximations have been worked out on the basis of some kind of N–N interaction. Among the microscopic models we would like to single out the TDHF mode, which is based on the idea that the average field formed by the N–N interaction is also responsible for the collective motion. There are no phenomenological parameters in these calculations, but they do not incorporate scattering by the individual nucleons or energy dissipation. The macroscopic models for describing nuclear reactions can be divided further into dynamic and statistical models. Since the number of particles actively involved in the reaction may be quite large—but not large enough to really justify use of thermodynamic equations—it is usually very difficult to

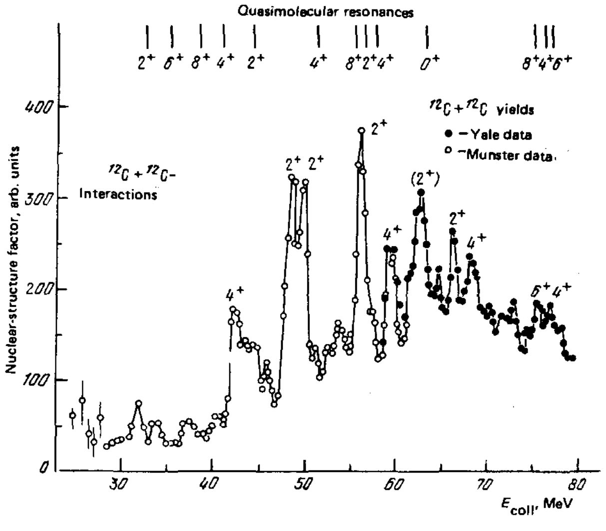

FIG. 8. Quasimolecular resonances in the ^{12}C+ ^{12}C system. The vertical lines at the top are theoretical results.

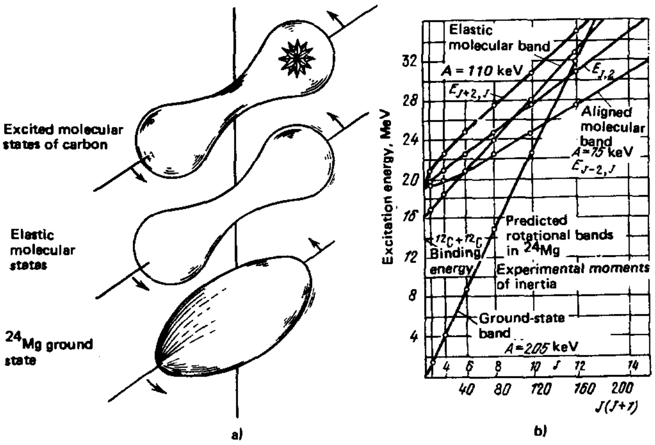

FIG. 9. a: Schematic diagram of the states of the ^{12}C+ ^{12}C system. b: Trajectories corresponding to various rotational bands. The curves are drawn through the experimental points. The corresponding moments of inertia are given. $A = \hbar^2/2J$ (the spin is denoted by J in part b).

describe these particles. Theoreticians have a lot of work ahead in deciphering the events which occur in ion-ion collisions.

Reactions induced by heavy ions have presented us with some unexpected phenomena, many of which still await explanation. For our discussion of some of these phenomena, we will consider one of the simplest reactions: the production of nuclear molecular states.[10] These states were first observed in 1960 in a ^{12}C + ^{12}C reaction; narrow resonances were observed in the reaction cross section as a function of the energy at excitation energies up to 40 MeV (Fig. 8). Fifteen years of persistent work finally clarified what was happening. Under certain conditions the two ^{12}C nuclei do not fuse but instead revolve around each other, remaining in the ground or 2^+ first excited state (Fig. 9). As a result, rotational bands form above the ground rotational band of the ^{24}Mg nucleus. Why are these levels so narrow at these high excitation energies, rather than broadened over other compound states? It turns out that there is a narrow corridor in the function $\rho(E,I)$ for this reaction (Fig. 10) in which the density of compound states is low.

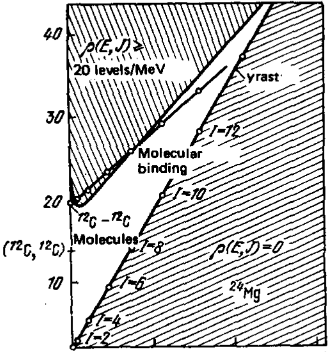

FIG. 10. Schematic diagram of the molecular resonance "corridor." The upper boundary of the corridor corresponds to $\rho(E, I) \geqslant 20$ levels/MeV. The quantity plotted along the ordinate is the excitation energy of ^{24}Mg.

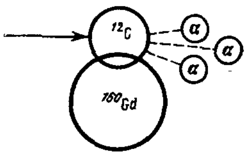

FIG. 11.

Rotational levels falling in this corridor thus have little chance to decay into other excited states. The theoretically predicted spectrum of molecular ^{24}Mg* (the vertical lines at the top in Fig. 8) agrees completely with the experimental spectrum. It is worthy of note that a similar corridor, but narrower, exists for the system ^{12}C + ^{16}O and (possibly) the system ^{30}S + ^{30}S, but it does not exist for ^{16}O + ^{16}O or ^{12}C + ^{13}C. Molecular interactions are also interesting because they permit a study of the effective potential V_{eff} between two nuclei, the individual inelastic channels (p, α, etc.), and how these channels affect the imaginary part of the potential.

A general observation in these reactions is that the nucleons of the ion and of the target retain their coherent motion even in deep inelastic collisions, so that the degrees of freedom of each of the two colliding nuclei must be considered separately in a description of the collision. For example, in bombardment by ions with energies ≤10 MeV/A the largest cross section (aside from the fusion cross section) corresponds to the reaction in which an ion loses almost all its kinetic energy (up to 100 MeV) but retains its original mass and charge. The fusion cross section σ_{fus} is always smaller than the calculated value σ_{fus}^{calc}. Particle-exchange reactions frequently proceed as a direct process, even when up to seven nucleons are exchanged, as in the reaction ^{197}Au (^{19}F^{12}B)^{284}Tl. The reaction ^{12}C + ^{160}Gd deserves a detailed description.[11] Here there is a large cross section for forward emission of α particles as a result of incomplete fusion or a breakup of the ^{12}C nucleus. The cross section for the reaction involving α emission increases with increasing ^{12}C energy (Table II). Interestingly, some 150–600 mb of σ_{singl} corresponds to the emission of three α particles simultaneously, $\sigma_{3\alpha}$ (Fig. 11). The α–γ coincidences show that the ^{160}Gd nucleus remains weakly excited in this case. In this case we are thus dealing with a quasielastic breakup of ^{12}C in a time-varying nuclear field $V(\mathbf{r}, t)$. This varying field $V(\mathbf{r}, t)$ may be so strong for fast ions that even an α particle will break up. In the experiment[12] ^{90}Zr + α (35 MeV/A) it has been observed that fast protons are emitted in the forward direction with an average energy

TABLE II. Cross sections for α emission, σ_{singl}^{α}, and total reaction cross sections, σ_{react}^{tot}, in collisions of ^{12}C with ^{160}Gd.

E (^{12}C), MeV	σ_{singl}^{α}, mb	σ_{react}^{tot}, mb
120	850	2260
160	1200	2600
200	2100	2800

$E_p^{av} \approx 40$ MeV. The basic mechanisms for the emission of fast protons are the pickup of a triton, while the proton remains a "spectator," and the quasielastic breakup of an α particle, which can be established from the p-t angular correlation.

Reactions involving the forward emission of α particles have been studied in the Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research in the collisions of ^{20,22}Ne ions (5–10 MeV/A) with Ta, Au, and Th nuclei.[13] The α spectra found have a large high-energy component, which ends at an α energy corresponding to the capture of the entire remaining nucleus (Ne – ^{4}He) as a whole to one of the discrete levels of a compound nucleus. Here $E_\alpha \approx 140$ MeV. The forward emission of α particles is two orders of magnitude more intense than for tritons and an order of magnitude more intense than for deuterons. The high-energy component of the α particles may result from several mechanisms, and correlation measurements are required for a study of these mechanisms.

Analysis of the products of collisions of relativistic ions shows that the entities involved in the reaction are those parts of the nuclei which make direct contact with each other (Fig. 12). The other fragments are simply moving "spectators." The colliding parts are greatly heated, and an ultradense medium may form, as may a shock wave; in all cases, fast nucleons and π mesons are emitted in a broad cone. All these events are presently being studied by singling out central collisions, for which the interpretation is less ambiguous. At present we cannot say for certain whether ultradense states of matter exist or whether shock waves form in nuclei.

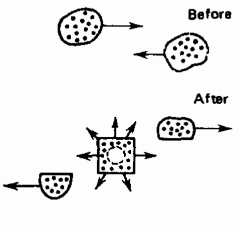

FIG. 12.

GIANT RESONANCES

Giant multipole resonances are natural vibrational modes of the system: zero-sound waves which propagate through the cold nucleus. The fact that such modes exist in a system as small as a nucleus is remarkable indeed. Some perturbation must be caused in a nucleus in order to excite giant multipole resonances. Then the nuclear density can be written as a function of the type

$$\rho(\mathbf{r}, t) = \rho_0 + \delta\rho(\mathbf{r}, t).$$

Expanding $\delta\rho(\mathbf{r}, t)$ in spherical waves, we have

$$\delta\rho(\mathbf{r}, t) = \sum_{n, l, \mathbf{k}} \rho_0 \alpha_{nl}(t)\, j_l(k_{nl} r)\, Y_{nl}(\cos\theta),$$

where j_l is the spherical Bessel function; θ is the angle between the position vector $\mathbf{r}$ and the wave vector of the vibration, $\mathbf{k}$, α_{nl} is a function of the time; and n is the overtone index. The wave vectors in a sphere take on several discrete values,

$$k_{nl} = \frac{x_{nl}}{R} = \mathrm{const}\, A^{-1/3}.$$

As a result, isoscalar vibrations of various multipolarities l arise with frequencies

$$\omega_{nl} = \frac{\pi}{\hbar} k_{nl} v_c,$$

where the vibrational velocity v_c is determined by the compressibility $b_{\mathrm{com}} = 15$ MeV according to the following formula:

$$v_c = \sqrt{\frac{b_{\mathrm{com}}}{M}}.$$

Since these vibrations take up a substantial fraction of the oscillator strength, they have been labeled "giant resonances." Polarization waves corresponding to out-of-phase oscillations of protons and neutrons also form in a nucleus. Among the nuclear polarization waves which have been familiar for a long time are the giant electric dipole resonances.

From the microscopic standpoint, the giant multipole resonances are correlated excitations involving a particle and a hole, two particles and two holes, etc. The existence of resonances reflects a structure in the continuous spectrum of nuclei. Giant multipole resonances were discovered in the early 1970s and were the object of intense study throughout the decade. They are excited by electrons, protons, tritons, α particles, and ions. The most detailed studies have been made of the quadrupole ($E2$) resonances in nuclei from ^{12}C to ^{238}U. The energy of the quadrupole resonance can be described quite well by

$$\hbar\omega\,(\mathrm{E2}) \approx 63\, A^{-1/3}\,\mathrm{MeV},$$

and nearly the entire intensity is concentrated in a single peak of width ≈3 MeV. The $E2$ resonance is thus convenient for study. The energies of the $E0$, $E1$, and $E3$ resonances have also been measured for several nuclei. Resonances of higher multipolarity are distributed over a broad energy range.

Many calculations have been carried out for the excitation cross sections of giant resonances, by both microscopic and macroscopic approaches. All lead to generally correct positions and resultant intensities for the resonances, but they have not yet succeeded in giving the peak widths correctly. Table III shows the results calculated for σ^l, the corss section for the excitation of resonances in the nuclei ^{40}Ca and ^{56}Ni by 1-GeV protons. We see that the values of σ^l_{res} are not small and that the giant resonances constitute an important channel for the inelastic scattering of particles by nuclei.

The decay of the giant resonances is a particularly interesting question. It occurs in a time of 10^{-22} s,

TABLE III Cross sections for the excitation of giant multipole resonances, σ^l_{res} (mb).

Nucleus	E0	E2	E3	E4	E5	E6	E7
^{40}Ca		17	9	20	11	6	
^{56}Ni	2.0	10	9	12	12	10	7

much too short for thermalization to occur in the nucleus, so that the usual statistical channels play only a minor role. For example, the giant quadrupole resonance in ^{16}O decays through the emission primarily of α particles. An analogous situation is observed in experiments on the excitation of giant quadrupole resonances by electrons in ^{40}Ca and in Ni isotopes. These results must be verified in reactions with protons and α particles. An important role may be played in the decay of giant resonances by α-cluster levels, whose excitation has been studied thoroughly in nuclei up to ^{40}Ca. Research on the various decay channels of the giant resonances is very important, and we can expect to see new results on the structure of excited nuclear states.

NUCLEAR FORCES

The problem of nuclear forces is as old as nuclear physics itself. Analysis of the huge amount of experimental information on nucleon scattering has revealed the radial distribution of the interaction potential, $V(r)$ (Fig. 13). If spin and isospin are taken into account along with the angular relations $(S, P, D, \ldots)$, it takes about 40 parameters to completely specify the potential $V(\mathbf{r}, \sigma, \tau)$. Several potentials have accordingly been proposed: the Hamada–Johnston potential, the Reid potential, etc. We were not content with this situation. The search for a physical understanding of nuclear forces resulted in the development of a meson theory of strong interactions. It was found that the potential curve (Fig. 13) can be described by the virtual exchange of $\pi^{\pm,0}$ mesons between nucleons at relative distances greater than 1 F. The strong attraction (the potential well) results primarily from 2π-meson exchange. The situation here is analogous to the appearance of molecular forces as a result of the virtual exchange of two photons—the so-called dispersion mechanism, which is determined by the existence of excited nucleon states N^* (Fig. 14). Such excitations cause nonzero polarizations, which in turn cause attractive forces. At shorter distances (<0.5 F) other known mesons may participate in the exchange, so that the situation becomes too complicated to be analyzed. At even shorter distances a phenomenological strong repulsion or "core" is introduced, and in this manner the curve in Fig. 13 can be described completely.

Today, however, we know that mesons are not elementary particles but instead consist of quark–antiquark pairs. Now a microscopic description of strong interactions must be constructed at a deeper level, on the basis of quantum chromodynamics. There is a paradox here: In quantum chromodynamics it is a simpler matter to explain and numerically derive the short-range repulsion than the long-range attraction. The behavior of the forces is explained in terms of the exchange of a quark and a gluon between two nucleons (Fig. 15). Because of quark confinement, this exchange can occur only when the nucleons come close together. Just how close this actually is we do not know at present, and this question is the subject of an intense discussion in the literature. Exchange of π mesons is not ruled out in quantum chromodynamics, but now the process is to be understood as the simultaneous exchange of quark–antiquark pairs. It may be that the virtual exchange of two gluons, similar to the exchange of two photons, is responsible for the appearance of van der Waals forces in nuclear interactions.

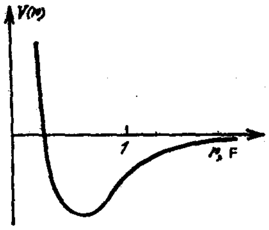

FIG. 13.

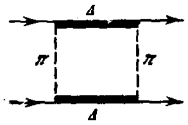

FIG. 14.

The current developments in relativistic nuclear physics, both theoretical and experimental are valuable in that they will build a bridge between the physics of elementary particles (quantum chromodynamics) and nuclear physics.

What effects should the quark model explain in nuclear physics, and what effects does it predict? We can cite, for example, the determination of the deuteron form factor at large momentum transfer q, deep inelastic collisions with transfer of large q, and the nature of scattering into a region forbidden to free nucleons. It may be that processes occur in a nucleus in which the color degrees of freedom of quarks are manifested. At the moment there is very little that we know about all this and much that we do not understand.

We can assume that we will eventually understand the forces acting between two nucleons. In a nucleus, however, these forces are renormalized, and substantially. Even for nuclear matter we cannot yet carry out this renormalization in a systematic way. Experience has shown, however, that for many effects in a nucleus it is sufficient to have simply a qualitative understanding of the interaction. Then by writing the effective interaction in a general form with an appropriate set of parameters we can carry out calculations for these effects and determine the parameters. It has become a popular approach to use a Skyrme interaction. The parameters of the Skyrme forces are determined from Hartree–Fock calculations of the basic nuclear properties, which

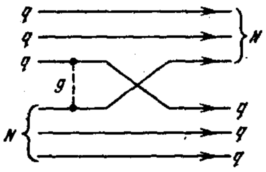

FIG. 15.

depend only on certain average characteristics of the interaction between particles of the nucleus. Among these quantities are the binding energy, the mass distribution, and the single-particle spectra. The Skyrme forces, however, are applicable to spin-saturation systems ($I = 0$) and are not applicable for calculating nuclear two- and three-particle spectra. Attempts to find an effective finite-radius interaction for the valence nucleons have so far been unsatisfactory. Much information has been acquired, however, on the effective interaction between valence nucleons. In particular, the parameters of the central forces, their spin structure, and their isospin structure have been determined quite reliably. Much information is available on the effects of tensor and spin–orbit forces. Consequently, although a lot of work lies ahead, there can be no doubt that an effective interaction of the type being sought (physically justified and convenient for calculations) will be found.

It follows from this discussion that nuclear physics is growing rapidly and that we can look toward the future with much optimism. The opportunities in nuclear physics will of course grow rapidly; promising new directions, difficult to predict at this point, will open up; and we will see some major new developments.

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