20 Nuclear Structure

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20.1 Introduction

The atomic nucleus is a finite many-body quantal system consisting of a well-defined number of protons, Z, and neutrons, N, commonly called the nucleons, which are bound together by the strong nuclear force. Under its influence, the nucleus displays a remarkable diversity of phenomena and symmetries involving many different degrees of freedom, and still, after decades of studies, when pushed to the very limits of its stability, it continues to surprise physicists as completely unexpected properties are revealed by increasingly sensitive instruments. The improved sophistication of experimental techniques in the past two decades has allowed us to study nuclei under extreme conditions, and to follow the evolution of nuclear structure to the limits in several directions. At the limit of angular momentum, we study extremely rapid nuclear rotations in individual nuclei. At the limit of excitation energy, we probe nuclear properties at high temperature. In nuclei very far away from the valley of stability, we seek the limits of existence of nuclear matter: Where are the proton and neutron drip lines, and where does the Table of Elements end?

The principal goal is to come to an understanding of the strong nucleon–nucleon interaction. It is affected by the nuclear medium, which responds differently when pushed to extremes in rotational frequency, temperature, isospin, or mass. The information we seek is revealed by studies of the excitation modes and decay properties of the nucleus. Many exciting new discoveries have been uncovered in nuclear-structure physics in recent years, only a few of which can be discussed in this chapter. It will focus on a selection of results under extreme conditions obtained with state-of-the-art γ-ray multidetector arrays.

20.2 Instrumentation

20.2.1 Electrostatic Accelerators

Electrostatic accelerators are ideal for the study of nuclear reactions (see Chap. 21) and nuclear structure. They can deliver a large variety of stable

beams, from protons up to very heavy ions, with large duty cycles and high intensities. The type of nuclear reaction to employ in a specific experiment is determined by the nucleus of interest and the particular quantum states one wants to investigate. Nuclei on the neutron-deficient side of stability are most efficiently reached by heavy-ion fusion-evaporation reactions, whereas moderately neutron-rich nuclei can be populated in, for example, quasi-elastic or multinucleon transfer reactions. However, the production rate of nuclei with extreme values of isospin is small in almost any kind of nuclear reaction involving stable beams and targets. This must be compensated for by high efficiency and selectivity of the detector systems.

The first electrostatic generator accelerating a nuclear beam was reported by Van de Graaff in 1931 [1], but it took until 1951 before the first real electrostatic accelerator was produced by HVEC. During the 1950s and 1960s, HVEC delivered more than forty tandem accelerators from their very successful EN and FN series of accelerators to laboratories and universities all over the world. These two decades saw a very rapid development of the basic nuclear models of the atomic nucleus, which was the result of a very close interplay between theory and experiment, and it is clear that the early tandem accelerators played an enormously important role in this development. Today it is possible to accelerate heavy ions to beam energies beyond the Coulomb barrier for many projectile–target combinations using tandem accelerators of the FN, MP, XTU, and ESTU types from HVEC, Pelletron accelerators from NEC, or high-voltage machines built by physicists at their home institutes. An example of the latter has been the VIVITRON tandem accelerator (terminated in December 2003) at the Institut de Recherches Subatomique (IReS) in Strasbourg. To extend our present knowledge of nuclear structure with stable-beam experiments requires high-intensity accelerators. However, for a full exploration of the nuclear landscape we must finally employ radioactive-ion-beam (RIB) facilities. Electrostatic accelerators will, in this context, continue to play a role as demonstrated at, for example, the Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory, USA, where the produced radioactive ions are injected into and accelerated by a 25 MV tandem accelerator.

20.2.2 Detectors

The most powerful tool to study the structure of nuclei is high-precision γ-ray spectroscopy of the decay of their excited states. During the last two decades, developments in the techniques of γ-ray spectroscopy have led to the construction of large 4π multidetector systems comprising several hundreds of escape-suppressed detector elements. These developments have set new limits on γ detector technology and have provided a significant step forward in basic nuclear-structure research.

One such state-of-the-art instrument has been EUROBALL [2–4], which is shown in Fig. 20.1. It comprises 239 Ge crystals covering 45% of the solid

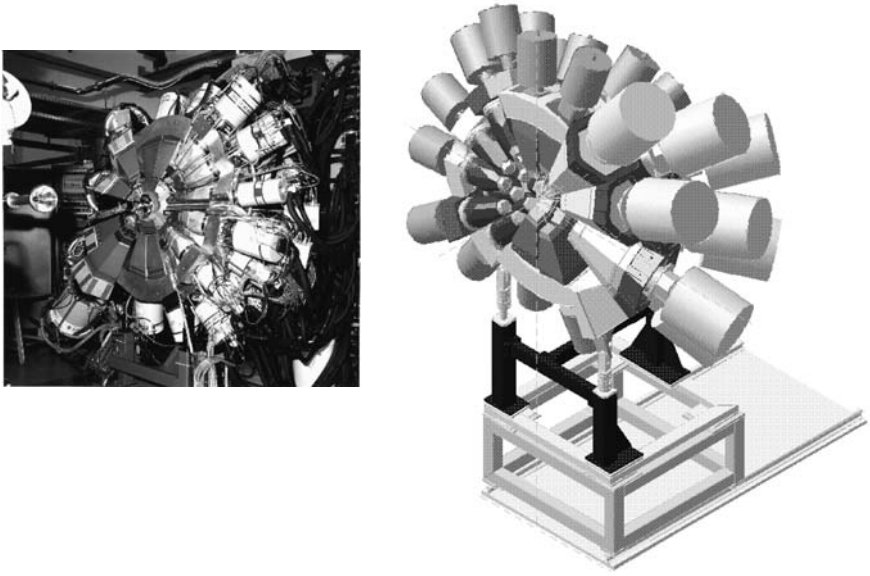

Fig. 20.1. The *left-hand* side shows a picture of the open EUROBALL array at Strasbourg, France. The *right-hand* side sketches the Ge detectors of EUROBALL. Courtesy of John Simpson

angle, and was installed at two of the main nuclear-structure facilities at Europe: the XTU-ALPI accelerator facilities of the Legnaro National Laboratory (LNL), Italy, and the VIVITRON tandem accelerator facility at IReS, Strasbourg, France. GAMMASPHERE is a similar instrument developed in the USA [5–7].

Both EUROBALL and GAMMASPHERE combine high efficiencies for detecting γ-rays with high energy resolution. In particular, they are very powerful for the measurement of high-multiplicity γ-ray cascades. Still, their performance is limited to an efficiency of about 10% for γ-ray energies of 1 MeV, and to a response function (signal-to-noise-ratio) with a maximum of 60% of the total intensity in the full energy peak. The latter is achieved by rejecting the signal from the Ge detector when the surrounding scintillator shield detects Compton-scattered γ-rays from the Ge crystal. These suppression shields limit the coverage with Ge detectors to less than one half of the solid angle, reducing the high-resolution efficiency considerably. The next major advance requires the replacement of the passive suppression shields by active Ge detectors. A solution to the problem of Compton scattering is the tracking of the γ-ray interaction path. Recent advances in crystal segmentation technology and digital signal processing have opened up the possibility of operating the Ge detectors in a position-sensitive mode with high count rates. This enables the construction of a compact 4π array made solely of

Ge detectors. It is expected that segmented Ge detectors combined with the tracking technique will improve the sensitivity for coincidence γ-ray detection by two orders of magnitude over the current generation of Ge arrays. Two such arrays are presently being developed, AGATA [8] in Europe and GRETA [9] in the USA.

To study exotic nuclei, the γ-ray detection has to be combined with efficient and selective ancillary detectors, such as devices for the detection of light charged particles, neutrons, evaporation residues, fission fragments, and binary-reaction products.

20.3 Limits of Angular Momentum

Nuclei generate angular momentum in basically two different ways, by means of the single-particle motion of the individual nucleons and by the collective vibrational or rotational motion of the nucleus as a whole.

The total angular momentum of a nucleon, $\boldsymbol{j}$, is the sum of its orbital angular momentum, $\boldsymbol{l}$, and intrinsic spin, $\boldsymbol{s}$. Owing to the specific properties of the so-called pairing interaction, nucleons prefer to couple into pairs with angular momentum zero, similar to the Cooper pairs of electrons. Therefore, in the ground state of an even–even nucleus, the total angular momentum is also zero, and nuclear matter in its ground state is superfluid. To generate angular momentum from single-particle motion requires the successive breaking of nucleon pairs combined with the promotion of individual nucleons to higher-lying orbitals, which generally leads to an irregular sequence of states and γ-decay patterns. In contrast, regular sequences of states are due to collective rotational motion. The states form rotational bands for which the excitation energy is proportional to the square of the angular momentum, i.e. $E_x \sim I(I+1)$.

Single-particle and collective modes of excitation can coexist in one single nucleus. Figure 20.2 shows the decay scheme of the doubly magic nucleus ^{56}Ni, which is spherical in its ground state and develops the expected irregular pattern on top of it (left-hand side of Fig. 20.2). At about spin $J = 10\hbar$ and an excitation energy of $\sim$10 MeV, however, two regular rotational bands compete with the spherical states (middle of Fig. 20.2). While most of the decay intensity proceeds via normal γ-decay paths into the ground state of ^{56}Ni, one state in the second rotational band emits, in about 50% of cases, a monoenergetic proton, leading to the spherical ground state of ^{55}Co [10].

In quantum mechanics, a rotation can arise only for systems having a deformed shape. In an even–even deformed axially symmetric nucleus, the rotation takes place around an axis R perpendicular to the symmetry axis z (see Fig. 20.2). The deformed nucleus is brought into rotational motion by bombardment with a nuclear projectile. The quantum mechanical description of the rotor gives rise to rotational quantum states, and information

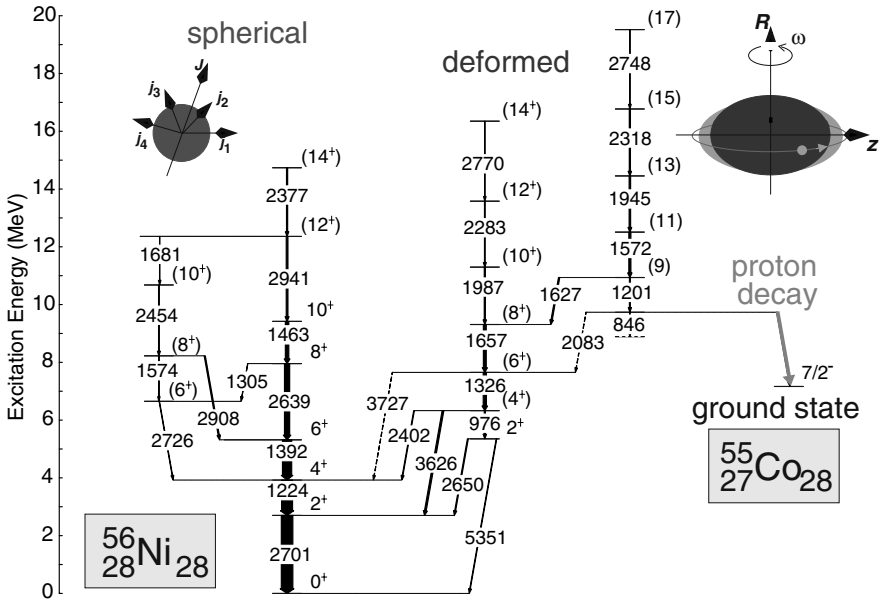

Fig. 20.2. Decay scheme of ^{56}Ni [10]. The γ-ray energy labels are in keV, and the states are labeled with their spin and parity if experimentally known. *Dashed* lines denote tentative transitions and states

on the properties and the behavior of these states is contained in a cascade of up to thirty γ-rays emitted as the nucleus deexcites to its ground state from the highly excited state in which it was produced. Rotating nuclei are extremely interesting because of the presence of both shell structure and superconductivity, and with up to 5×10^{20} revolutions/s they mark the fastest-rotating complex systems known. Such an extremely rapid rotation induces very strong centrifugal and Coriolis forces acting on the individual nucleons, which counteract the strong force itself. Under the influence of these forces the nuclear many-body system may stabilize in some exotic deformed shape (see Fig. 20.3), but these forces also have other dramatic consequences for the structure of the nucleus. The Coriolis force, for example, will try to align the angular momenta of the individual nucleons along the axis of rotation, which will destroy the Cooper pairs responsible for superconductivity. At some rotational frequency many pairs may be broken, causing nuclear superconductivity to be quenched, or even to disappear, giving rise to a phase transition from superfluidity to normal nuclear matter. Large rotational velocities can also induce a gradual shape transition from the deformed state, which rotates, to a nearly spherical shape incapable of rotational motion. Such an abrupt end of the rotational motion, a band termination, has been seen in a number of nuclei [11]. Some nuclei can form states of unusually high angular momentum by breaking just a few nucleon pairs. It is of particular

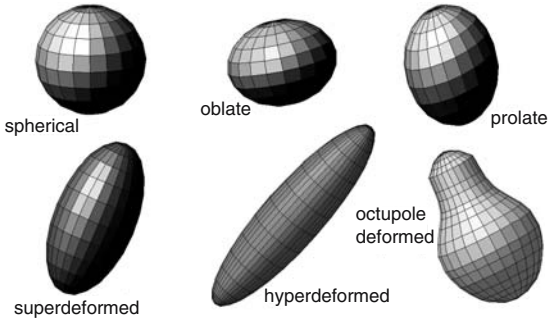

Fig. 20.3. Shapes of nuclei

interest to probe the properties of such highly excited single-particle states in deformed axially symmetric nuclei. These so-called K-isomers can have lifetimes of several years [12].

The advances in nuclear instrumentation have allowed new insights into nuclear behavior at low angular momentum also. Vibrational multiphonon states have been observed in several nuclei, which provide a more profound understanding of the mechanisms of nuclear vibrations. Important concepts in the description of low-lying collective states in nuclei are the dynamical symmetries, which have gained enormous success with the interacting-boson model [13]. Recently, a related concept, that of the so-called critical point symmetries, has been introduced to elucidate the nature of quantum phase transitions in nuclei [14]. Experimental programs around these symmetries are ongoing at the tandem accelerator laboratories at Yale University, USA, and the University of Cologne, Germany.

20.3.1 Superdeformation and Chaos in Nuclei

The most common deformed shapes of nuclei are axially symmetric prolate shapes. They are found in the ground states of nuclei in, for example, the rare-earth and actinide regions of the nuclidic chart. Some of the actinide nuclei have been found to be superdeformed in a second minimum of the potential-energy surface [15], in which the ratio between the long and short axes of the nucleus is 2:1 (see Fig. 20.3). At high angular momentum, superdeformation has been inferred from long cascades of equally spaced γ-rays, first discovered at the tandem accelerator at Daresbury Laboratory, UK, in 1986 in the nucleus ^{152}Dy [16]. With the EUROBALL and GAMMASPHERE arrays, designed to pick out high-multiplicity cascades of γ-rays, discrete nuclear quantum states of superdeformed rotational bands have since then been identified in many nuclei in several mass regions throughout the nuclidic chart [17].

The rotational motion in the superdeformed band is ordered, i.e., it is well characterized by a set of quantum numbers. The heads of the superdeformed

bands lie about 3–5 MeV above the normally deformed states with similar angular momentum. Since the level density increases exponentially with excitation energy, the superdeformed states are embedded in a sea of numerous normal deformed states, which may be described in terms of chaotic motion. The superdeformed states represent order in chaos, and the γ decay-out from the superdeformed bands serves as a probe to study chaos in nuclei [18].

20.3.2 Hyperdeformation and Clustering Phenomena

A prolate axially symmetric structure with a long-to-short axis ratio of 3:1 is called hyperdeformed. It has been predicted in different mass regions at very high angular momenta and excitation energies, and possible evidence for such a highly deformed structure has been sought in many experiments. The entrance channel into the hyperdeformed structure is very weak, and much emphasis has been devoted to studying the interplay between reaction dynamics, binding energies, and fission barriers to optimize the population of the hyperdeformed structures. It has been possible to observe, through the so-called ridge structure in two-dimensional γ-ray spectra, rotational structures from very weak decay paths of the nucleus. The width between the ridges is inversely proportional to the moment of inertia of the deformed nucleus, and in some nuclei the deduced moments of inertia correspond to very large deformations. Ongoing experimental work is trying to find evidence of discrete γ-ray transitions deexciting the hyperdeformed rotational states. An extensive experimental search for these transitions was recently undertaken in ^{126}Ba [19] at EUROBALL.

Very elongated shapes are also predicted in light nuclei. They are related to nuclear clustering phenomena, i.e., to strongly bound substructures such as alpha particles. Three alpha particles in a row, for example, would constitute a hyperdeformed structure in the ^{12}C nucleus. Their existence is mainly deduced from the observation of resonances in binary reaction channels, but recently such states have been searched for in γ-ray spectroscopy using EUROBALL coupled to dedicated ancillary detectors.

20.3.3 Triaxial Rotational Motion and Wobbling

At high excitation energy, nuclei may also develop shapes in which the axial symmetry is broken. This has to do with a subtle balance between the effects of the Coriolis and centrifugal forces and the influence of specific nucleon orbitals coming close to the Fermi surface of the nucleus. The rotation of an even–even nucleus in its ground-state configuration gives rise to a regular rotational band. However, the regularity may be influenced by the excitation of individual nucleons to higher-lying orbitals, which will tend to align their angular momenta with the axis of collective rotation. A classical image of such a situation is known from studies of the rigid top, which under specific initial

conditions will produce a characteristic precession phenomenon. Generally, one associates the word "wobbling" with this type of motion. A prerequisite for a wobbling mode in a nucleus is the breaking of the axial symmetry of the nucleus. The precession motion is represented by small-amplitude fluctuations of the rotational axis away from the principal axis, which destroys the regularity of the rotational band. In addition, the wobbling mode of the nucleus is associated with a wobbling-phonon quantum number, giving rise to one- and two-phonon states, on top of which the rotational motion is superimposed. Excitations of the wobbling mode were predicted long ago [20, 21] and have only recently been identified in Lu isotopes [22, 23] owing to the high sensitivity of EUROBALL.

20.3.4 Magnetic Rotation and Chiral Symmetry

Low-lying excited states in near-spherical nuclei are based on single-particle excitations, which implies an irregular pattern of emitted γ-rays. However, regular patterns of energies in γ-ray cascades have been detected in nuclei that were known to be almost perfect spheres. The observed angular momenta in these nuclei are generated by a few of the valence protons and valence neutrons. The behavior has been termed "magnetic rotation" because the sequences of transitions arise not from the collective rotation of a charged, prolate deformed nucleus, which emits electric quadrupole radiation, but from the anisotropy of the currents in the nucleus. These currents produce a rotating magnetic dipole moment, giving rise to a regular sequence of magnetic-dipole radiation. This has been investigated at both the EUROBALL and the GAMMASPHERE detector array [24].

A related topic is spontaneous chiral symmetry breaking, giving rise to left-and right-handed systems as in molecules. This has been discovered in odd–odd nuclei with triaxial shapes. The angular momenta of a valence proton, a valence neutron, and the core rotation are mutually perpendicular. The angular-momentum vectors can thus form a left- and a right-handed system, related by the chiral operator, which combines time reversal and rotation by 180 degrees. Spontaneous chiral symmetry breaking is manifested as degenerate doublets of γ transitions in two rotational bands [25].

20.4 Nuclear Structure Far from Stability

Most nuclear models, both phenomenological and microscopic, give a relatively good description of the properties of stable and near-stable nuclei, but it remains to be seen to what extent these models are directly applicable to nuclei with extreme values of the ratio N/Z. One of the central issues of contemporary nuclear-structure physics is to explore these nuclei, because they are also of immediate interest in astrophysical processes. They are loosely

bound quantum systems, and their structures, their dynamics, and their spectral responses are different from those of stable nuclei. The proton drip line lies relatively close to the valley of stability. However, since neutrons have no charge, many of them can be added to stable nuclei before the next one added becomes unbound, and neutron skins and halos may develop. Neutron-rich nuclei are much more difficult to reach experimentally than neutron-deficient nuclei.

What are the properties of the effective nucleon–nucleon interaction in a nuclear medium which are different from those in stable nuclei? The average mean field experienced by a single nucleon will be modified. The spin–orbit splitting of the mean-field orbitals will change owing to a more diffuse nuclear surface of the weakly bound nucleons. This will influence the magic numbers for nuclei far from the valley of stability. Superconducting correlations will play an enhanced role. One expects to encounter novel types of shell structures, new collective modes, new pairing phases, or regions of nuclei with special deformations and symmetries. There is a great need for experimental information on the proton-rich as well as neutron-rich side of the valley of stability to obtain a complete picture of the internal structure of weakly bound nuclei.

20.4.1 Neutron–Proton Pairing

Isospin, or isotopic spin, $\boldsymbol{t}$, is simply a mathematical form to express the fact that the proton and the neutron are two different quantum states of the same particle, the nucleon. They have the same isospin quantum number $t = 1/2$ but different isospin projection quantum numbers, $t_z = -1/2$ for the proton and $t_z = +1/2$ for the neutron. A pair of nucleons thus has total isospin $T = 1$, with projections $T_z = -1, 0$, and $+1$, for the proton–proton (p–p), neutron–proton (n–p), and neutron–neutron (n–n) pairs, respectively, or $T = 0$ with projection $T_z = 0$ for an n–p pair. Nucleons are fermions, and thus their intrinsic spin is $s = 1/2$. Quantum mechanically, there are only two possible spin directions for each nucleon, $s_z = +1/2$ (spin up) and $s_z = -1/2$ (spin down), which sum to $S_z = 0$ or 1 for a nucleon pair (see Fig. 20.4). In the $T = 1$ isospin triplet state, the three different pairs all must have $S_z = 0$ owing to the Pauli principle, but the n–p pair may also couple to $S_z = 1$ in the $T = 0$, $T_z = 0$ isospin singlet state. The total isospin projection of the nucleus is $T_z = (N - Z)/2$, which is obtained by summing over all the nucleons in the nucleus. For an isospin-symmetric nucleus, this gives $T_z = 0$.

The importance of n–p pairing is well known from the binding properties of the deuteron, but its effects on the structure of heavier nuclei are normally hidden because of the preponderance of like-nucleon pairs. In $N = Z$ nuclei, however, the correlation from n–p Cooper pairs may coexist with, or replace, the p–p and n–n Cooper pairs, finally giving rise to a possible n–p pair condensate.

The mass of any nucleus is less than the sum of its proton and neutron masses. In creating the nucleus, some of the original mass of the Z protons and N neutrons has been transformed into binding energy according to the famous law of Einstein, $E = mc^2$. The energy gain can be calculated according to the mass formula of Weiszäcker from the 1930s. This formula contains a term which takes into account the pairing interaction and the fact that even–even nuclei are more strongly bound than their odd–even or even–odd neighbors. In the 1960s, however, it was discovered that the $N = Z$ nuclei were lighter than the mass formula predicted. To account for this extra binding, a new term was introduced, the Wigner term, which takes into consideration the very special situation when the numbers of protons and neutrons are exactly equal. It was not, however, understood why this term was needed. One possibility may have to do with the fact that, differently from electrons, nucleons have four different possibilities for forming pairs (Fig. 20.4). The $N = Z$ nuclei gain extra energy and become lighter because of the $T_z = 0$ neutron–proton pair correlations. The effect is only observed in $N = Z$ nuclei. If there are two more neutrons than protons, or vice versa, the effect is only half as big, and if there is an inbalance of four nucleons the effect is completely gone [26]. To form this very special neutron–proton pair condensate, it seems as if the first prerequisite is isospin symmetry of the nuclear matter.

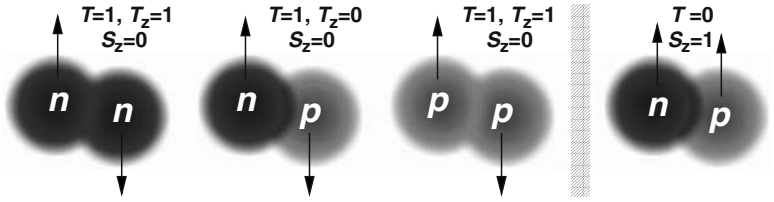

Fig. 20.4. Coupling schemes of dinucleons in the isospin formalism

20.4.2 Doubly Magic $N = Z$ Nuclei

The $N = Z$ nuclei are quantum systems where the protons and neutrons occupy orbitals with all quantum numbers equal except charge. There are 99 such nuclei which are bound with respect to particle emission. The lightest is the deuteron, which has one proton and one neutron. It is bound in its $T = 0$ state but not in its $T = 1$ state, i.e., the $T = 0$ n–p pair interaction is a few hundred keV more attractive than the corresponding $T = 1$ coupling. However, this preference changes at larger values of Z. The heaviest $N = Z$ nucleus in which it has been possible to study excited states is ^{88}Ru [27]. Large variations are found in the shapes of the $N = Z$ nuclei, ranging from spherical via oblate to prolate deformation [28, 29]. They are thus sensitive probes of how small changes in the properties of the last few valence nucleons

can result in dramatic changes in the shape of the nucleus and, hence, in the average nuclear mean field.

At the proton and neutron numbers 2, 8, 20, 28, and 50, which correspond to the elements helium, oxygen, calcium, nickel, and tin, the nuclei are nearly spherical in their ground states. These are the known magic numbers, which are related to the shell structure of the nucleus. In the spherical-shell model, each nucleon is assumed to move in an average potential generated by its interactions with all the other nucleons in the nucleus. Such a potential leads to the prediction that the quantum levels in a nucleus form shells within which several nucleons can reside. A magic number is the maximum number of nucleons which the Pauli principle allows for a particular shell. A critical ingredient of the average potential to account for the observed magic numbers is the spin–orbit interaction, which is a property of the nuclear force reflecting the fact that it is dependent on the direction of the nucleon's intrinsic spin vector $\boldsymbol{s}$ relative to its orbital angular-momentum vector $\boldsymbol{l}$. The shell model also takes into account the residual interaction between the valence nucleons that is not absorbed into the average potential. It provides a beautiful framework for predicting and understanding the lowest-lying states in near-spherical nuclei.

The magic $N = Z$ nuclei are in fact doubly magic. Their protons and neutrons occupy the same quantum states, and the proton and neutron wave functions have a large overlap. The wave functions reinforce each other's structure and amplify shell effects, and these nuclei are ideal testing grounds for the spherical-shell model (see Fig. 20.2). The nucleus ^{100}Sn is a special case, since it is the heaviest doubly magic isospin-symmetric nucleus that is stable against particle emission. The bare fact of its existence was proven a few years ago at the accelerator facilities of the Gesellschaft für Schwerionenforschung (GSI) in Darmstadt, Germany [30] and at the Grand Accelerateur National d'Ions Lourds (GANIL) in Caen, France [31]. To gain insight into the structure of ^{100}Sn requires the study of γ-rays emitted from its excited states, which is not feasible with present-day instruments owing to the very low production rate of ^{100}Sn. However, it is possible to study nuclei close to ^{100}Sn. The closest neighbors with known excited states are presently ^{98}Cd [32] and ^{102}Sn [33], which are only two proton holes and two neutrons, respectively away from the ^{100}Sn core. They were observed for the first time at the tandem accelerator laboratory of the Niels Bohr Institute in Denmark, and the lifetimes of a low-lying isomeric 8^+ state in ^{98}Cd and a 6^+ state in ^{102}Sn were measured. These lifetimes provide information on the polarizability, or rigidity, of the ^{100}Sn core. A doubly magic nucleus is expected to be stiff against such polarization effects. The measured lifetimes in ^{98}Cd and ^{102}Sn indicate that the ^{100}Sn core is indeed stiff against polarization attempts from protons, but rather soft against the interaction with neutrons. This may be an effect of the closeness of ^{100}Sn to the proton drip line, or of the importance

of the $T = 0$ n–p pairing, or it may indicate a breakdown in isospin symmetry between neutrons and protons.

20.4.3 Mirror Nuclei and Isospin Mixing

Isospin-breaking effects can preferably be studied in pairs of mirror nuclei, in which the numbers of protons and neutrons are interchanged, i.e., they lie on opposite sides of the $N = Z$ line. Isospin-breaking effects lead to shifts of typically 10–100 keV between the excitation energies of corresponding states in a mirror pair, the so-called mirror energy differences (MEDs), which have proven to be precise and challenging probes of nuclear structure. The experimental studies so far have concentrated on the $1f_{7/2}$ shell, i.e., nuclei between ^{40}Ca and ^{56}Ni [34]. This region is one of the best understood theoretically, and high-quality wave functions are available from modern shell-model calculations, which greatly simplifies the task of explaining quantitatively the MEDs. The most striking outcome of these studies is the importance of nuclear-charge-symmetry-breaking effects that may be as important as the Coulomb force [35].

The result of a recent study of the lighter $A = 35$ mirror pair [36] is displayed in Fig. 20.5. A comparison of the excitation schemes of the weakly populated $T_z = -1/2$ isotope ^{35}Ar with the well-known $T_z = +1/2$ mirror partner ^{35}Cl reveals two remarkable features: (i) a dramatic difference in the decay patterns of the $7/2^-$ states, and (ii) a very large MED value for the $13/2^-$ states.

The explanation of the latter requires consideration of the hitherto neglected relativistic electromagnetic spin–orbit coupling between nucleons, which for electrons gives rise to the fine structure in atomic physics. Shell-model calculations show that the wave functions of the $13/2^-$ states are rather pure – a single proton or neutron for ^{35}Ar or ^{35}Cl, respectively, in the

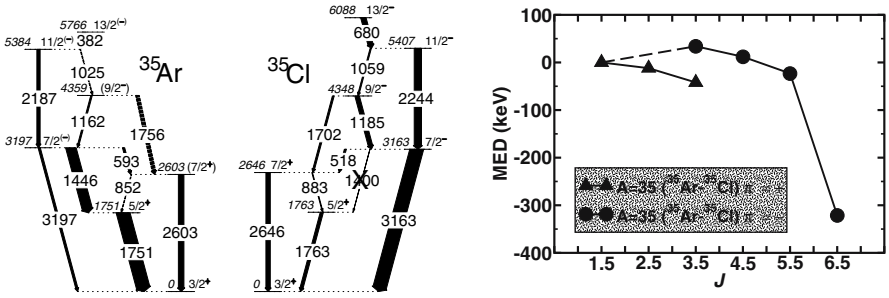

Fig. 20.5. The *left-hand* side provides relevant parts of the decay schemes of the $A = 35$ mirror nuclei ^{35}Ar and ^{35}Cl [36]. The *right-hand* side shows the mirror energy differences of the $A = 35$ pair, MED $= E_x(^{35}\mathrm{Ar}) - E_x(^{35}\mathrm{Cl})$, as a function of the angular momentum J

$1f_{7/2}$ orbital above the $N = Z = 20$ shell gap coupled to a $J^\pi = 3^+$, $T = 0$ neutron–proton pair in the $1d_{3/2}$ orbital below this gap. The excitation of a particle from a $j = l - s$ orbital ($1d_{3/2}$) into a $j = l + s$ orbital ($1f_{7/2}$) combined with the single-particle character of the states leads to a contribution of some 200 keV from the electromagnetic spin–orbit coupling to the MED of the $13/2^-$ states. Note that the opposite signs of the gyromagnetic factors of protons and neutrons lead to a coherent contribution when one is looking at the *difference* between the energies of the excited states. The remaining part of the MED of the $13/2^-$ states is thought to be due to established isospin-breaking sources. The wave functions of all other states in Fig. 20.5 involve mixtures of proton and neutron excitations and are thus similar for both members of the mirror pair, which results in a cancellation of the MED [36].

Breaking of the isospin symmetry is also reflected in a mixing of different T states. It is expected to occur most strongly in the heaviest $N = Z$ nuclei. An understanding of the mechanism of isospin mixing is crucial to performing reliable corrections when deriving the coupling constant from, for example, the $\log(ft)$ values of superallowed Fermi beta decay. Such measurements can have a direct impact on the unitarity test of the Cabibbo–Kobayashi–Maskawa (CKM) matrix for fundamental interactions. One way to study the violation of isospin symmetry is through the observation of isospin-forbidden $E1$ transitions in even–even $N = Z$ nuclei. Another way is by comparing $E1$ transitions in mirror nuclei. In ^{35}Ar (see Fig. 20.5) the 1446 keV $E1$ branch from the 3197 keV $7/2^-$ state clearly dominates the 3197 keV $M2$ transition, while the corresponding 1400 keV $E1$ decay is essentially absent in ^{35}Cl. This state decays directly to the ground state through the strong 3163 keV $M2$ transition [36].

20.4.4 Exotic Particle Decay of Nuclei

Proton decay from ground states or low-lying isomeric states limits the existence of nuclear matter on the neutron-deficient side of the nuclidic chart. In fact, proton-rich nuclei offer a unique opportunity to study the nuclear system beyond the drip line. The protons are no longer bound, but because of the Coulomb and centrifugal barriers of the proton, even excited states may live long enough such that they can be studied by γ-ray or proton emission. The proton escapes the nucleus by quantum mechanical tunneling, which is a widespread phenomenon in the natural sciences. Examples range from biophysical transport via chemical bonding to electron tunneling in quantum transistors.

Ground-state proton decay competes with β^+ radiation and the (partial) half-life decreases rapidly with increasing decay energy, i.e., the more exotic the isotope the larger its proton decay branch will be, until the last proton cannot be held inside the barrier anymore. Typically, proton-unstable nuclei are produced in fusion–evaporation reactions, are then in-flight mass separated, and finally implanted in pixelized silicon detectors. A space–time

correlation between the implantation signal and the subsequent proton decay is applied to identify a proton-emitting nucleus or study its decay in detail [37, 38]. Most of the experimental studies are being performed at the national laboratories in Legnaro, Italy, and Argonne and Oak Ridge, USA. In parallel, recent years have seen significant steps in the theoretical description: decay rates of spherical and deformed proton emitters can be predicted reliably, and fine structures in the decay have proven to be sensitive probes of the wave function compositions of the nuclear states involved [37, 38]. The first evidence for two-proton radioactivity has been found in ^{45}Fe following projectile fragmentation of 75 and 650 MeV/nucleon ^{58}Ni beams at GANIL and GSI, respectively, in 2002 [39, 40].

During recent years, the new nuclear decay mode of discrete-energy prompt proton and α-particle emission from excited states has been established in nuclei near ^{56}Ni [41, 42]. An example of prompt proton decay is shown in Fig. 20.2. Unlike the ground-state proton emitters, the prompt particle emission competes with γ-rays instead of β^+ radiation. This places the timescale of the decays into the $10^{-12} - 10^{-15}$ s regime, and allows their study in "prompt" coincidence with preceding and subsequent γ-rays emitted from the parent and daughter nuclei, respectively. The prompt particle decays proceed from highly deformed or superdeformed initial states into spherical daughter states. This implies a drastic rearrangement of the nuclear mean field in the course of the decay. Hence, the decay mode may be viewed as a self-regulated two-dimensional quantum tunneling process, which is unique in Nature.

20.5 Outlook

An enormously rich variety of nuclear-structure phenomena has been uncovered in recent studies of atomic nuclei using stable beams and stable targets. Electrostatic accelerators have played a very important role in these studies. The field of study concerning nuclei at the limit of angular momentum has been enriched enormously. Owing to the development of very sensitive instrumentation and refined experimental techniques, it has also been possible to extend the field of studies to nuclei far from stability, still using stable beams and targets. Large parts of the EUROBALL and GAMMASPHERE experimental programs have been dedicated to the investigation of the structure of neutron-deficient nuclei through a large variety of dedicated ancillary detectors for reaction products.

In the case of nuclei not too far away from the valley of stability, we can continue to investigate them using high-intensity beams of stable ions in combination with very efficient detectors, but γ-ray detector arrays are now also starting operation at the existing radioactive-ion-beam facilities. RISING [43] is the next phase of the EUROBALL collaboration. It allows efficient γ-ray spectroscopy of exotic nuclei produced in fragmentation or induced fission of

relativistic heavy-ion beams, which are selected by the fragment separator (FRS) at GSI. Other highly efficient γ-ray arrays are EXOGAM [44] at Spiral I at GANIL, and MINIBALL [45] at REX-Isolde at CERN, Switzerland. These existing facilities already provide exciting nuclear-structure data, and they offer tantalizing glimpses of scientific opportunities in the years to come.

However, it is the extremes in the ratio N/Z of neutrons to protons which define the limits of existence for nuclear matter. This field of research in nuclear physics will be opened up by the second-generation radioactive-beam accelerators. There is presently an increased scientific interest in the physics that can be probed with such beams, and enormous worldwide activity is going on in the construction of several large radioactive-nuclear-beam facilities throughout Europe, the USA, and Japan (see, for example, [46–48]). These facilities will make possible a considerable enlargement of the field of nuclear spectroscopic studies. When the drip lines are approached, detailed information on the rp- and r-process nuclei will become available. Exploring these limits will enhance new information, not only about the fundamental properties of the nuclear many-body system, but also about astrophysical processes and the origin of the elements, and about fundamental symmetries.

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