Chapter 1

Deformation and clustering in light nuclei

1.1 Introduction

Questions relating to how states of matter arise and what the building blocks are from which they are made will never stop to interest people. After the discovery of the atom and the nucleus physicists started to investigate atomic nuclei and their properties. During this period many fundamental discoveries were made such as the observation of new elementary particles involved in radioactive decay. Today, a large part of the Segré chart of the nuclides is well known. Numerous theoretical nuclear models have been developed and accepted or rejected based on experimental work during this period. In addition, modern and more powerful accelerator facilities have been developed.

One of the interesting problems discussed in the last 30 years is that of cluster structure in nuclei and the existence of so called 'nuclear molecules'. Different projects and people have been involved in these investigations. Now, after twenty years of scepticism from a large part of the physics community it has been proven that such structures exist. Still, there is a lot of work which has to be done towards understanding such structures, especially for light nuclei. This work is a small

piece from the big puzzle of 'nuclear structure', but putting such pieces together will eventually make it possible to see the whole picture.

In light nuclei, the nucleons have been observed to cluster together forming sub-structures within the atomic nucleus, for states where the nucleons are only just bound together. This fact is well expressed in the *Ikeda Diagram* (see Figs. 1.1 and 1.2). In neutron-rich nuclei low-lying states, close to the threshold for neutron emission, show a pronounced α-particle cluster structure. These are states with large prolate deformations. For the neutrons outside the tightly bound core (so called 'valence neutrons') a concept based on molecular orbitals can be used to describe their behaviour.

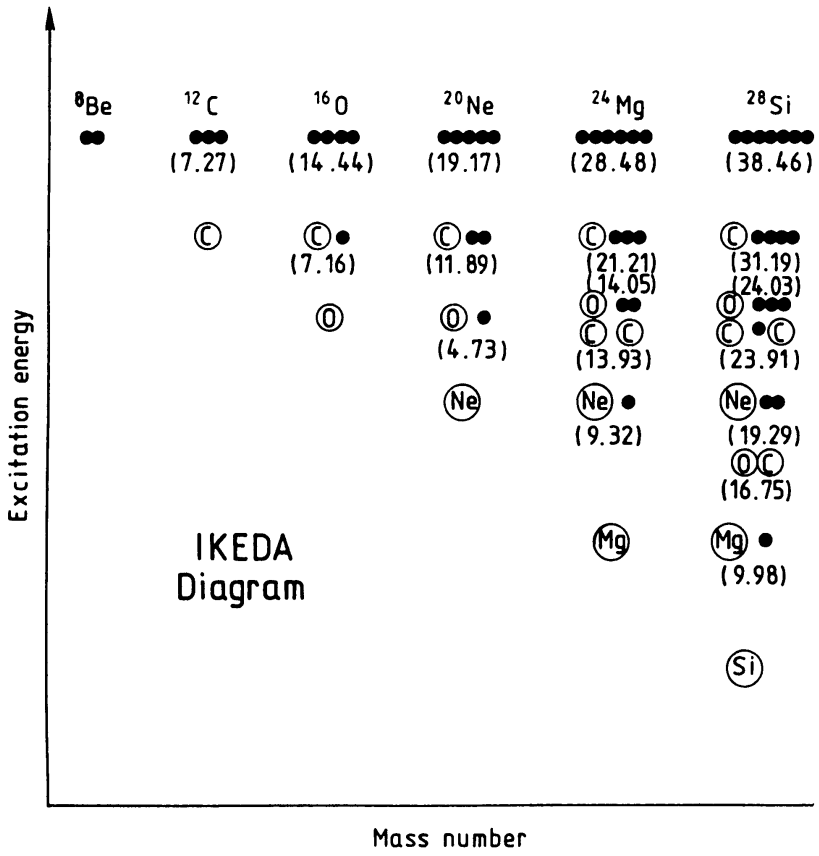

Figure 1.1: Ikeda Diagram [Ike68, Hor72] showing cluster states in $N = Z$ nuclei and their thresholds (in MeV) for the decomposition into clusters.

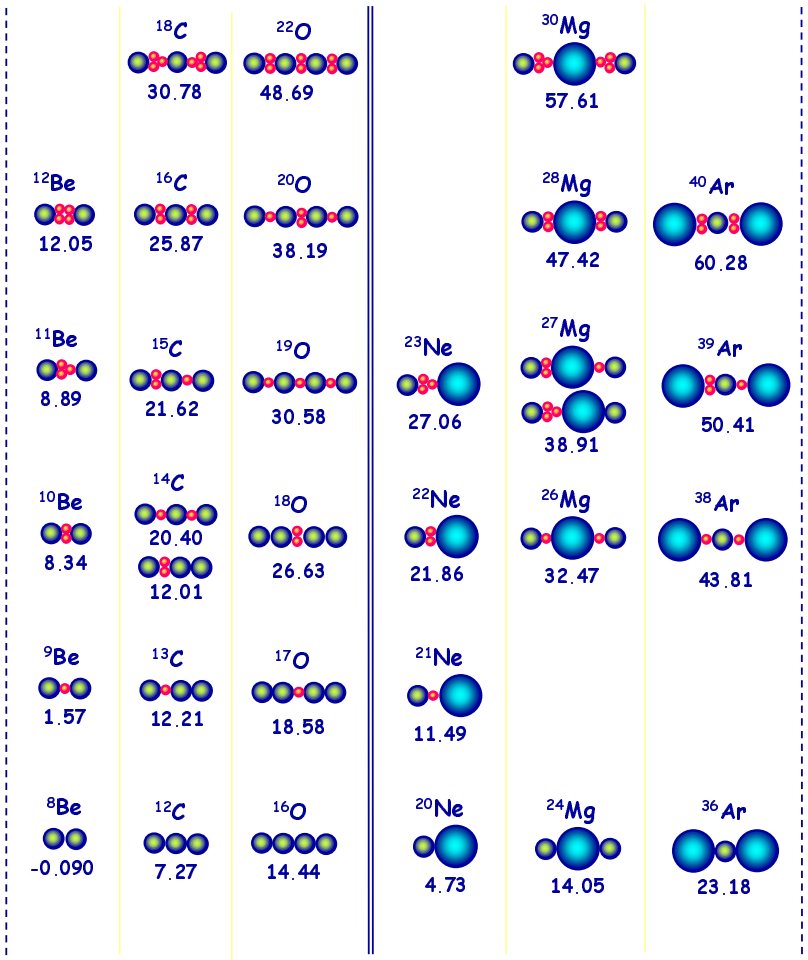

Figure 1.2: Extended Ikeda Diagram, which schematically illustrates the molecular shape isomers based on α (green) and ^{16}O (blue) clusters plus some covalently bound neutrons (red) in neutron-rich light nuclei. Numbers under the configurations indicate the thresholds (in MeV) for decaying into the subunits [vO01].

The physics of molecular orbitals for nucleons (mostly neutrons) has been developed and successfully applied in the last decades for the description of transfer processes in heavy-ion reactions at low energies [vO70, Ima87, Bis88, vO96b, Spa00]. In these models weakly bound neutrons and strongly bound cores are used. The valence neutrons move in the field of two clusters and some aspects from atomic molecular physics can be applied to such systems.

Thus, conditions for the formation of stable or quasi-stationary molecular states can be formulated [vO01]:

• strongly bound cores.

• weakly attractive core-core potential which, in addition, becomes repulsive at small distances.

• weakly bound single-particle orbitals of valence neutrons in order to guarantee large amplitudes of the wave functions at larger distances in the overlap region.

• large transfer probability, which is typically reached if the valence states are in the resonance or in a quasi-resonance matching condition between the two states of the separated centres.

Covalent binding between α-particles due to valence neutrons produces particular structures in light neutron-rich nuclei, like in the beryllium isotopes, namely long-lived states with a two-centre structure. The long lifetime arises because of the dramatic change in the shape of the state needed to decay to lower-lying 'normal' states. Such unusual arrangements of nucleons also give rise to reflection asymmetric shapes, like in atomic molecules, a signature of which are deformed bands as parity doublets. These cases are well known in atomic physics and discussed by Herzberg [Her50]. For such structures using the two centre shell-model a correlation diagram for all nucleons (see Fig. 1.3) can be calculated [vO70, Sch71]. The molecular orbits merge at small distances with the Nilsson orbits (see Fig. 1.5) of the deformed compound nucleus. The molecular orbitals are classified according to the well known quantum numbers of molecular valence

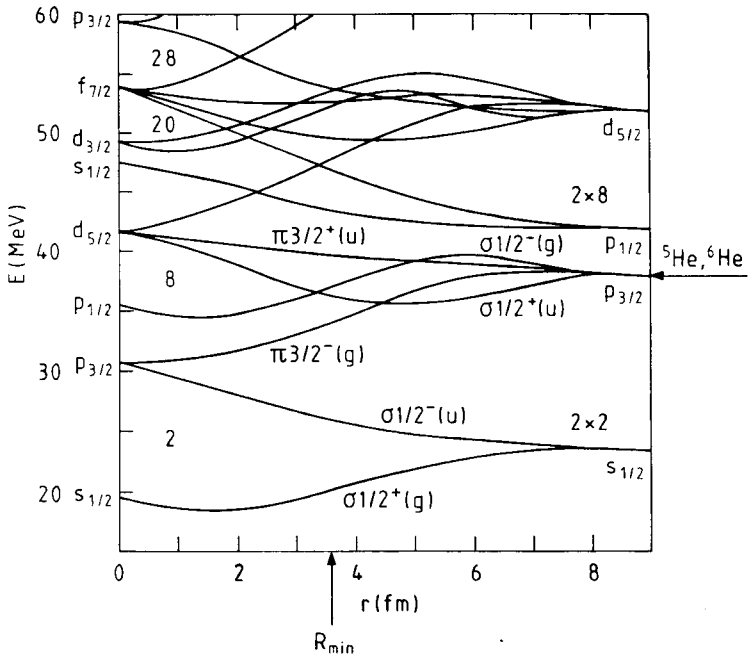

Figure 1.3: Correlation diagram for molecular orbitals in a two-centre shell-model picture. The molecular orbitals are labeled by their quantum numbers (see text). The distance between the two centres is denoted by r.

states: the K-quantum number for the projection of the total angular momentum on the nuclear deformation axis, and the σ and π orbitals for the m=0 and m=1 projections of the orbital angular momentum l respectively. In addition to the parity, the *gerade (even), g,* and *ungerade (odd), u,* symmetry appears for the case of two molecular cores.

1.2 Aims and techniques of the experiments

Some spectroscopic properties that are important for molecular structures are:

- large transition probabilities for γ-decay or/and a large probability for cluster emission.
- the reaction mechanism in which the nucleus is produced.

- large moment of inertia.
- rotational bands with intense intra-band γ-ray transitions.

The study of the atomic nucleus using particle and γ-ray spectroscopy and particle-γ coincidence techniques has several advantages. From one side it gives the opportunity to investigate the electromagnetic transitions below and across the particle-emission threshold, and from the other side the study of the γ-ray decay scheme in these nuclei helps to establish a clear signature of collectivity - namely rotational structures and in particular parity doublet structures characteristic of reflection asymmetric two-centre structures. Using γ-ray spectroscopy it is possible to find the connection between previously known states in these isotopes and furthermore to observe new behaviour.

The main goal of this work is the study of the level schemes of beryllium and neon isotopes in order to established their structures as related to the molecular model. The emission of clusters in compound nuclear reactions, observed in these studies, is another important part of the work presented here.

1.3 Deformed shell model (Nilsson model)

The spherical shell model [May49] can explain many features of spherical nuclei, but needs modifying to describe nuclei with many nucleons outside a closed shell. The residual interaction between these many valence nucleons may be more simply described by a deformed potential.

For nuclear rotation to be observable, the nuclei have to be non-spherical, so that they have a preferred axis. For deformed nuclei, assuming a constant nuclear volume (*i.e. incompressibility*), the nuclear radius can be described by:

$$R(\theta,\phi) = R_{av}\left[1 + \sum_{\lambda=2}^{\infty}\sum_{\mu=-\lambda}^{\lambda}\alpha_{\lambda\mu}Y_{\lambda\mu}(\theta,\phi)\right] \tag{1.1}$$

where $\alpha_{\lambda\mu}$ are the coefficients of the spherical harmonics $\mathrm{Y}_{\lambda\mu}(\theta,\phi)$ [Eis70]. The λ=1 terms are normally excluded from the sum as these correspond to a transla-

tion of the centre of mass. The indices λ and μ, determine the surface coordinates as a function of θ and ϕ, respectively. For example,

$$R(\theta, \phi) = R_{av} \left[1 + \beta_2 Y_{20}(\theta, \phi)\right] \tag{1.2}$$

is independent of ϕ. This means that such nuclei are axially symmetric and can be either prolate or oblate (see Fig.1.4). The deformation parameter β_2 $(= \alpha_{20})$, can be related to the axes of the spheroid by:

$$\beta_2 = \frac{4}{3}\sqrt{\frac{\pi}{5}}\frac{\Delta R}{R_{av}} \tag{1.3}$$

in which the average radius is, $R_{av} = R_0 A^{1/3}$, and ΔR is the difference between the semi-major and semi-minor axes.

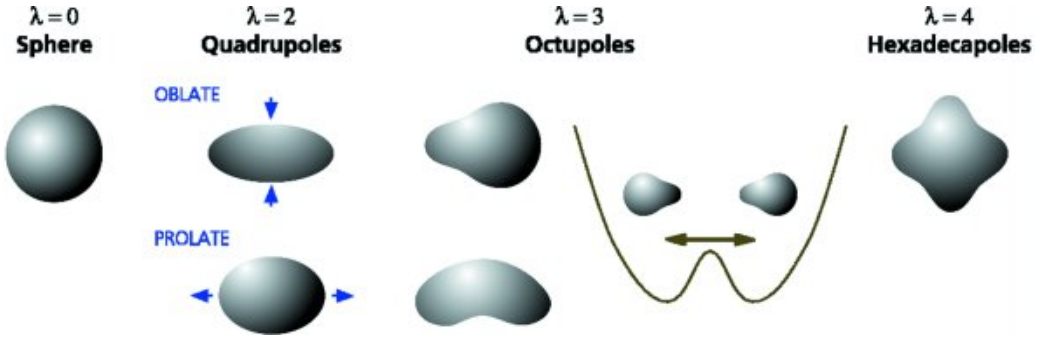

Figure 1.4: Currently observed nuclear shapes [Luc01]. The different shapes can be parametrised by spherical harmonic functions, where λ characterises the different orders of the corresponding distributions.

The larger the value of β_2 the more deformed the nucleus. Positive and negative β_2 values correspond to prolate and oblate shapes respectively.

In some circumstances the quadrupole deformation parameters ε_2 and δ are used. These are related to β_2 by the Equations (1.4), taken from [Fir96].

$$\delta = \frac{\Delta R}{R_{r.m.s.}}$$

$$\varepsilon_2 = \delta + \frac{1}{6}\delta^2 + \frac{5}{18}\delta^3 + \frac{37}{216}\delta^4 ...$$
$$\beta_2 = \sqrt{\frac{\pi}{5}}\left[\frac{4}{3}\varepsilon_2 + \frac{4}{9}\varepsilon_2^2 + \frac{4}{27}\varepsilon_2^3 + \frac{4}{81}\varepsilon_2^4 ...\right] \quad (1.4)$$

Higher order axially symmetric effects have also been observed in nuclei, such as hexadecapole deformation quantified by β_4 (or ε_4).

The shape parameters introduced so far all describe axially symmetric nuclear shapes, but quadrupole (λ=2) deformations can give rise to asymmetric shapes. These triaxial distortions are governed by the γ shape degree of freedom, and this describes a stretching/squashing effect at right angles to the major nuclear axis. Gamma is measured in degrees, where γ=0° and γ=60° correspond to prolate and oblate shapes respectively. Completely triaxial shapes have γ=30°.

The model that describes axially symmetric nuclei is called the *Deformed Shell Model*. In this model the Schrödinger equation is solved using the potential that describes, as closely as possible, the actual shape of the nucleus. Another result of the deformation is that the orbital angular momentum, l, and the intrinsic spin, s, are no longer good quantum numbers and thus, states with different l-values, but the same parity can mix. The energy of the states now depends on the component of the single-particle angular momentum (j) along the symmetry axis, which is denoted by Ω. For each orbital with angular momentum j, there are $2j+1$ values of Ω ($=m_j$ in the absence of other couplings). However, levels with $+\Omega$ and $-\Omega$ have the same energy due to the reflection symmetry of axially symmetric nuclei, so that each state is now doubly degenerate, *i.e.* two particles can be placed in each state. For example the $f_{7/2}$ orbital can have $|\Omega|$ equal to 7/2, 5/2, 3/2 and 1/2. The ordering of these Ω levels depends on the particular shape of the nucleus since the lowest in energy is the orbital which interacts (overlaps) the most with the nuclear core. For prolate shaped nuclei the states with the lowest Ω values are the most tightly bound, whereas for oblate shaped nuclei, the states with the highest Ω occur lowest in energy. Such deformed shell model calculations were first performed in 1955 by Nilsson [Nil55] with an anisotropic harmonic

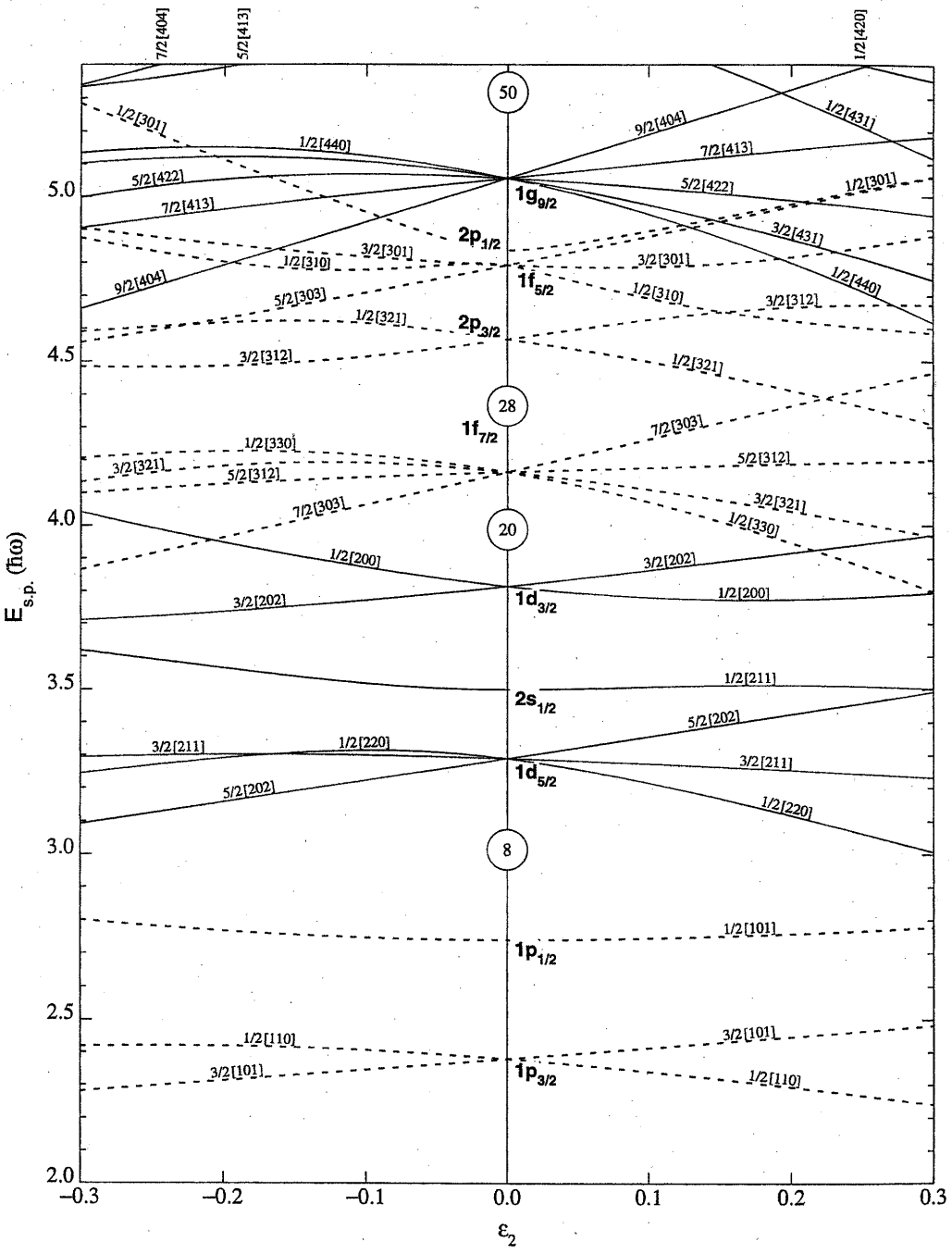

Figure 1.5: Nilsson orbitals for nuclei up to Z=N=50 taken from [Fir96]. The level ordering is given as a function of the quadrupole deformation parameter, ε_2. Dashed lines indicate negative parity and solid lines indicate positive parity. Positive and negative values of ε_2 correspond to prolate and oblate shapes respectively. See text for more information.

oscillator potential and the calculated states (called *Nilsson orbitals*) are labelled by $\Omega[Nn_z\Lambda]$ (see Fig.1.5), where N is the total oscillator shell quantum number and determines the parity, given by $(-1)^N$. Lambda (Λ) is the projection of the particle orbital angular momentum, l, on the nuclear symmetry axis, and n_z is the number of oscillator shell quanta along the direction of the symmetry axis.