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A Study on the Structures of Nuclei and Nuclear Thermodynamics

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Abstract – The present Paper, entitled "A Study on the Structures of Nuclei and Nuclear Thermodynamics", Focuses On The Structure of Nuclei in The Nuclear Physics and nuclear thermodynamics in the particles and nuclei. The first part of the paper shows Nuclei that are in their ground state or are only slightly excited are examples of degenerate Fermi gases. The nuclear density is determined by the nucleon interaction – essentially by the strong repulsion at short distances and the weak attraction between nucleons that are further apart. The average distance between the nucleons is much larger than the radius of the nucleon hard core. Up to now we have concerned ourselves with the properties of nuclei in the ground state or the lower lying excited states. We have seen that the observed phenomena are characterised, on the one hand, by the properties of a degenerate fermion system and, on the other, by the limited number of the constituents. The nuclear force generates, to a good approximation, an overall mean field in which the nucleons move like free particles.

Keywords:- Nuclei, Nuclear thermodynamics, Structures, Nucleons, Free Particles, Fermi Gases etc.

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INTRODUCTION

Nuclei that are in their ground state or are only slightly excited are examples of degenerate Fermi gases. The nuclear density is determined by the nucleon nucleon interaction – essentially by the strong repulsion at short distances and the weak attraction between nucleons that are further apart. We have already seen in Sect. 6.2 that nucleons are not localised in the nuclei but rather move around with rather large momenta of the order of 250 MeV/*c*. This mobility on the part of the nucleons is a consequence of the fact that, as we have seen for the deuteron, the bonds between nucleons in the nucleus are "weak". The average distance between the nucleons is much larger than the radius of the nucleon hard core. The fact that nucleons actually move freely inside the nucleus is not at all obvious and of such great conceptual importance that we shall demonstrate it by considering hypernuclei, i.e., those nuclei containing a hyperon as well as the usual nucleons. We will see that a Λ particle moves inside such nuclei like a free particle inside a potential whose depth is independent of the nucleus under consideration and whose range is the nuclear radius. The shell model is an improvement upon the Fermi gas model in that it has a more realistic potential and the spin-orbit interaction is now taken into consideration. Not only the nuclear density but also the shapes of the nuclei are fixed by the nucleon-nucleon interaction. A nucleus in equilibrium is not always a sphere; it may be ellipsoidal or even more deformed. This good agreement between the predicted and measured values is, however, rather coincidental. In a more exact calculation one must take into account the fact that the density inside a neutron star grows up to 10 0 and one then would obtain radii which are much smaller than those measured. On the other hand at a density of 10 0, the inter-neutron separations are only about 0.8 fm, this means that the hard cores touch and a strong repulsion takes place. Taking this into account we can conclude that the gravitational pressure is in equal measure compensated by the Fermi pressure and by nucleon-nucleon repulsion. We can also expect an admixture of hyperons in equilibrium with the neutrons for such high densities as are found at the centre of neutron stars. It may also be that the overlap of the neutrons, which is largest at the centre of the star, means that the quarks are no longer confined in the individual neutrons. Neutron stars could be also partially composed of quark matter.

We have seen that the observed phenomena are characterised, on the one hand, by the properties of a degenerate fermion system and, on the other, by the limited number of the constituents. The nuclear force generates, to a good approximation, an overall mean field in which the nucleons move like free particles. In the shell model the finite size of nuclei is taken into account and the states of the individual nucleons are classified according to radial excitations and angular momenta.

Thermodynamically speaking, we assign such systems zero temperature. In the first part of this chapter we want to concern ourselves with highly excited nuclei. At high excitation energies the mean free path of the nucleon inside the nucleus is reduced; it is only about 1 fm. The nucleus is then no longer a degenerate fermionic system, but rather resembles, ever more closely for increasing excitations, the state of a normal liquid. It is natural to use statistical methods in the description of such systems. A clear description may be gained by employing thermodynamical quantities. The excitation of the nucleus is characterised by the temperature. We should not forget that strictly speaking one can only associate a temperature to large systems in thermal equilibrium and even heavy nuclei do not quite correspond to such a system. As well as this, excited nuclei are not in thermal equilibrium, but rather rapidly cool down via the emission of nucleons and photons. In any thermodynamical interpretation of experimental results we must take these deficiencies into account. In connection with nuclear thermodynamics one prefers to speak about *nuclear matter* rather than nuclei, which implies that many experimental results from nuclear physics may be extrapolated to large systems of nucleons. As an example of this we showed, when we considered the nuclear binding energy, that by taking the surface and Coulomb energies into account one can calculate the binding energy of a nucleon in nuclear matter. This is just the volume term of the mass formula, (2.8).

The Fermi Gas Model

We wish to show in this chapter that both the nucleonic momentum distribution that we encountered in quasi-elastic electron-nucleus scattering (Sect. 6.2) and the nucleon binding energies can be understood in terms of the Fermi gas model and that, furthermore, the principal terms of the semi-empirical mass formula (2.8) necessarily emerge from this model. The protons and neutrons that together build up the nucleus are viewed in the Fermi gas model as comprising two independent systems of nucleons. As spin 1/2 particles they naturally obey Fermi-Dirac statistics. It is assumed that the nucleons, inside those constraints imposed by the Pauli principle, can move freely inside the entire nuclear volume.

The potential that every nucleon feels is a superposition of the potentials of the other nucleons.We now assume in our model that this potential has the shape of a well, i.e., that it is constant inside the nucleus and stops sharply at its edge The number of possible states available to a nucleon inside a volume *V* and a momentum region d*p* is given by

$$\mathrm{d}n = \frac{4\pi p^2 \mathrm{d}p}{(2\pi\hbar)^3} \cdot V\,.$$

At zero temperature, i.e., in the nuclear ground state, the lowest states will all be occupied up to some maximal momentum which we call the *Fermi momentum* *p*F. The number of such states may be found by integrating over

$$n = \frac{V p_{\mathrm{F}}^3}{6\pi^2\hbar^3}\,.$$

REVIEW OF LITERATURE

A spectrum is characterized by its central momentum and standard deviation. The value of <Pl>was found to be in the range −10 to −130 MeV c−1 for various fragments (a negative sign for <Pi>indicates that the fragment speed is less than that of the projectile). Although the central part of the spectrum is symmetric for the Pl land Pt directions, a longer tail is observed in the Pt direction.

Oladipo Samuel Ekundayo (2005)

The width of the momentum spread is found to be essentially independent of the target mass and beam energy, but does depend on the mass number of the projectile (AP) and of the fragment (AF). The dependence of σ(Pll) on AP and AF can be expressed as

$$\sigma(\mathrm{P}_1)=\sigma_0\sqrt{AF\,(A_{\mathrm{p}}\text{-}\mathrm{A_F})/(\mathrm{A_p}\text{-}1)}$$

Marianne Yoshioka (2000)

Marianne Yoshioka explained the £0 based on the nucleon Fermi motion and associated £0 with the Fermi momentum as

$$\sigma^2{}_0 = (\mathrm{P}^2)/3=\mathrm{P}^2{}_f/5$$

Using data from four national surveys, **Jeffrey S. Levin1, Robert Joseph Taylor2 and Linda M. Chatters3 (2008)** presents findings on racial and gender differences in religiosity among older adults.

According to **Sherkat and Ellison (2008),** The σ(Pt)is the same if a high-energy projectile is used. The transverse momentum distributions of fragments from 11Be and 11Li reactions with a carbon target were measured at 790A MeV .

Aylin Mente (2008) revealed this component is observed in all the data shown in figure 8, indicating that it is from the diffractive scattering, as considered above. In addition, a narrow peak is seen in each of the spectra on top of this component for others. In these reactions, a projectile hast wo valence neutrons. One of them becomes unbound if the other is removed and can thus be expected to be emitted simultaneously without any further collisions. This is why one could expect that this narrow spectrum might give information concerning the internal momentum of the halo neutron. Figure shows the neutron-separation-energy dependence of the width. The £0 for the fragments in one- and two-neutron removal shows a monotonic rise for larger Sxn. The solid line in figure shows the value calculated by (5.6), assuming a two-neutron cluster for two-neutron removal (<є> = S2n). The linere produces the data well. On the other hand, the width £of the neutron distribution does not follow the same tendency. The width for 8He and 9Li is as small as that for 11Li, which thus shows that the other reaction mechanism is important.

Haralson, Mitchel, Jr.(2009) investigated the influences the neutron Pt spectra were also measured at lower energies, as shown in figure 11 .They show essentially the same behavior. However, a difference can be seen in the spectra with heavy (high-Z) targets. The neutron distribution from the 11Be +C ->n +10Be +X reaction shows no narrow peak, because 11Be is one neutron halo and the neutron is scattered by the reaction. However, a narrow peak rapidly develops when the target becomes heavier. the probability of exciting the projectile by a strong interaction is relatively.

This indicates the progressive importance of the Coulomb interactions, because the nuclear reaction does not change greatly. This also indicates that the probability of exciting the projectile by a strong interaction is relatively small.

Haralson, Mitchel, Jr.(2009) finding was not consistent with the present result an extraction of the strength of the correlation was first attempted by means of a comparison of the one- and two-neutron momentum distributions. Although this analysis was performed using the observed neutron and fragment momentum distributions, it turned out not to be meaningful because the observed neutron momentum distribution reflects not the internal motion, but the decay Q value, as discussed above. Because of this complexity, no determination has so far been made for the internal neutron momentum distribution, therefore this method cannot be applied.

JS Shrauger (2010) who explored, the microscopic three-body calculation is expected to provide accurate information, because the core 4He is extremely tightly bound. Such a calculation has been reported by many authors; they all reproduce the momentum distribution of the 4Hefragment well. Here, as an example, the results of three-body calculations by Zhukov *etal* are presented.

AIMS AND OBJECTIVES

The aim of structure nuclei and nuclear thermodynamics is to give a unified description of nuclear and particle physics because the experiments which have uncovered the substructure of atomic nuclei and nucleons are conceptually similar. With the progress of experimental and theoretical methods, atoms, nuclei, nucleons, and finally quarks have been analysed during the course of this century. The intuitive assumption that our world is composed of a few constituents — an idea which seems attractive, but could not be taken for granted — appears to be confirmed. Moreover, the interactions between these constituents of matter can be formulated elegantly, and are well understood conceptionally, within the so-called “standard model”. Once we have arrived at this underlying theory we are immediately faced with the question of how the complex structures around us are produced by it. On the way from elementary particles to nucleons and nuclei we learn that the “fundamental” laws of the interaction between elementary particles are less and less recognisable in composite systems because many-body interactions cause greater and greater complexity for larger systems. This book is therefore divided into two parts. In the first part we deal with the reduction of matter in all its complication to a few elementary constituents and interactions, while the second part is devoted to the composition of hadrons and nuclei from their constituents. We put special emphasis on the description of the experimental concepts but we mostly refrain from explaining technical details. The appendix contains a short description of the principles of accelerators and detectors. The exercises predominantly aim at giving the students a feeling for the sizes of the phenomena of nuclear and particle physics. Wherever possible, we refer to the similarities between atoms, nuclei, and hadrons, because applying analogies has not only turned out to be a very effective research tool but is also very helpful for understanding the character of the underlying physics.

We have aimed at a concise description but have taken care that all the fundamental concepts are clearly described. Regarding our selection of topics, we were guided by pedagogical considerations. This is why we describe experiments which — from today’s point of view — can be interpreted in a straightforward way. Many historically significant experiments, whose results can nowadays be much more simply obtained, were deliberately omitted.

THERMODYNAMICAL DESCRIPTION OF NUCLEI

We have already in Sect. 3.4 (Fig. 3.10) distinguished between three sorts of excitations in nuclei:

– The ground state and the low-lying states can be described in terms of single particle excitations or via collective motion.

– Far above the particle threshold there are no discrete states but only a continuum.

– In the transition region below and barely above the particle threshold there are lots of narrow resonances.

These states do not, however, contain any information about the structure of the nucleus. The phenomena in this energy range in nuclei are widely referred to as *quantum chaos*. In the following we shall concern ourselves with the last two of these domains. Their description involves statistical methods and so we will initially turn our attention to the concept of *nuclear temperature*.

Compound nuclei. In neutron capture by heavy nuclei a multiplicity of resonances are observed. An example of such a measurement is seen in Fig.19.4 below, where the cross-section for neutron scattering off thorium displays very many resonances. One should note that the energy scale is in eV, the separation of these resonances is thus six orders of magnitude smaller than the gaps in energy separating lower lying states. This observation was already explained in the thirties by Niels Bohr in the so-called compound nucleus model. Neutrons in the nucleus have a very short free path due to the strong interaction and they very rapidly distribute their energy among the nucleons in the nucleus. The probability that all the energy supplied is held by one single nucleon is small. The nucleons cannot therefore escape from the nucleus and this leads to a long lifetime for the compound nucleus states. This lifetime is mirrored in the narrow widths of the resonances. This picture has been greatly refined in the intervening decades. Thus the compound nucleus state is not reached immediately, but rather the system, via successive collisions, passes through a series of intermediate states. The compound nucleus state is the limiting case in which the nucleons are in thermal equilibrium.

Quantum chaos in nuclei. In the theory of classical deterministic systems we distinguish between regular and chaotic orbits. Regular orbits are stable orbits which are not greatly affected by small external perturbations. The particles undergo periodic motion and the entire configuration of the system thus repeats itself. Chaotic orbits are very different. They are not periodic and infinitesimally small perturbations lead to big changes. While predictions for the development of regular systems may be made to an arbitrary accuracy, the uncertainties associated with predicting chaotic systems increase exponentially.

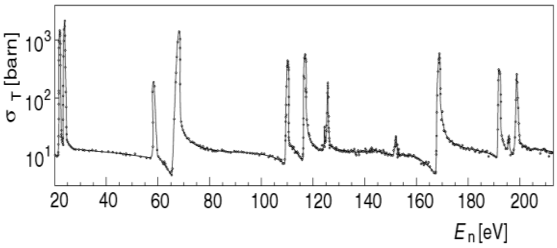

Fig. 19.4. Total cross-section for the reaction ^{232}Th+n as a function of the neutron energy. The sharp peaks correspond to resonances with orbital angular momentum $\ell = 0$ (from [Bo69]).

THE PHASES OF NUCLEAR MATTER

The liquid–gas phase transition. Peripheral heavy ion reactions have proven themselves most useful as a way to heat up nuclei in a controlled way. In a glancing collision of two nuclei (Fig. 19.5) two main fragments are produced which are heated up by friction during the reaction. In such reactions one can measure rather well both the temperature of the fragments and also the energy supplied to the system. The temperature of the fragments is found from the Maxwell distribution of the decay products, while the total energy supplied to the system is determined by detecting all of the particles produced in the final state. Since the fragment which came from the projectile moves off in the direction of the projectile, its decay products will also move in that direction and may be thus kinematically distinguished both from the decay products of the target fragments and also from the frictionally induced evaporative nucleons. The contributions from the energy supplied to the fragments and from the energy lost to friction during the glancing collision may thus be separated from one another.

NUCLEAR THERMODYNAMICS

Since the universe is still in an early stage of its expansion the previous history of our universe would be similar in all three cases. The age of a universe with a sub-critical density is given by the inverse Hubble constant

$$t_0 = \frac{1}{H_0} \,,$$

and is about 14 thousand million years.

The first three minutes of the universe.

In the initial phase of the universe all the (anti)particles and the gauge bosons were in thermo dynamical equilibrium, i.e., there was so much thermal, and thus kinematical, energy available that all the (anti)particles could transform into each other at will. There was therefore no difference between quarks and leptons, which means that the strength of all the interactions was the same. After about 10−35 s the temperature had decreased so much due to the expansion that a phase transition took place and the strong interaction decoupled from the electroweak interaction, i.e., the strongly interacting quarks barely interacted with the leptons any more. At this stage the ratio between the numbers of quarks and photons was fixed at about 10−9. After about 10−11 s, at a temperature $kT \approx 100$ GeV, a further phase transition took place in which the weak interaction decoupled from the electromagnetic interaction. We will discuss this process below. When, after about 10−6 s, the continuous expansion of the universe had lowered its temperature down to $kT \approx 100$ MeV, which is the typical energy scale for hadronic excitations, the quarks formed bound states in the shape of baryons and mesons. The protons and neutrons so-produced were in thermal equilibrium due to weak processes. After about 1 s and at a temperature $kT \approx 1$ MeV, the difference between the neutron and proton masses, the neutrinos had too little energy to maintain the state of equilibrium between the protons and neutrons. They decoupled from matter, i.e., they henceforth essentially no longer interacted at all and propagated freely through the universe. Meanwhile the ratio of protons to neutrons increased up to a value of 7. After about three minutes of expansion the temperature had fallen to $kT \approx 100$ keV. From this moment the thermal equilibrium between nucleons and photons was broken, since the photon energies were no longer sufficient to break up the light nuclei, through photofission processes, into their constituents at the same pace as they were produced by nucleon fusion. In this phase the big bang nucleosynthesis of deuterium, helium and lithium nuclei took place.

RESULTS & DISCUSSION

Reaction Cross Sections

Early estimates of the size of neutron rich isotopes of lithium and heliumemployed the optical limit of the Glauber model in which the nuclearone-body densities were taken to be simple Gaussians. They predicted an enhanced size for these nuclei compared with that obtained from the usual scaling. But by retaining the few-body degrees of freedom inthe projectile wave function, its important structure information is retained. As a consequence, studies that evaluated the reactioncross section within a few-body approach , rather than take the opticalmodel limit, predicted an even larger matter radius, as shown in Fig. . Thismay at first sight seem contrary to what we might expect, since such a model allows for new breakup channels to become available, predicting a larger reaction cross section and hence a smaller radius to bring the cross sectionback down to the experimental value again. However, the Johnson-Goebelinequality relation , shows that for a given halo wavefunction, the optical limit model always *overestimates* the total reaction crosssection for strongly absorbed particles, thus requiring a smaller halo size thansuggested by the full few-body calculation.

Elastic and Inelastic Scattering.

Much can been learned about the structure of nuclei from elastic scattering.But for unstable systems such as halo nuclei the scattering has to be carriedout in inverse kinematics with the nucleus of interest as the beam scatteringfrom a stable nucleus or single proton. Over the past decade, a number ofmeasurements of the angular distribution for the scattering of halo nuclei from a stable target (often 12C) were unable to distinguish between elasticand inelastic scattering due to the poor energy resolution in the detectors.

The Breakup Reactions.

Halo nuclei are very weakly-bound and consequently easy to break up. Itis therefore not surprising that breakup cross sections are much easier tomeasure than elastic ones. Numerous breakup measurements have been performed,even when the radioactive beam intensity was rather low. In parallel,the theoretical community has been attempting to model these reactions accurately.

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