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THE COMPLEMENTARITY BETWEEN NEUTRON CAPTURE AND HEAVY-ION REACTIONS IN NUCLEAR STRUCTURE STUDIES

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INTRODUCTION

For the study of the structure of atomic nuclei a great variety of methods are employed. In the experimental field, the spectroscopy of radioactive decay, the spectroscopy of the radiation following neutron capture, conventional reaction studies with light charged particles, investigations with heavy-ion reactions, high-resolution electron-scattering experiments, photonuclear reaction studies, reactions with unstable particles at high-energy accelerators, and optical methods, in particular with lasers,[1]) yield a wealth of data which contain information about nuclear structure.

The areas of current interest are continually widening. Qualitatively new and very interesting aspects[2]) have recently shown up in nuclear regions far from stability and in processes where nuclei are under extreme conditions, as e.g., in states of very high angular momenta.[3]) Of course, detailed studies of certain nuclear phenomena have necessarily been restricted to nuclei in or near the valley of stability because of experimental limitations. Studies of fission, of giant resonances, of the nuclear charge distribution, of nuclear collectivity at high spins, of the properties of high-lying states in terms of the couplings[4]) between the elementary excitation modes observed at low energy are a few examples.

In what follows, I briefly deal with neutron capture and heavy-ion reactions with emphasis on the aspect of their complementarity for the study of nuclear structure. The nuclear levels of interest are limited both with respect to excitation energy and angular momentum as indicated in fig. 1.

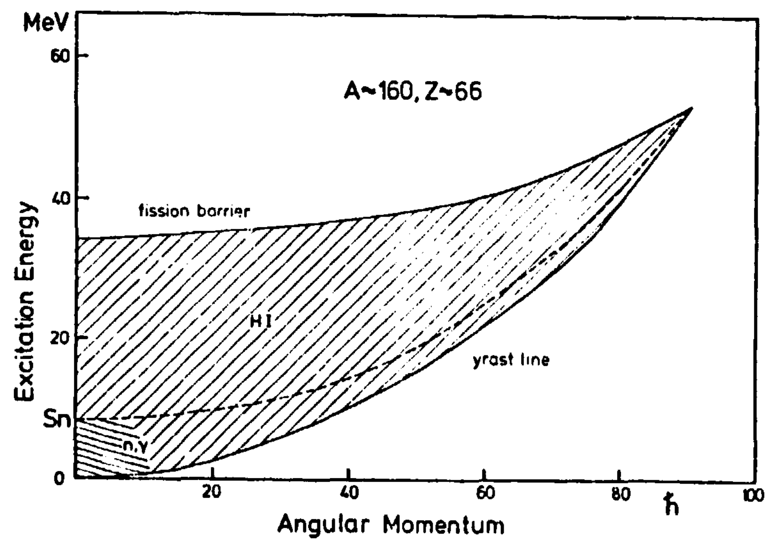

Fig. 1. Region of states that can be populated through heavy-ion induced reactions (HI) and slow-neutron capture (n,γ). The actual HI population distribution depends on the type of heavy-ion reaction.[5] The (n,γ) population is in general well understood[6] on the basis of the statistical model.

Usually, the (n,γ) reaction permits only the study of states with low spins up to ~ 6ħ. In exceptional cases, where the targets have spins > 5ħ such as ^{176}Lu (7$^-$) or ^{180}Ta (8$^+$), states with higher spin can be studied.[7,8] Also the study of γ-rays following neutron capture in 11/2$^-$ isomers can provide such information.[9] Heavy-ion induced reactions can, on the other hand, lead to the population of states with angular momenta up[10] to the limiting spins.[11] Slow and resonance neutron capture result in the excitation of low-spin states up to about 10 MeV. In a heavy-ion bombardment a broad region of levels is excited with energies of the order of 10 MeV above the yrast line but with very little population of low-spin states.

Neutron capture and heavy-ion reactions therefore yield complementary sets of data which allow a more comprehensive study of nuclear structure phenomena. Because of limitations with respect to the availability of targets a particular problem must often be studied in different nuclei. The complementarity is perfect in cases where a nucleus can be reached both in neutron capture and through a heavy-ion reaction. An example of this kind, where the interpretation of the results from a heavy-ion induced γ-ray study[12] has found significant support through (n,γ) spectroscopy,[13] has already been discussed.[14]

SPECTROSCOPIC METHODS

The investigation of the structure of an atomic nucleus requires detailed data of its level energies, their spins and parities, the matrix elements of the transitions connecting the excited states, their moments and information about the nuclear shape.

The spectroscopy of the γ-radiation and conversion electrons following slow-neutron capture yields a great wealth of information about low-spin states, in particular because of the quality of the data, which normally is much higher than in heavy-ion induced γ-ray studies and which in favorable cases allows the observation of very weak inter- and intraband transitions[15] that are essential for nuclear structure work. Detailed (n,γ) spectroscopy on targets with high cross sections permits the determination of a fairly complete scheme of the low-spin states up to an excitation energy of about 1.5 MeV. The complementary heavy-ion induced γ-ray studies normally allow the observation of states up to a spin of the order of 20ħ in a very narrow energy band above the yrast line. The detection and study of higher lying states with spins > 10ħ is usually quite difficult.[16-18]

A unique feature of the (n,γ) work is the possibility of measuring primary γ-transitions which directly yield the energies of excited levels. Such transitions cannot be isolated in (HI,xnγ) work. However, in special cases, even for x = 2, careful measurements[19] of the excitation functions close to the barriers (see fig. 2) yield very useful information about level energies.

The determination of spins in neutron capture frequently requires the measurement of angular correlations of the γ-rays. In in-beam (HI,xnγ) spectroscopy the alignment of the evaporation residues with respect to the beam[20] allows spin assignments with the aid of simple, one-dimensional measurements of the γ-ray angular distribution. Such measurements clearly show, e.g., that the spin of the first excited state in $^{146}_{64}Gd_{82}$ is 3^-.[21-22]

Information about transition matrix elements can be gained from the branching ratios of the assigned (n,γ) transitions. Absolute values require the knowledge of lifetimes which are difficult to obtain in a delayed γ-γ coincidence measurement for $t_{1/2} \lesssim 1$ ns. Here (HI,xnγ) measurements can yield the necessary data through recoil-distance[23] or Doppler shift attenuation measurements.[24-26] The range of measurable lifetimes has been considerably extended through the application of the so called "inverse" reaction[27] where a heavy projectile is used for the bombardment of a light target. In this case one obtains very large Doppler shifts permitting

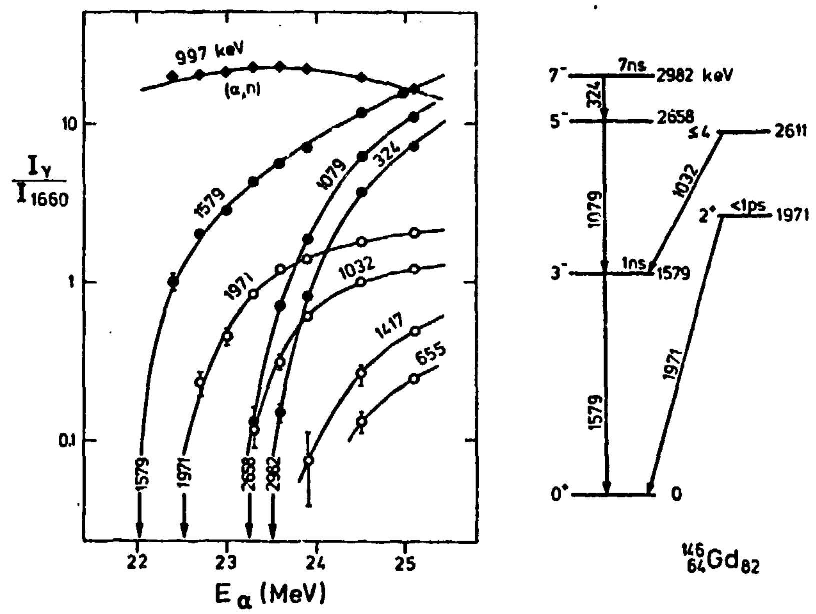

Fig. 2. Excitation functions for the $^{144}Sm(\alpha,2n)$-reaction normalized to the 1660 keV $2^+ \rightarrow 0^+$ transition in ^{144}Sm excited through (α,α'). The numbers above the arrows in the lower left of the figure are the energies of the levels fed by γ-rays whose energies serve as labels of the excitation functions. These data yield the position of the 2^+ level in ^{146}Gd.

lifetimes as short as ~ 90fs to be measured.[27]) Furthermore, with the use of a deuterium target one can study the reaction $^2H(A,p\gamma)A+1$, where the heavy-ion beam consists of the isotope A. This reaction is the inverse of the (d,p) process which yields very valuable information complementing the (n,γ) data.[28]) A considerable reduction of the background is achieved in the $^2H(A,p\gamma)$ study through the measurement of the γ spectrum in coincidence with the outgoing protons.[27])

Heavy ions can also be employed for measurements of magnetic moments or quadrupole moments. The ion-implantation perturbed angular correlation technique in conjunction with the $(^{16}O,4n)$ reaction has served for the determination of g-factors.[29]) Observation of the reorientation precession[30]) has allowed the determination of quadrupole moments of excited states[31]) in ^{103}Rh by Coulomb excitation.

Another piece of information that is of interest in nuclear structure studies is the sign of the nuclear quadrupole deformation. The sign can be determined through $(\alpha,\alpha'\gamma)$ correlation measurements. The result of such work[32]) shows that ^{24}Mg is prolate. Similar studies[33]) demonstrate that ^{28}Si is oblate.

The (n,γ) reaction is a tool for the excitation of levels with low spin. The nucleus in the capture state is "hot" and "cools" by means of the de-exciting γ-ray cascade which mainly affects the internal degrees of freedom of the nucleus. In (HI,xnγ) reactions the evaporation residues are generated several MeV above the yrast line in states of high angular momentum. Cooling thus occurs as the population approaches the yrast line, on which, in the case of exclusive rotation of the nuclear potential, the nuclei should be considered as "cold." If decoupled nucleons[34] contribute to the angular momentum, this simple picture loses its validity. Therefore care should be exercised in the interpretation of yrast states especially in regions where nuclei exhibit a closed shell character like ^{146}Gd and ^{147}Gd.[35] Conventional yrast plots based on the level schemes shown in fig. 3 appear quite normal. Approximate backbending plots, however, show extreme distortions. They are not suited as a basis for the nuclear structure discussion of the levels of ^{146}Gd and ^{147}Gd, which can be well understood[35] in the framework of the shell model. A detailed understanding of the nuclear cooling at large angular momenta is of considerable current interest.

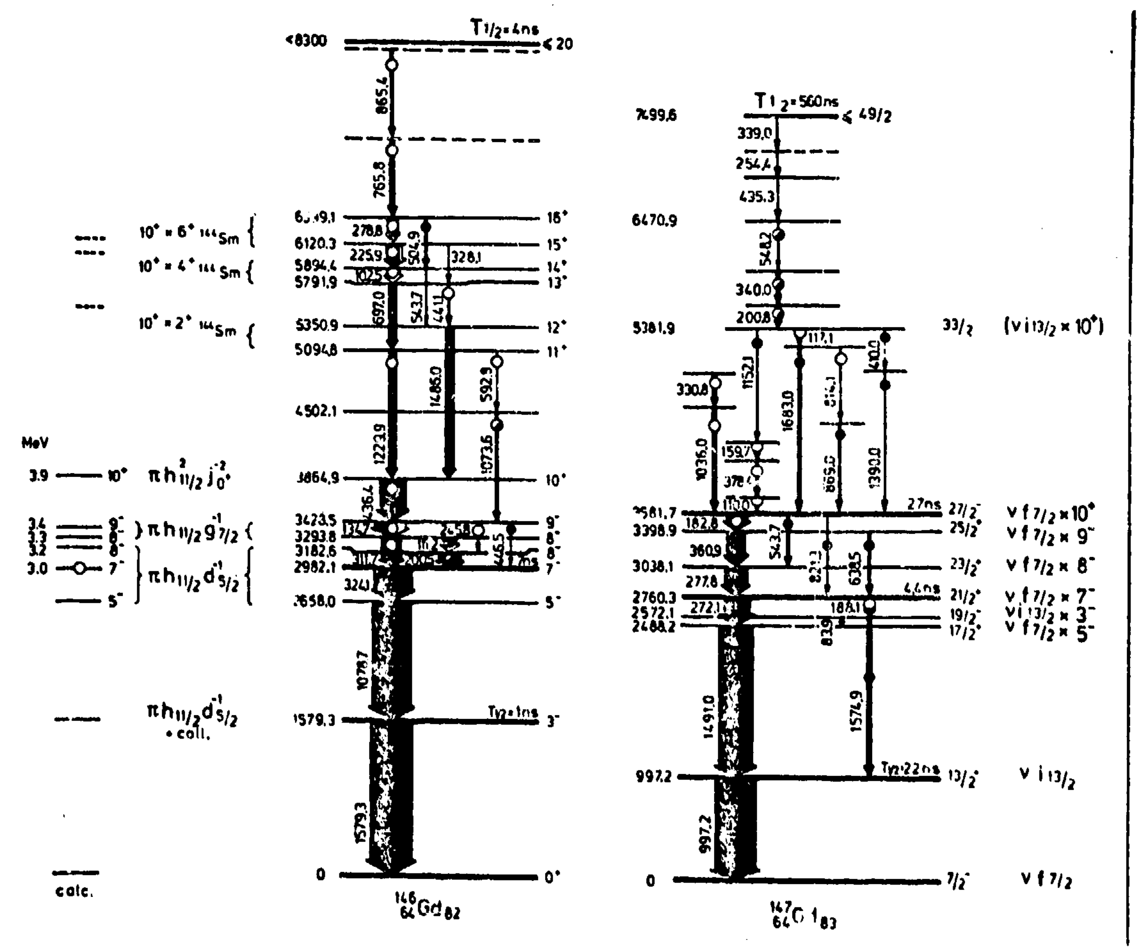

Fig. 3. Partial level schemes[35]) for ^{146}Gd and ^{147}Gd.

NUCLEAR ROTATION AND COUPLING OF NUCLEONS TO THE CORE

The rotational behavior of nuclei in states of low spin has been investigated in a great number of studies. In many cases use was made of the (n,γ) reaction, as e.g., in the case of ^{164}Dy, where the γ-vibrational and octupole bands were studied,[36] in the investigation of the ground state band and γ-band up to I=8 and of the Coriolis coupling of two quasiparticle bands in ^{168}Er[37]) and in the study of the quality of the rotational bands in ^{177}Lu.[7])

For the investigation of the nuclear rotational motion at high spin, heavy ions are needed and γ-ray spectroscopy is carried out in beam after (HI,xn) reactions or Coulomb excitation. Such studies have provided information about yrast states with spin up to ~ 24ħ,[38]) about K-isomers,[39]) about backbending,[40]) and about the nuclear moment of inertia at very high spins.[41])

In the region of well-deformed nuclei the detailed (n,γ) study[42]) of ^{169}Yb has provided a large amount of information about the low-spin members of ~ 15 rotational bands. Through complementary (α,xnγ) work[43]) the high-spin members up to I ~ 25/2 of the rotational bands built upon the |633↑|, |521↓|, and |512↑| orbitals have also been observed. The complementary investigation of even-even deformed rare earth nuclei is limited by the availability of targets. Reactions induced by heavy ions lead to neutron-deficient nuclei, which, in general, are inaccessible to the (n,γ) reaction, although in a few cases the same nuclei can be reached, e.g., by (α,2n) and (n,γ).

A very high degree of complementarity between (n,γ) and HI reactions is achieved if Coulomb excitation by heavy ions is employed. After the development of this tool into a powerful method,[44]) it has been refined[45]) and applied for the study of high-spin states in nuclei as neutron rich as ^{164}Dy (see fig. 4) and ^{160}Gd.[47]) For these studies ^{208}Pb projectiles were used with energies between 4.7 and 5.3 MeV/amu. States were observed with spins up to I=22 and 24, respectively, and their energies suggest that these nuclei have a quite pure rotational structure. The motivation[48]) of this work, the Coulomb excitation study of lighter isotopes of Dy and Gd and (HI,xnγ) studies employing "inverse" reactions like ^{26}Mg(^{136}Xe,4n) ^{158}Dy, was the determination of B(E2) values for the transitions between the high-spin states in order to shed light[49]) on the causes for backbending. The use of the inverse reaction has considerably facilitated the recoil-distance measurements of lifetimes, and the B(E2) values obtained rule out a secondary minimum as cause of the backbending. B(E2) values of the ground-state band levels, e.g., in ^{164}Dy, have also been determined using Coulomb excitation, employing a Doppler broadened line shape technique[50]) and also the recoil distance Doppler shift method.[51])

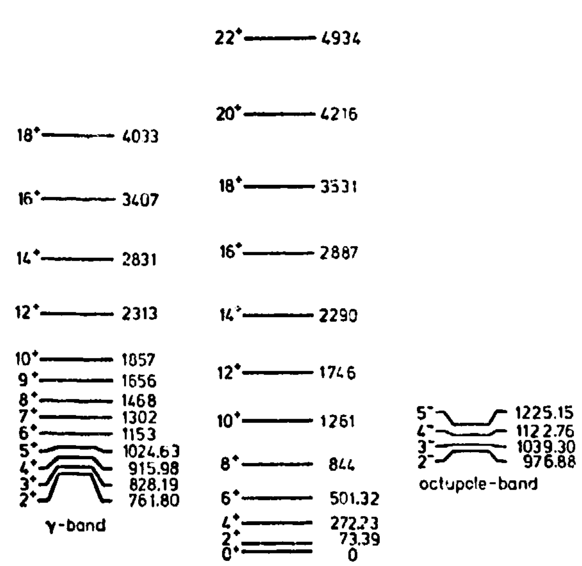

Fig. 4. Level scheme and rotational band structure of ^{164}Dy as obtained from (n,γ)[36]) and Coulomb excitation[46]) studies.

In the transitional region for $84 \leqslant N < 90$ complementary experiments on the even-even Sm isotopes have been carried out through (α,xnγ) studies[52,53]) through Coulomb excitation with ^{16}O ions[54,55]) and through neutron capture γ-ray spectroscopy.[56]) Studies of such nuclei are of considerable interest in connection with the Interacting Boson model.[57]) An example of complementary work on an odd-A nucleus in this transitional region is the high-resolution (n,γ) spectroscopy[58,59]) and (α,xnγ) studies[60]) of ^{151}Sm.

Very little is known about odd-odd nuclei in the transitional region mentioned above. The availability of suitable targets has limited (n,γ) spectroscopy to ^{152}Eu, and an enormous amount of data has been obtained[61]) about this nuclide because of the favorably high (n,γ) cross section. The study of the level scheme of ^{152}Eu is interesting for two reasons: first, to determine whether ^{152}Eu exhibits well developed rotational bands, and second to determine in which way the angular momenta of the odd proton and odd neutron couple[62]) to form high-spin states. For the latter reason a (HI,xnγ) study of this odd-odd nucleus was clearly desirable. It turns out, however, that such a study is quite difficult. One reason for this is the fact that the available targets require a Li beam which implies that the γ-ray spectrum from the reaction of interest is diluted by the spectrum from parasitic processes.[63]) For the maximization of the input angular momentum and because of voltage limits the ^{150}Nd(Li,4n) reaction was chosen at a beam energy of 36 MeV for which ℓ_{max} should be around 17ħ. The second difficulty is the exceptionally high level density in ^{152}Eu, even at low excitation

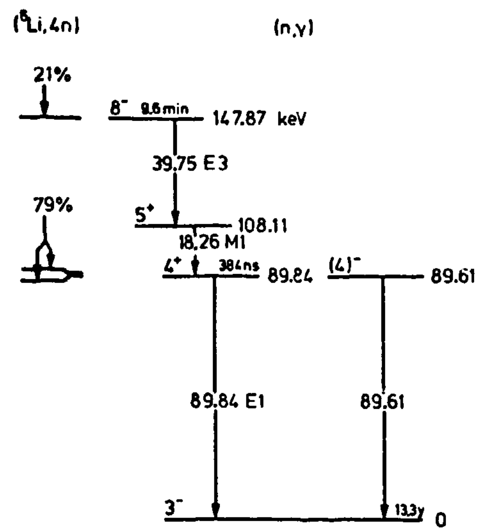

Fig. 5. Partial level scheme of ^{152}Eu. The 8⁻ state[65] is populated[64] in the (^{6}Li,4n) reaction with only 21% of $I_\gamma(89.8)+I_\gamma(89.6)$.

energies, where 36 excited states have been observed below 225 keV.[61] In spite of the predominant population of yrast states, which simplifies the γ-spectra somewhat, the (^{6}Li,4n) γ-ray spectra are expected to consist of very many lines in accordance with observation.[64] Finally, the particular energies and half-lives of the low-lying yrast states depicted in fig. 5 impede the measurement of γ-ray coincidences. The preliminary (^{6}Li,4nγ) study[64] has shown that the population of the 8⁻ level[65] amounts to 21% of the total feeding of both states at 89 keV. This feeding of a level with I=8 is only about one third of the normal population of the 8⁺ state of the yrast band in a deformed even-even nucleus under similar reaction conditions.[63] This suggests considerable branching of the yrast transitions in ^{152}Eu and makes its (HI,xnγ) spectroscopy very difficult.

As γ-ray spectroscopy following Coulomb excitation of the radioactive ^{152}Eu is impracticable, the alternative method of inelastic proton scattering has been employed[66] for the study of its ground state band. The observed proton spectrum reveals a very well-developed band up to the 7⁻ state. This, together with calculations[67] based on the electromagnetic data,[61] shows that the ground state of ^{152}Eu has a very good approximation to the configuration $(\pi|413\downarrow| + \nu|505\uparrow|)K=3$ and $\beta \approx 0.28$.[66] Obviously it is the $|505\uparrow|$ orbital which stabilizes the deformation in ^{152}Eu. A much more detailed knowledge of the structure of this nucleus is of considerable interest in the light of a recent proposal[68] of three distinct shapes existing in ^{151}Eu.

A lighter odd-odd nucleus which, because of its largely unknown structure, has been studied by the complementary techniques (HI,xnγ) and (n,γ) is ^{104}Rh. In a coincidence measurement[69,70] of γ-rays following slow neutron capture a 43-ns isomer was observed, which in view of its mode of decay should have $I^\pi = 5^-$ or 6^-. The population of the isomer through a cascade of three low-energy γ-ray transitions with nearly the same (n,γ) intensity suggested the presence of a special structure in the levels involved. Furthermore, the relatively large isomer ratio can only be understood if the feeding cascade originates from a level with rather low spin, because the capture state has $I^\pi = 0^-$ or 1^-. In order to gain additional information about the isomer and about yrast states in ^{104}Rh, the ^{100}Mo(^{7}Li,3nγ) reaction was studied[70] at 27 MeV. The strongest lines observed were those depopulating the isomer whose lifetime could be confirmed. A populating cascade, different from the (n,γ) cascade and consisting of five γ-rays, was found. The (^{7}Li,3nγ) and (n,γ) data suggest the tentative level scheme[70] shown in fig. 6. The upper levels most likely constitute the $\pi(g_{9/2})^{-5} \otimes \nu h_{11/2}$ multiplet, with its high-spin branch forming the yrast cascade and the low-spin members giving rise to the (n,γ) cascade with its pronounced structure. The structure of the other low-lying states in ^{104}Rh is the subject of current research.[71]

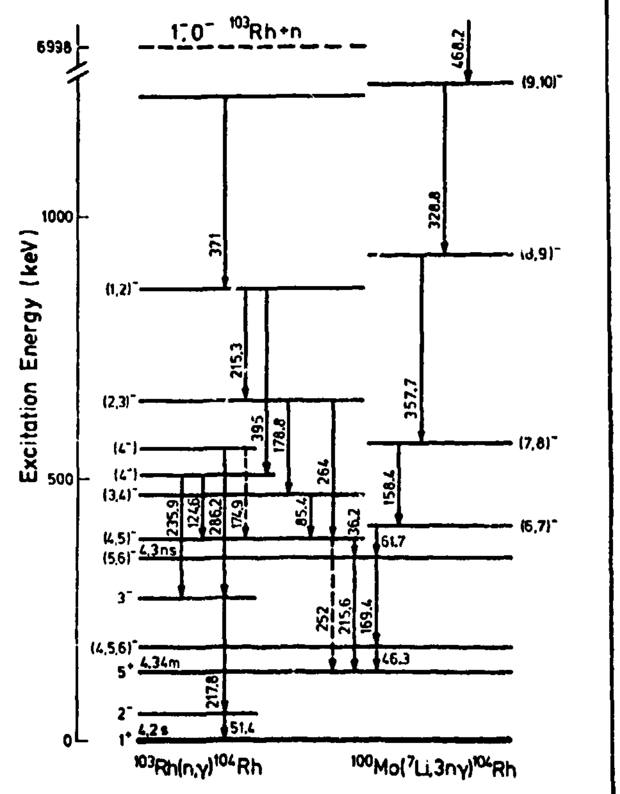

Fig. 6. Tentative partial level scheme of ^{104}Rh obtained from (n,γ) and (^{7}Li,3nγ) singles and coincidence data.[70]

Complementary spectroscopy has been carried out of the nearby Ru isotopes for the investigation of the coupling of the valence neutron to the core. Extensive (n,γ) work[72]) has led to the establishment of a fairly complete low-energy level scheme of ^{105}Ru. As all four orbitals $d_{5/2}$, $s_{1/2}$, $g_{7/2}$, and $d_{3/2}$ contribute to the positive parity states, the structure of these states is expected to be very complex. This has so far prevented a successful interpretation within the framework of existing models. The negative parity states, however, should result only from the coupling of the $h_{11/2}$ neutron to the ^{104}Ru core, since core-excited states with negative parity are not expected below ~ 2 MeV. As is shown in fig. 7, the energies are known of states with spin I^{π} = 11/2$^-$, 15/2$^-$, and 19/2$^-$, observed in ^{103}Ru in the (α,nγ) reaction.[73]) These levels can be envisaged as a decoupled band.[34]) Such an interpretation of the 11/2$^-$ state in ^{105}Ru would imply prolate deformation of the core and suggest the occurrence of negative parity states with low spins and corresponding excitation energies. Deformation parameters of β_2 = +0.27 and γ = 0 are obtained from Coulomb excitation[74]) of the 2$^+$ state at 358 keV in ^{104}Ru. This 2$^+$ energy served as the basis for the calculation[75]) of the low-spin negative parity states in ^{105}Ru. Figure 7 demonstrates, however, that the observed negative parity states have considerably lower energies than those expected[75]) for a particle coupled to a rigid rotor, a model which explains the positions of the 11/2$^-$, 15/2$^-$, and 19/2$^-$ states in ^{103}Ru quite well. A similar discrepancy is known to exist in ^{153}Tb. Obviously, to obtain a detailed understanding of these low-spin negative parity states will require a more realistic description of the coupling of a particle to the dynamic core of a transitional nucleus.

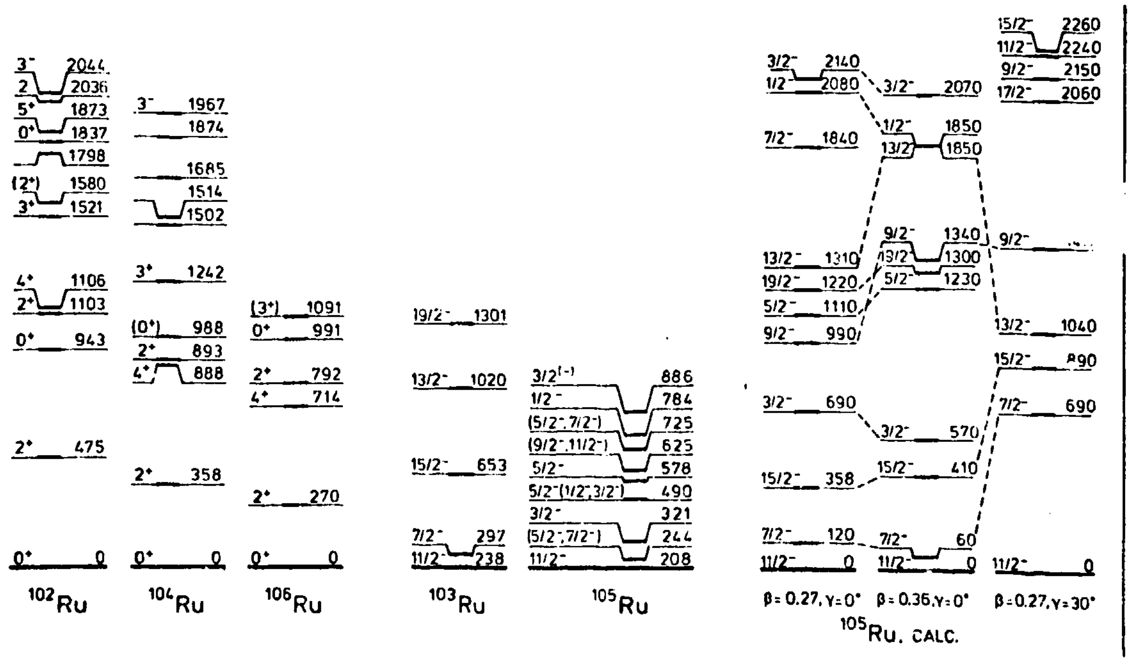

Fig. 7. Comparison of the observed[72]) and expected[75]) negative parity states in ^{105}Ru.

The discussion of the negative parity states in ^{105}Ru clearly demonstrates the necessity of the investigation of excited low-spin states, which can be studied in radioactive decay and through (n,γ) spectroscopy. These low-spin states are nonyrast levels which contain essential nuclear structure information that unfortunately is not as easy to extract as in the case of high-spin states because of the larger mixing of the low-spin levels. Also the interpretation of the backbending phenomenon could benefit from information about higher lying low-spin states which might be members of bands whose high-spin states are seen in (HI,xn) reactions. Very little is known[76]) about such states so far, and studies of nuclei which can be reached through (HI,xn) reactions, Coulomb excitation and (n,γ) would be very helpful. A few f-p shell nuclei which can be investigated through (n,γ) and (HI,xnγ)-reaction spectroscopy and where (α,xnγ) data are already available are ^{71}Ge,[77]) ^{75}Se,[78]) and ^{77}Se.[79])

DE-EXCITATION AND STRUCTURE OF HIGH-LYING STATES

Limitations in our instrumental resolution and techniques have prevented the exhaustive study of levels in heavier nuclei above ~ 1.5 MeV for low spins and beyond I ~ 37ħ[80]) on the yrast line. Information about higher-lying states is very difficult to obtain, and in general only some kind of averaged data are available like strength functions,[81]) an averaged g-factor[29]) and the γ- ray multiplicity, the average number of photons emitted in the reaction.

Such multiplicity measurements in the (n,γ) process were carried out many years ago,[82-84]) and they have served for the explanation of isomer ratios,[85]) for the determination of the spin cutoff coefficient[86]) in the nuclear level density formula, and they confirm the statistical depopulation of high-lying states. Calculations[87]) of the (n,γ) spectrum and the multiplicity have been performed even recently, which shows that there is still interest in such data. Information about the speed of the primary transitions in the (n,γ) process can be obtained from the known γ-widths of the low-energy neutron resonances and their statistical γ-decay. In heavy-ion fusion reactions the lack of information about the γ-widths of high-lying states necessitates statistical model calculations,[88]) which are basic for comparisons with experimental data and which are complementary to the (n,γ) calculations. After a first multiplicity measurement[89]) in (HI,xn) reactions, such studies have been undertaken by various groups[90-95]) in the past few years. These data yield information about the angular momenta of the evaporation residues prior to their γ-decay, about angular momentum limits,[95]) the nuclear moment of inertia at very high spin,[96]) and the γ-ray cascade.[97])

The investigation of individual levels several MeV above the yrast line is extremely difficult because of the inadequate experimental resolution. An exception is the (n_{res},γ) reaction which serves like a microscope for the selection of individual states just above the neutron-binding energy. At time-of-flight arrangements, effective use can be made of neutrons with energies up to ~ 300 keV[98]) so that states can be studied in a reasonably broad energy window. In cases where the neutron capture state has a very complex structure, its decay agrees with the statistical model, in accordance with Niels Bohr's compound-state picture. Deviations from such a mode[99,100]) of decay indicate the predominance of special structures in the capture state. Such structures are the subject of detailed, current theoretical work.[101]) Extensive measurements of primary γ-ray spectra following slow- and resonance-neutron capture have shown that such deviations occur in several regions of the nuclear chart, where e.g. channel capture[102]) or the valence neutron model[103]) roughly explain the observed partial widths.[104]) Studies of γ-spectra from 24-keV neutron capture in even Mo isotopes[105]) provide evidence for other simple processes contributing to the capture, and it is likely that the presence of three quasiparticle components in the capture state wave functions[106]) are the reason why the valence model does not quantitatively describe the observation. Other data[98]) obtained on the titanium isotopes support the dominance of single-particle effects in neutron capture and support the presence of 2p-1h states in addition to the valence neutron. It has thus been successfully demonstrated that the (n_{res},γ) reaction is sensitive to the wave functions of such highly excited states. The determination of the amplitudes of their components is, however, still very difficult.

Photoexcitation of high energy γ-rays produced in a very intense (n,γ) source is another process for studying highly excited states in stable nuclei.[107,108]) In photoexcitation one can determine the spin and parity of the excited level, the strengths of primary E1 and M1 transitions and sometimes mixing ratios, and one also obtains information about the nuclear level density, which is of considerable interest in connection with the problem of the disappearance of shell effects.[109]) In these studies, the incident γ-lines can directly excite high-lying levels through random overlap, or the energy of the incident (n,γ) line can be varied by up to ~ 1 keV through nuclear scattering which allows high-resolution work, or it can be varied by up to ~ 5 MeV through Compton scattering where the resolution is typically ~ 175 keV. A resolution of 70 to 100 keV has been obtained with Bremsstrahlung when the events of interest were recorded in coincidence with the radiating electrons.[110]) At such facilities a resolution of $\leq$ 10 keV seems possible.[111]) High resolution can be maintained and an energy variation larger than that from the (n,γ) reaction (typically 10 to 20 keV for observation angles between 0° and 180°) can be achieved if the incident photons are produced in the complementary (p,γ) reaction.[112])

Such data are even more suited for comparison with the averaged values obtained[101]) from a semi-microscopic calculation of radiative strength functions. Using target nuclei with $A \leqslant 44$, one now has available[113]) about 500 γ-lines which can serve for the excitation of practically all levels between 6 and 10 MeV. For resonance fluorescence experiments use can be made[114]) of the kinematically broadened, $\sim$ 130 keV wide 6.92 and 7.12 MeV lines from the $^{19}F(p,\alpha\gamma)^{16}O$ reaction at $E_p \approx$ 2 MeV.

Information about the structure of states at intermediate and high excitation energies is also of interest in view of recent progress in the calculation of the fragmentation of single-particle states.[115]) Such fragmentation appears to be important for the interpretation of the α-spectra from the interaction[116]) of fast neutrons with odd-A ytterbium isotopes. These α-spectra differ considerably from the prediction of the Hauser-Feshbach[117]) theory and lend support to the knock-on model and the presence of preformed α-like structures in the resulting nuclei.[116]) Also in-beam γ-ray spectroscopy during the bombardment of $f_{7/2}$ nuclei with energetic α-particles and the observation of lines from nuclei differing from the target by up to 3 α-particles[118]) weakly suggests the existence of α-particles in the surface of these nuclei. At lower excitation energies such effects might become visible for nuclei with Z or N exceeding the magic numbers by 2, assuming the (n,α) channel is open even for slow neutrons.[119,120]) These conditions are fulfilled, e.g., for ^{143}Nd where the spectroscopy[121]) of the complementary HI reaction $^{140}Ce(^{16}O,^{12}C)^{144}Nd$ lends some support to the assumption of a selective population of states at 6 to 8 MeV in ^{144}Nd, which would then suggest special structures for these states. Gamma transitions in the $(n,\gamma\alpha)$ process are expected[101]) to populate levels with a large number of quasiparticles, so that this reaction might be one of the few methods to investigate the largest many quasiparticle components in highly excited states. It appears, however, as if these studies yield only crude information about the ratio[122]) of the hindrance factors of the M1 and E1 transitions between high-lying states, the decay of which seems[122]) totally consistent with the statistical prediction. Also in other studies no evidence has been found for the predominance of α-particles in the surface of heavy nuclei.[123]) More information about the structure of such high-lying states can probably be obtained from future high-resolution transfer-reaction studies with heavy ions.

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