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LASER MEASUREMENTS AND NUCLEAR STRUCTURE

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Abstract The nuclear states amenable to laser studies are reviewed with respect to their structure. Systematic predictions are made, e.g. for magnetic moments of parity-mixed intrinsic orbitals in the Ac isotopes and for the shape of the known high-spin isomers in the Pb region.

Laser measurements can in principle probe the structure of any nuclear species that is made available for a sufficient length of time by determining the spin, the size, the surface deformation and the radial distribution, and the electric and magnetic moments including the sign. There are recent reviews on this[1,2]. The lower limit on the lifetime of the nuclear states that can be studied is ultimately set by the lifetime of the atomic states employed by the laser, and certainly it should be possible to study nuclear states of the order of 1000 ns or more. The purpose of this paper is to survey such states from the nuclear structure point of view and to focus on some open problems of current theoretical interest.

All the known long-lived nuclear states can be sorted into four groups:

(i) Ground and near-ground states. Measurements are conceivable for over 5000 ground states. Moment measurements of some kind have so far been made for

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about 600. A fair fraction of all odd and odd-odd nuclei also have low-lying isomeric states which as a group represent the same kinds of structure as the ground states.

(ii) Shape isomers, notably the fissioning isomers in the actinides.

(iii) Two-quasiparticle isomers.

(iv) Yrast traps, very high spin isomers involving more than two valence particle spins.

These groups will be discussed in turn.

Ground-state properties and systematics far from stability are obviously interesting in many ways, and only a few topics can be addressed here. First a passing comment on the odd-even staggering of $\delta\langle r^2\rangle$, observed for example in the light cesium isotopes. A staggering emerges from the deformed shell model, as illustrated by Fig. 1. There the mechanism is clear from the well-known expression for the

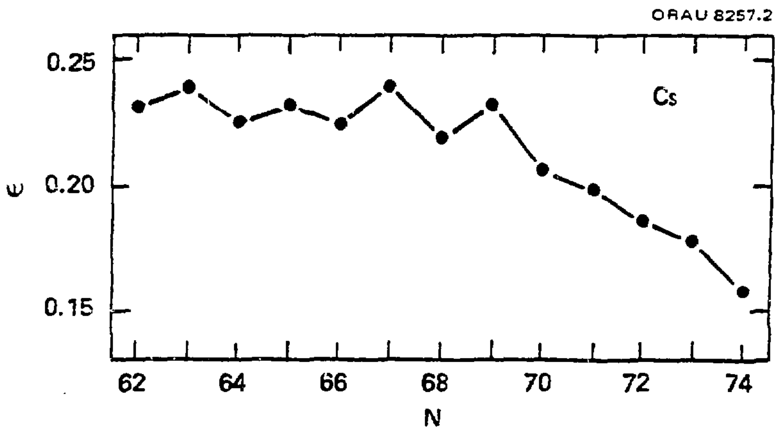

FIGURE 1. Equilibrium deformation ε for some light Cs isotopes from the potential-energy calculations of Möller and Nix[3].

BCS quasiparticle energy, $E = [(e-\lambda)^2 + \Delta^2]^{1/2}$. The single-particle energy and the pair field may both vary with deformation ε, whereby the odd quasiparticle exerts a driving force $-dE/d\varepsilon$ on the system. Usually the pairing gap parameter Δ is larger than $e-\lambda$, which tends to emphasize the variations of Δ^2. In Cs the sign of the odd-even staggering can be thought to arise because Δ decreases with increasing deformation. It would be interesting to see a systematic evaluation of data on this premise. If another model is to be used, it should also be fundamental enough to describe coupling between the collective quadrupole and pairing degrees of freedom on a microscopic basis.

Secondly, let us consider ground-state magnetic moments. There exist familiar theoretical techniques for evaluating core polarization effects in spherical nuclei[4]. For non-perturbative quadrupole effects there is the likewise familiar Nilsson model, which can be applied with the inclusion of triaxiality and Coriolis coupling[5,6]. As an example, in ^{133,135}Ce the $1/2^+$ ground states are predicted to have $\mu \sim -0.36$ n.m. The ground state of ^{127}Ce could also be $1/2^+$, but with $\mu \sim +0.42$ n.m. since the quadrupole field brings out the [411 1/2] configuration rather than $d_{3/2} \times s_{1/2}$.

Not so familiar are non-perturbative effects of parity-breaking modes. As we shall see now, it might be possible to establish the existence of parity-mixed intrinsic states by certain μ measurements. First, to clarify the concept of a static parity-breaking deformation, let us draw the analogy with ordinary deformation which breaks rotational symmetry. If a nucleus really did break spherical symmetry spontaneously, angular momentum would not be a good quantum number. In real life symmetry has to be restored by projection with the D-functions, and the states of different spin split apart into a rotational band. Nevertheless, all the states of the band have the same intrinsic structure, and it is physically relevant to describe the nucleus as non-spherical even in a perfectly spherical 0^+ state. Similarly, if the nucleus were to break reflection symmetry the parity would be mixed. In real life parity is restored by taking a linear combination of left-right and right-left asymmetric states, and the parities split apart. However, the two states of parity + and - have identical intrinsic structure. Likely candidates for this are known in the Ra-Ac-Th region[7]. Parity doublets in odd-A cases, previously interpreted as pairs of completely different Nilsson orbitals which happen to come close in energy, could alternatively arise from a single parity-mixed Nilsson orbital.

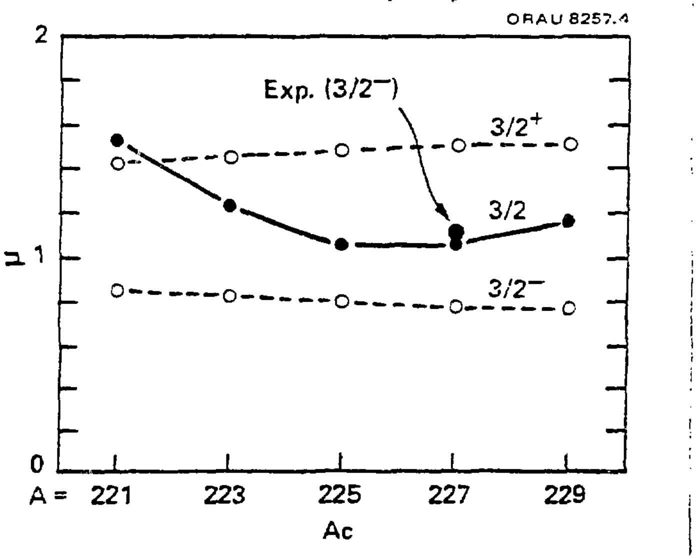

FIGURE 2. Magnetic moments for low-lying states of Ac. The solid curve is calculated at the parity-mixed equilibrium deformations while the dashed curves are obtained under the constraint of intrinsic reflection symmetry.

The crucial test would be a measurement to see whether the intrinsic wave functions are indeed identical. In the $3/2^{\pm}$ and $5/2^{\pm}$ doublets of the Ac isotopes the relevant reflection symmetric orbitals are spin-flipped and would have quite different magnetic moments, as shown in Fig. 2 for $3/2^{\pm}$. The $5/2^{\pm}$ case is similar but with $\mu^{+} = 2.6$, $\mu^{-} = 1.3$ and $\mu^{mixed} = 2.2\text{-}2.3$ for $^{221-229}$Ac. It is indicative but inconclusive to see the one experimental point near the parity-mixed curve - confirmation would come from observing two members of a doublet very close to each other.

Fission isomers are in some ways like ground states - even more elongated shapes are predicted to be ground-state for the neutron-rich actinides that participate in the astrophysical r-process[8]. Systematic data could be very valuable to structure theory. For example, there are nucleonic states with extreme values of the quantum numbers that cannot be observed anywhere else. Also the elongation could make it easier to look for anisotropic spin polarization[9]. Laser neasurements have been reported by Beene *et al.* at this conference. It may be noted that interesting systematics for isotopic sequences are to be expected, just as for ground states. For example, Figure 3 shows the calculated deformation[8] of the known fission isomers in Am. A sharp increase is predicted around N = 150. Plotting ε^2 instead of ε in this figure, which enhances the fluctuations for large ε, is motivated by the quadratic relation between deformation and $\delta\langle r^2\rangle$. The calculated effect is due to deformation-driving orbitals above the N = 144 gap, viz. [871 1/2], [741 3/2], [990 1/2]. In ^{245}Pu the calculation even suggests shape coexistence within the second well, an

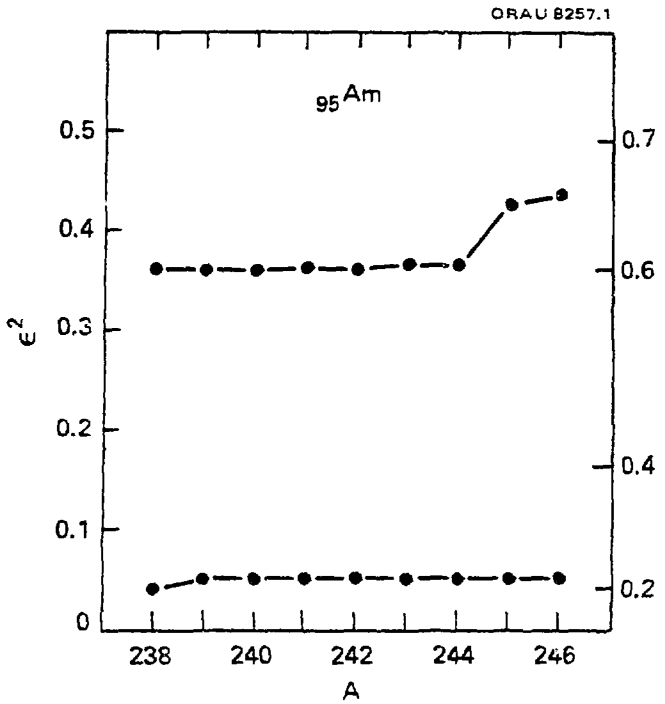

FIGURE 3. The deformation of fission isomers (upper points) and ground states (lower points) in Am isotopes calculated by Howard and Möller[8].

interesting generalization of the coexistence phenomenon in connection with shell gaps discussed at this conference by Wood. A combination of $\delta\langle r^2\rangle$ and magnetic moment measurements might help to identify the nucleonic orbitals, and Table I gives some relevant theoretical matrix elements.

The two-quasiparticle isomers are usually described as very simple configurations, and it becomes interesting to analyze quantitatively such things as the additivity of moments and polarization effects in spherical and deformed nuclei. For example, a sequence like the 8^+ states in ^{90}Zr, ^{92}Mo and ^{94}Ru, with lifetimes of 125 ns, 190 ns and 7100 ns respec-

TABLE I The Matrix elements of Nilsson orbitals at $\varepsilon = 0.61$, $\varepsilon_4 = 0.065$ needed[10] for magnetic moments and decoupling factors. The columns contain proton orbitals 54 to 38, ordered by decreasing energy, neutron orbitals 81 to 64, and then again the subset of $\Omega = 1/2$ orbitals. The "uncertainty" is the change in the last digit in going to $\varepsilon = 0.66$, $\varepsilon_4 = 0.06$.

$\bar{N}$	Ω	$\langle s_z \rangle$	$\bar{N}$	Ω	$\langle s_z \rangle$
	protons			neutrons	
4	5/2	0.495	6	7/2	-0.110-249
4	7/2	-0.474-5	7	5/2	-0.185-33
5	1/2	-0.391+1	9	1/2	0.074+44
7	5/2	0.310+3	6	11/2	0.479-1
6	1/2	0.295+17	8	7/2	0.084+247
6	3/2	-0.246-29	8	1/2	0.209-102
5	3/2	0.385+44	7	3/2	0.165+42
5	9/2	0.481+1	7	9/2	0.422+6
6	7/2	0.412+11	6	5/2	0.376+17
5	5/2	-0.392+3	8	5/2	0.285-10
7	3/2	0.273-11	5	3/2	-0.382-53
7	1/2	0.092+34	5	11/2	0.500
6	1/2	-0.086-104	5	1/2	0.402+33
4	9/2	0.500	7	3/2	-0.119-24
4	1/2	-0.427+51	5	7/2	-0.363-67
6	5/2	0.358-5	7	1/2	0.081+50
4	3/2	0.457+11	6	1/2	-0.272-29
			8	3/2	0.240+53

$\bar{N}$	Ω	$\langle 1/2 \vert s_+ \vert -1/2 \rangle$	$\langle 1/2 \vert j_+ \vert -1/2 \rangle$	$\bar{N}$	Ω	$\langle 1/2 \vert s_+ \vert -1/2 \rangle$	$\langle 1/2 \vert j_+ \vert -1/2 \rangle$
	protons				neutrons		
5	1/2	0.109+1	-0.93-10	9	1/2	0.574+44	6.86+2
6	1/2	-0.796-17	-1.21+10	8	1/2	-0.709+102	-1.04+91
7	1/2	0.592+34	6.22-26	5	1/2	0.902+33	-0.53+5
6	1/2	-0.414+104	3.35-87	7	1/2	0.581+50	-0.87+54
4	1/2	-0.073-51	0.79+50	6	1/2	-0.228+29	0.82+2

tively, might be interesting to examine in the light of the simplest shell model description[11] and the renormalization discussed at this conference by McGrory.

Yrast traps, or very high spin isomers, support high-frequency rotation in a way that is unusual for many-body systems. The majority of the nucleons pair off to spin zero and participate in the rotation only implicitly through the Pauli principle and by helping to define a mean field with precisely one axis of symmetry. A few unpaired nucleons can then spin around in this mean field and build up a formidable total spin by aligning their spins along the unique symmetry axis. The non-spherical axial symmetry is essential to this picture, and the self-consistent variation of the deformation between different "optimal" configurations is suggested to account for most of the residual interactions[12]. The deformation aspect of the theory has been made plausible by the success of the model in

TABLE II Theoretical deformation ε (± 0.01) for known $\tau \geq 100$ ns yrast traps in the lead region. Method of calculation as in Ref. 14.

Nucleus	I^π	ε	Nucleus	I^π	ε	Nucleus	I^π	ε
215Ra	25/2+	−0.02	211At	39/2−	−0.06	205Po	19/2−	−0.08
214Ra	17−	−0.02	210At	19+	−0.08	212Bi	15−	−0.02
	14+	−0.02		15−	−0.04	207Bi	21/2−	0.02
213Fr	29/2+	−0.02	209At	29/2+	−0.06	203Bi	25/2+	0.06
	21/2−	0	205At	21/2−	−0.10	205Pb	25/2−	0.02
212Fr	14+	0	212Po	16+	−0.02	203Pb	29/2−	0.04
214Rn	20+	−0.02	209Po	31/2−	−0.06	201Pb	29/2−	0.06
	16+	−0.02		17/2−	−0.02	199Pb	29/2−	0.06
212Rn	30+	−0.10	207Po	19/2−	−0.06	205Tl	23/2+	0.02
	22+	−0.04						

accounting for energy spectra, e.g. in ^{212}Rn [13,14], but so far the only direct experimental test is a measurement[15] of the quadrupole moment of a 550 ns isomer in ^{147}Gd, where the sign of the quadrupole moment and the spin of the isomer remain undetermined except by the theory. To encourage further efforts, Table II gives predicted deformations in all the known $\tau > 100$ ns yrast traps of the lead region. As an example, Fig. 4 gives more details of the calculation for ^{210}At. Aligned particle states lead to increasingly oblate shape and good agreement between theory and experiment for the 11^+, 15^- and 19^+ energies. An alternative 15^- configuration is shown where the residual interaction is repulsive because the $\nu i_{13/2}$ hole state is prolate. In

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Theory Nilsson M-Scheme											Experiment ^{210}At
	πh				i	νi	p	g			E (MeV)
ε	9/2	7/2	5/2	3/2	13/2	13/2	1/2	9/2			
−0.08	1	1			1		-2	1	3,940	19^+	4,028 (4 μs)
0.02	1		1	1		-1			3,400	15^-	
−0.04	1	1			1		-1		2,408	15^-	2,550 (580 ns)
−0.02	1	1	1				-1		1,363	11^+	1,363 (27 ns)

FIGURE 4. Deformation, particle (1) hole (−1) configuration and energy of high-spin states in ^{210}At.

nuclei with more holes, however, the axially symmetric prolate shape is favored, and in borderline cases the coexistence of prolate and oblate states results from the calculations, though no such cases are found among the known isomers in Table II. Direct spin measurements would be valuable in themselves, e.g. for the 16^+ (or 18^+) isomer in ^{212}Po.

One may hope that laser techniques can be developed to make some of these measurements feasible.

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