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Possible Manifestations of Oblate Shapes at High Spin in the Yrast Region of $A = 160-180$ Nuclei

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The possible manifestations of an oblate-shape region at high spin in $A = 160-180$ nuclei are considered. We focus attention on the fact that rotational band phenomena indeed can exist in nuclei with oblate shapes. From estimates of transition energies, the yrast cascade there could consist largely of low-energy, alternating $M1$ transitions within bands and $E2$ transitions between bands. If the recently found stretched-dipole transitions are confirmed as $M1$, these results may be an indication for the existence of oblate shapes at high spin.

Along the yrast line up to very high spins the nuclear shapes first expected[1,2] in the region $A = 160-180$ were at low spins ($I \lesssim 30$) prolate, at very high spins ($I > 50$) oblate, and between ($I \approx 30-50$) a more or less large transitional triaxial region. The properties of states along the yrast line also strongly depend on shell-model effects. Several microscopic calculations[3-5] have shown that usually shell corrections are so large that they almost completely destroy the oblate region in practically all strongly deformed nuclei with $N = 92-110$. Oblate states at very high spin in all these calculations appear at most as exceptions to the general rule. Of course these shell-correction calculations cannot be considered as very precise. So the question is, do oblate shapes exist at high spin in real nuclei with $A \approx 160-180$?

First consider the expected properties of levels along the yrast line.[2] Because of strong rotation, and therefore strong Coriolis coupling in the prolate and triaxial region, a large number of particles have their angular momenta aligned along the axis of rotation, and the intrinsic spin I_0 of the aligned particles is very large. When a nucleus begins to be oblate, its axis of symmetry begins to coincide with the direction of this alignment. What happens at this moment? Collective rotational motion about this axis of alignment is now impossible, because it means rotation about the axis of symmetry. From these considerations were derived the following two important conclusions[2]:

(I) Levels in the oblate region are not collective, but more nearly pure quasiparticle, and they form multiplets as in the near-magic nuclei. The residual interaction between the particles preferentially pushes down the level of the multiplet with high spin, and with irregularities in shell-model level spacings neighboring levels in the yrast line can have $\Delta I \gg 2$. In such a case the level of this pair can be expected to be a long-lived isomeric state with very large spin, the so-called isomeric traps[2] (a pure shell-model effect). When no isomeric traps were found[6] in the region $A = 160-180$ (they were found only in near-magic $N \approx 82$ nuclei), this was immediately explained as

a result of shell corrections which destroyed the oblate region.

(II) The yrast levels in the prolate and the triaxial regions of the yrast line are expected to be connected by strong collective $E2$ transitions.[7] (Multiparticle states can give rise to some exceptions in the region of discrete γ rays.[8]) As one goes from these regions into an oblate region, $E2$ transitions should continue to be more important between the many-particle multiplets (when isomeric states do not exist) except that now they will be noncollective. But the expectation of $E2$ transitions is in disagreement with recent experimental data.[9] In the continuous γ spectra in ^{174,175}W and ^{161}Yb after (HI, xn) reactions, there were found *large* numbers of nonstatistical, stretched $I \to I - 1$, $L = 1$ γ transitions with small energy, $E_\gamma \lesssim 0.5$ MeV.[9] Such *large* numbers of dipole transitions contradict the published calculations as discussed above.

Now let us consider in more detail the properties of the oblate region of the yrast line. As noted, previous considerations of this region[2-5] have not included rotational bands because oblate nuclei cannot rotate about the axis of alignment since it is the axis of symmetry. Such nuclei *can rotate*, however, about a perpendicular axis! The corresponding rotational band must be of the strong-coupled type with levels with spins $I = K$, $K + 1$, $K + 2$, $K + 3$, etc., with $\Delta I = 1$ and can have strong intraband stretched $M1$ transitions, provided there is a difference in the g factors associated with angular momentum parallel and perpendicular to the symmetry axis. These bands may or may not be mixed by Coriolis mixing. The calculated oblate states[3] are really band heads which indeed may be connected by noncollective $E2$ or $E1$ transitions as a rule. The calculations for very high-spin states also ignore pairing or other residual interactions. Realistically we should expect that residual nucleon-nucleon interactions should cause some configuration mixing among states of a given spin near the yrast limit. The mixing of states and the consideration of rotational motion, perpendicular to the oblate symmetry axis, can contribute to the smoothing of the yrast limit and the elimination of traps, especially as the oblate deformation becomes smaller. From Eq. (4-126) of Ref. 7, we can infer that for high spins and loss of pairing the rigid-body moments of inertia $\mathscr{I}_\parallel$ and $\mathscr{I}_\perp$ of a spheroid should be not too different in order for rotational bands to be parallel to the yrast envelope of band heads. Thus, small oblate deforma-

tions would seem favorable for $M1$ cascades and elimination of traps. Shrinkage of deformation with spin is a common feature of theoretical calculations. For this oblate region, one would expect typical $M1$ transitions with

$$E_\gamma = (\hbar^2/\mathscr{I}_{\text{rig}})I,$$

because

$$E_\gamma = (\hbar^2/2\mathscr{I}_{\text{rig}})\{(I(I+1) - K^2) - [I(I-1) - K^2]\}$$

and if $2\mathscr{I}_{\text{rig}}/\hbar^2 \approx 160$ MeV^{-1}, then $E_\gamma \lesssim 600$ keV for $I \approx 50$. (Such spin values are somewhat higher than would have been reached in the experiments of Ref. 9, but there can be sizable shell fluctuations away from $\mathscr{I}_{\text{rig}}$.) But can such $M1$ transitions compete with $E2$ transitions? In the calculations of Anderson *et al.*[3] for ^{158}Yb between spins 40 and 50, the yrast level energies increase about 5 MeV or 500 keV for each unit charge in spin. This number is very comparable to the above rotational energy spacings for the $\Delta I = 1$, $M1$ transitions. Thus, even without K mixing, the yrast cascade could consist largely of an alternating $M1$, $\Delta I = -1$, $\Delta K = 0$ transition within a rotational band and $E2$, $\Delta I = -2$, $\Delta K = -2$ transition between bands (to lower K). Competition of $M1$ with $E2$ is favored for oblate over prolate by a K^2 dependence of $B(M1)$. These hypotheses may be amenable to testing through the sign of the $M1$-$E2$ mixing amplitudes, which in Ref. 9 is stated to be negative. Such would imply $(g_\parallel - g_\perp)/Q_0 < 0$. Theoretical cranking calculations would be needed to estimate the g factors microscopically.

In summary, we have pointed out that nuclei in the oblate-shape region at high spin can be expected to exhibit rotational motion which can yield strong intraband stretched $M1$ transitions where the deformation is small and yrast traps where the deformation is large. Thus, if the $L = 1$ soft ($E_\gamma \lesssim 0.5$ MeV) stretched γ transitions are confirmed to be $M1$ transitions, these recent experimental results[9] can be considered as experimental evidence for the existence of a small-deformation oblate region at high spin in the region $A = 160-180$.

Note added.—Since our paper was submitted, Westerberg *et al.* [Phys. Rev. Lett. 41, 96 (1978)] have found in the reaction ^{150}Nd(^{20}Ne, xn) that the gamma-ray continuum is essentially pure $M1$ radiation at 500 keV. This finding is certainly in line with our arguments.

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Isotope Shift of Eleven Cesium Isotopes Determined by Atomic-Beam Laser Spectroscopy

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Isotopes of $^{123-137}$Cs produced by spallation of lanthanum and separated in mass by the ISOLDE on-line facility have been transformed into an atomic beam which is illuminated with a tunable cw dye laser. From the sensitive detection of the optical resonance lines at 459 nm, the hyperfine structure of $^{123-132}$Cs, ^{137}Cs, and ^{130m}Cs has been determined. The interpretation of isotope shifts, in terms of variation of charge radii, is discussed.

A previous experiment[1] had shown that the hyperfine structure (hfs) and isotope shift (IS) of short-lived sodium isotopes produced by spallation could be studied on line by a new mehtod of Doppler-free optical spectroscopy associated with a mass spectrometer. Recent developments[2] have increased the precision to about 1 MHz and also the sensitivity, so as to reach the very neutron-rich $^{26-31}$Na produced by the CERN proton synchrotron.

The purpose of the present Letter is to describe an extension of the method to the determination of hfs and IS of mass-separated radioactive cesium isotopes that are available at the ISOLDE isotope separator on line with the CERN synchrocyclotron.[3] The same setup—with further modifications that are described elsewhere[4]—has been used to discover the D_2 atomic resonance line of the element francium.

In essence, the experiment[1] rests upon the detection of optical transitions that occur when a tunable-laser beam interacts with a perpendicular collimated beam of the atoms to be studied. If the laser is tuned to the frequency of one of the D lines, optical pumping will change the population distribution between the magnetic substates $m_J = \pm \frac{1}{2}$ of the ground state of the atoms. This change is detected by means of a magnetic filter consisting of a six-pole magnet which focuses the atoms with $m_J = +\frac{1}{2}$ and defocuses the atoms with $m_J = -\frac{1}{2}$.

The experimental setup is summarized in Fig. 1. The 60-keV Cs^+ ions from ISOLDE first have to be converted into the thermal atoms of an atomic beam. For that purpose they are implanted at a grazing incidence (2°) in the inner surface of a tantalum tubular target coated with yttrium. Since this is known to be a low-work-function material, upon heating at about 900°C, the implanted cesium should reevaporate largely in the form of neutral atoms. In order to enhance the directivity of the atomic beam, the tubular target is an assembly of three tubes 40 mm long and 1 mm in diameter. Tests with stable $^{133}Cs^+$ indicated that the desorption time was 150 msec (half-maximum).