LOW-ENERGY NUCLEAR DYNAMICS

Structure Near Magic Numbers Highlighted

W. Von Oertzen from the Hahn-Meitner Institute, Berlin, introduces highlights in the field of low-energy nuclear multiparticle dynamics which were reported at the *15th EPS Nuclear Physics Divisional Conference.*

Fission studies of cold and hot nuclei continue to be a rich field, where the specific properties of the nuclear multiparticle system need to be considered. This statement, which is also valid for the field of low-energy (cold) fusion, has important consequences for the synthesis of the heaviest elements that is being pursued at the Flerov Laboratory for Nuclear Reactions (FLNR), Dubna, and at the Gesellschaft für Schwerionenforschung (GSI), Darmstadt. Moreover, γ-ray spectroscopy with large detector arrays (EUROGAM and GASP in Europe and GAMMA-sphere in the USA) is set to have an exciting future in the next few years.

Understanding the nuclear multi-particle system at low temperature is a field which is very active in Europe, including Russia. Major scientific challenges will remain for the coming decades and the richness can certainly stand up to that of other fields. The items accompanying this introduction aim to bring some of the fundamental issues in the field to a broader audience. Most were taken up at the 15th *EPS Nuclear Physics Divisional Conference on Low-Energy Nuclear Dynamics* (LEND-95) where the main topics were: i) the physics of exotic nuclei and reports on secondary beam experiments; ii) nuclear fission; iii) deformed shells and nuclear spectroscopy; iv) fusion reactions and the production of heavy elements. There were particular highlights in nuclear structures connected to "magic" numbers namely, the properties of ^{10}He [below], the discovery of element number 110 [page 101], and new symmetries in superdeformed nuclei [below] as well as a discussion of ^{100}Sn which has been reported upon recently in *Europhysics News* **25** (1994) 48].

^{10}He

A Milestone for Exotic Nuclei

^{10}He is not doubly magic but shows several unusual structural properties which are consistent with extrapolations from other exotic (neutron-rich) nuclei. The doubly magic nucleus would be the hypothetical ^{12}He which is certainly also unbound.

It has been known more than 10 years that the ^{10}He isotope — a potentially double magic nucleus (with atomic number $Z = 2$ and neutron number $N = 8$) is unstable (as are ^{9}He and ^{7}He). Its ground-state quantum numbers are expected to be 0^+. In the usual case this would lead to a very large spectral line-width in the emission of two neutrons (several MeV). A. Korschennikov [*Nucl. Phys. A* **559** (1993) 208] was able to predict that ^{10}He should have a very narow width ($\approx$ 300 KeV) if the sequential decay mode *via* ^{9}He + 1 neutron is closed, and only the "democratic" direct three-body decay is possible. The ground-state resonance was shown to exist in an experiment by A. Korschnnikov *et al.* [*Phys. Lett. B* **326** (1994) 31] by measuring the total mass of 2n + ^{8}He from a fragmentation reaction of ^{11}Li on ^{12}C at RIKEN in Japan. The properties of ^{10}He have since been determined precisely at the Hahn-Meitner Institute using the unusual ^{10}Be(^{14}C, ^{14}O) ^{10}He reaction.

This double-charge exchange reaction involving a radioactive ^{14}C beam (half-life $\tau_{1/2}$ = 5736 a) and radioactive target ($\tau_{1/2}$ = 1.6 x 10^6 s) was measured with the Q3D magnetic spectrometer at a ^{14}C energy of 334 MeV [Ostrovski *et al., Phys. Lett. B* **338** (1994) 13] to give precise positions and widths of the 0^+ ground state and of two groups of states belonging to excited states of ^{10}He. The width of the 0^+ is in fact 300 KeV ($\pm$ 200KeV) and the binding energy is determined to be 30 KeV below the n + ^{9}He threshold. Hence, there still is a small branch of sequential decay owing to the width of the ground states of ^{10}He and ^{9}He. The spectrum (after background subtraction) is shown in the figure. One sees a broad state at 3.24 MeV (or perhaps two states), which is most likely connected to the quantum numbers 2^+, and a narrow state at 6.80 MeV. This type of spectrum is quite different from that for the ^{14}C nucleus (also $N = 8$), for example, where a gap of 6 MeV is observed. It can be explained by assuming that the shell gap between $2s_{1/2}$ and $p_{1/2}$ has disappeared. The position of the $2s_{1/2}$ shell is known to decrease with increasing neutron number in light nuclei, while the difference between the $d_{5/2}$ and $p_{1/2}$ configurations defining the position of a 3^- state — attributed to the 6.8 MeV state — are known not to vary with neutron excess.

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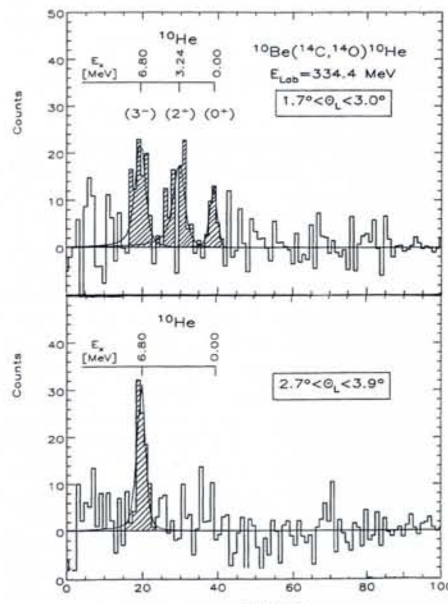


^{14}O spectra for the ^{10}Be(^{14}C,^{14}O)^{10}He reaction in angular ranges of 1.7-3.0° for the $I = 0(0^+)$ transition (upper panel) and of 2.7-3.9° for the $I = 3(3^-)$ transition (lower panel).

SUPERDEFORMED NUCLEI

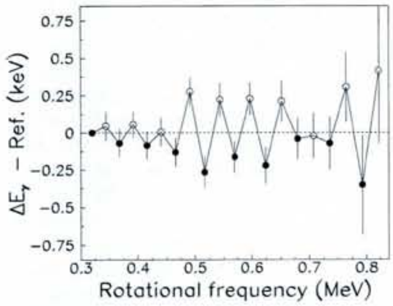
Identical Bands and Evidence for a C_4 Symmetry

Modern γ-ray spectrometers are revealing evidence for superdeformed states with a four-fold symmetry about the rotation axis.

The identification of rotational bands in atomic nuclei about 40 years ago led to the conclusion that nuclei may possess a deformed shape. In most cases, rotational bands consist of sequences of levels with the same parity that are connected by enhanced quadrupole (E2) γ-transitions. The levels are designated by two quantum numbers, namely parity π and signature α. The signature quantum number is associated with the invariance with respect to 180° rotation around an axis perpendicular to the symmetry axis of the intrinsic Hamiltonian. It takes the values of $\alpha = I(\mathrm{mod}\,2)$, where I is the level angular momentum (spin). Therefore, bands in even-even or odd-odd nuclei have α = 0 or 1, while those in odd-mass nuclei have α = +0.5 or −0.5.

Superdeformed (SD) rotational bands at high angular momentum occur in nuclei where there is a second minimum in the potential energy surface at large deformation. The bands studied to date lie in four regions of the chart of nuclides at mass numbers A = 80, 130, 150, and 190 and are associated with nuclei having a deformation corresponding to a prolate ellipsoid with an approximately 2:1 axis ratio. Perhaps the most unexpected discovery was the observation that SD nuclei differing by one mass unit may possess almost identical γ-ray sequences [Byrski T. *et al., Phys. Rev. Lett.* **64** (1990) 1650]. The very close similarity of the γ-ray transition energies implied equality (to within a few parts per thousand) of the moments of inertia of the bands. This was very remarkable, as the observed difference was much smaller than the expected variation of about 1% in the rigid body moment of inertia simply due to the mass difference.

Energy differences ΔE_γ between two consecutive γ-ray transitions of the SD band in ^{149}Gd as a function of rotational frequency ($\hbar\Omega = E_\gamma/2$) after subtraction of a smooth reference given by $\Delta E^{ref}_\gamma(I) = [\Delta E_\gamma(I+2)+2\Delta E_\gamma(I)+\Delta E_\gamma(I-2)]/4$. States separated by $\Delta I = 4$ have the same symbols.



With the advent of a new generation of γ-ray spectrometers it is now possible to perform detailed spectroscopic studies of SD nuclei. Using the EUROGAM II array located at Strasbourg's Vivitron accelerator, many weakly populated excited SD bands have been discovered in the various mass regions mentioned above. It turns out that the transition energies of a number of bands obey rather closely the relationship:

$$E^A_\gamma(I) = E^B_\gamma(I') + k[E^B_\gamma(I') - E^B_\gamma(I'-2)]$$

with $k = 0$, 1/2, 1/4, or 3/4. Here $E^A_\gamma(I)$ denotes the energy of γ-ray de-exiting a level with spin I in a given SD band of nucleus with mass number A whereas $E^B_\gamma(I')$ represents the energy of a γ-ray emitted by a level with spin I' in a given SD band of nucleus B. It should be emphasized that the above relation has been verified over a wide range of angular momenta (30-60 $\hbar$) and that nuclei A and B may differ by up to four mass units. The observation of these "identical" bands requires not only that the moments of inertia be identical for the bands concerned but also that the phasing of the γ-ray energies be quantized, *i.e.*, k tends to be quantized in integral multiples of 1/4. The challenging issue posed by these bands, namely what is the origin of the unexpected stability of the moment of inertia, remains the primary question. A satisfactory solution could potentially lead to new insights into the structure of nuclei, to a better understanding of effective interactions, or even point to the exciting possibility that a hitherto unnoticed symmetry exists in atomic nuclei.

In the superdeformed regime, spin sequences with $\Delta I = 2$ form the rotational bands. This implies rotational invariance (C_2 symmetry) and as mentioned before, the signature is a good quantum number. With the high sensitivity and efficiency of the EUROGAM array, there is now experimental evidence for the presence of a higher symmetry in the SD rotational spectra. The analysis of four-fold and five-fold coincidence events produces extremely clean γ-ray spectra which require little background subtraction. This is essential for a very precise determination of γ-ray energies (typically 0.1 keV for a 1 MeV transition). The energy difference $\Delta E_\gamma(I) = E_\gamma(I) - E_\gamma(I-2)$ between two consecutive transitions in some SD bands (^{149}Gd and ^{132}Ce, for example) exhibit an anomalous staggering. The amplitude of the oscillations is weak but definitely outside the experimental error bars, so that the staggering effect certainly originates from a perturbation of the SD energy levels. The effect of the perturbation on $\Delta E_\gamma(I)$ can be experimentally determined by comparing the $\Delta E_\gamma(I)$ values with a smooth reference. As shown in figure for the case of ^{149}Gd, the absolute value of the relative energy differences corresponds on average to approximately 230 eV in the frequency region between about 0.5 and 0.7 MeV, with alternating signs. This pattern can be produced by a similar alternating effect in the γ-ray transition energies, the E_γ values being alternately shifted up and down by about 115 eV. The SD energy levels are consequently separated into two sequences with the spin values I, $I+4$, $I+8$, ... and $I+2$, $I+6$, $I+10$, ..., with the levels being, for example, alternately pushed up and down by about 58 eV relative to their unperturbed position. Considering the fact that these SD states are at an excitation energy of about 25 MeV above the ground state, the observed shifts correspond to a 10^{-6} perturbation on the energy levels.

The existence of a $\Delta I = 4$ staggering in some superdeformed bands is now well established but its origin is not yet understood. The phenomenon has been interpreted as a manifestation of a perturbation which is invariant under a rotation of 90° about the rotation axis (C_4 symmetry). The observed quantum effect could be analogous to a C_4 bifurcation in non-linear dynamics. Detailed theoretical calculation are eagerly awaited. It is, however, clear that the systematics of which bands do or do not show the effect should become available soon from the very high statistics data on weaker, excited superdeformed bands generated by the new arrays such as the upgraded EUROGAM II detector.

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LEND-95 (*15th Nuclear Physics Divisional Conference*)

Low-Energy Nuclear Dynamics

The *15th Nuclear Physics Divisional Conference* of the EPS was held in St. Petersburg, Russia, on 18-22 April 1995. This was the first time that the Divisional Conference has taken place in Russia. The programme for the 147 participants from 19 countries extended over 4 days with 70 oral contributions (12 as invited lectures). A full day was devoted to special lectures, a poster session and an excursion to Puschkin. Plenary sessions in the morning with invited lectures were followed by two parallel sessions in the afternoon. Oral presentations were selected from over 150 abstracts submitted to the organizing committee; the remaining contributions were made in a poster session. Many young people, including postdocs and students participated and were given the opportunity to make an oral presentation.

The conference was organized jointly by the Flerov Laboratory for Nuclear Reactions at the Joint Institute for Nuclear Research, Dubna, and the Hahn-Meitner Institute (HMI), Berlin. It was held in the Educational Centre, just inside the city limits of St. Petersburg, where housing, meals and conference halls were available for all participants. The city centre was close by so one could visit the old capital of the Russian empire and enjoy the city's rich cultural assets. The local organization was in the hands of many secretaries from the JINR, and in particular under the careful eye of Rumania Kapakchiev who was the acting scientific secretary.

The G.N. Flerov Prize of the Joint Institute of Nuclear Research was awarded on April 18, in the morning session, to H.G. Bohlen, W. Von Oertzen, and A.A. Oglobin for work connected with studies on the structure of exotic isotopes of light nuclei such as $^{8-10}$He, $^{10-11}$Li and $^{12-14}$Be which have been pursued within a German-Russian collaboration (at HMI) as well as within a Russian-Japanese collaboration (at RIKEN in Japan; see p. 103).

The perspectives for the physics of nuclear collisions at the highest energies (beyond the LEND-95 energy range) were discussed by H. Specht in a special lecture and a round-table discussion on the Saturday showed that plans for future facilities delivering exotic beams were abundant. The richness of west European laboratories was the more obvious in these plans, while many Russian laboratories were happy if they succeeded in paying salaries. Collaboration between west European institutions and Russian laboratories is urgently needed in order to help the Russians survive the difficult economic conditions which they will have to live with now and in the near future.

The consensus of discussions held during the conference was that fundamental issues in nuclear multiparticle systems at low temperature needed a well formulated forum for their presentation. *Nuclear Physics News International* which is published on behalf of NuPECC in association with the EPS Nuclear Physics Division should be used more intensively to bring them to a broader audience.

The conference was supported by the European Commission's DG-XII for science and the proceedings will be published by World Scientific. The EPS Division Board meeting during the conference accepted a proposal to hold the next Divisional conference in Italy in September 1997.