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GROUND STATE STUDIES AT ISOLDE

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ABSTRACT

A large number of nuclei far from the stability line have been studied in their ground and isomeric states at the ISOLDE on-line isotope separator at CERN. This report gives references to recent works, and describes future developments for a laser ion source, and further improvements of the techniques for determining nuclear masses, the spins, moments, and changes in nuclear charge radii. The odd-even staggering of the charge radii of the nuclei around $Z=82$ are briefly discussed.

1. INTRODUCTION

The ground state studies covered by this contribution concern the determination of the nuclear mass, the spin, the magnetic dipole and the electric quadrupole moments, and finally the change in charge radii. With the exception of masses the information is accessible by a measurement of the hyperfine structure (HFS) and isotope shift (IS) of optical transitions. These data are urgently needed to test nuclear models, to establish level schemes, or to extrapolate the properties of nuclear matter even further to the limits of nuclear stability against proton and neutron emission, i.e. to the drip lines. Also new phenomena might be discovered which are not expected from our knowledge of stable and long-lived nuclei.

Nuclear shape coexistence, which was extensively discussed during the symposium, might serve as an example to illustrate the importance of data from measurements of the mass, the HFS and IS. The most convincing signature of shape transitions or shape coexistence is the determination of the positions and depths of the minima in the energy-deformation curve. This information can indeed be obtained by a determination of the mass (depth), of the IS which yields the deviation from spherical shape ($\langle\beta^2\rangle$) when measured relative to a spherical nucleus, and of the isomer shift which is a measure of the difference in deformation for the co-existing states ($\delta\langle\beta^2\rangle$). Furthermore, the spectroscopic quadrupole moment indicates oblate or prolate shape and gives additional information on the location of the minima ($\langle\beta\rangle$). Finally, the determination of the nuclear spin and magnetic moment pins down the configuration and orbitals involved.

In fact, the first information on phase transitions and shape coexistence was obtained by optical spectroscopy: In 1949 Brix and Kopfermann [BRI49] found a

sudden jump of the IS's when going from $N=88$ to $N=90$ in the rare earth isotopes. This led to the discovery of the quadrupolar shape of nuclei. In 1972, our group found a strong discontinuity of the IS's of the neutron-deficient Hg isotopes [BON72] which was the first evidence for shape coexistence. Until recently, the sharpness of both shape transitions was theoretically not understood. Today we know that it is caused by the near neighbourhood of a magic ($Z=82$) or semimagic ($Z=64$) configuration which is now called reinforcement of magicity.

2. STATUS OF GROUND STATE STUDIES AT ISOLDE

Most data on ground state properties of nuclei far from stability have been obtained at the on-line mass separator ISOLDE at CERN, where the isotopes of over 60 elements are available with high yields (up to 10^{11} atoms per sec and mass number) and half lives down to 10^{-2} sec. [CER85]. Fig. 1 shows the chart of nuclei and indicates those regions where optical spectroscopy has been performed in long isotopic chains. Similar systematics of mass measurements have been restricted until now to the isotopes of the alkaline elements [AUD84].

Some of the results obtained at ISOLDE for ground and isomeric states are discussed in the contributions to this symposium by C. Ekstroem, H.T. Duong, and E. Roeckl. A description of the ISOLDE-2 (operating) and the ISOLDE-3 (under construction) facilities can be found in the contribution by B.W. Allardyce. Additional information and references are given in the proceedings of recent conferences on nuclei far from the stability line [OAK82, KAN84, LUE84, DAR84].

This contribution concentrates on a discussion of some on-line techniques for ground state studies which are now under development and will be applied at ISOLDE in the near future. The plans for a nuclear-orientation set up at ISOLDE are outlined in the contribution to this symposium by N. Stone.

3. MASS MEASUREMENTS

The Orsay group has demonstrated the power of on-line, direct mass measurements using a Mattauch-Herzog spectrometer [AUD84]. This program was terminated in 1983 because the masses of all accessible alkaline isotopes were measured. Several ISOLDE groups are now preparing the second generation of mass measurements in long isotopic chains.

USING THE ISOLDE-3 MASS SEPARATOR: The high resolution of ISOLDE 3 (design value = $3 \cdot 10^4$) enables direct mass measurements. Such measurements were proposed at the Workshop "On-line in 1984 and beyond" held at Zinal [ZIN84]. In these experiments, the transmission signals have to be split in order to obtain the necessary accuracy. However, the feasibility of this technique has already been demonstrated by the Chalk River group [SHA84].

Fig. 1: Chart of nuclei. The stable isotopes are represented by black squares. The known isotopes are indicated in addition to the magic proton and neutron numbers. The smooth lines enclose regions with a nuclear deformation $\beta \geq 0.2$. Those isotopes are marked by open bars where optical spectroscopy yielded information on nuclear ground state properties in long isotopic chains. This picture gives the status as of September 1985.

RF MASS SPECTROMETER: A very much improved version of Smith's RF spectrometer is under construction at Orsay [COC84]. First it will be used to measure the $p-\bar{p}$ mass difference at the antiproton storage ring LEAR at CERN, with an accuracy of the order of $\Delta M/M = 10^{-9}$. Later on it is planned to install the apparatus at ISOLDE for mass measurements of radioactive isotopes with an accuracy better than 10^{-6} .

A high resolution of about 10^6 is achieved by passing the ions through electrostatic deflectors into 2 cyclotron orbits ($r = 0.5\text{m}$) in a homogenous magnet, and analyzing the outcoming beam by electrostatic deflectors. In the magnetic field the RF field changes the beam radius by 5 mm for ions in resonance, allowing them to pass through a slit (Fig. 2). Since the transmission of the ISOLDE beam is measured as a function of the applied RF frequency, and the expected transmission in resonance is about 10^{-4} , this technique can be applied to the whole variety of available ISOLDE beams.

PENNING TRAP: A different approach to mass measurements was developed at Mainz. Thermal ions can be confined in a static homogenous magnetic field and a superimposed electrostatic quadrupole field. A measurement of the cyclotron frequency enables the measurement of the mass of the stored ion. A resolving power of 10^6 to 10^8 and accuracies of 10^{-7} to 10^{-8} have been achieved with this technique for light masses [GRA80, VAN85].

Fig. 2: RF mass spectrometer built at Orsay.

Fig. 3: Principle (right) and experimental set-up (left) for mass measurements in a Penning trap.

The experiment prepared for ISOLDE aims for a resolving power of 10^6 and an accuracy of better 10^{-6} which corresponds to an uncertainty less than 100 keV for an ion with mass number 100 [DAB84]. The set up is shown in Fig. 3. The ion trap for the measurement of the cyclotron frequency is placed in a superconducting magnet. The resonance is measured by a time-of-flight technique [GRA80]. In order to fill the trap with about 10 ions from the outside world, the ion beam of ISOLDE is stopped on a filament mounted inside an auxiliary ion trap. After heating the foil, the radioactive ions are surface ionized, stored, cooled and then ejected by a short pulse. The bunched ions can now be caught in the precision trap by retardation and by lowering for a short time the potential of its entrance electrode. These ions are then used to perform the resonance experiment, after which the process is repeated to refill the trap with a new sample. The time for each cycle is about 1 second. Clearly, the technique would greatly benefit from an ISOLDE beam bunched in the ion source (see below).

Both traps have been tested and perform almost as specified (ratio of incoming to ejected ion intensity about 10^{-4} for the bunching trap, resolution of the precision trap = $3 \cdot 10^5$ for $A = 28$). The transfer of the ions from the bunching trap to the precision trap is now under study.

4. LASER ION SOURCE

Resonance ionization spectroscopy (RIS) with pulsed tunable lasers offers new possibilities for constructing pulsed, highly selective ion sources with high efficiencies. Fig. 4 shows the principle of RIS and the planned set up. The efficiency of the ion source is determined mainly by the ratio of the repetition rate of the lasers to the frequency of collisions of the atoms with the walls of the ionization chamber [KLU85]. Hence, a pump laser with the highest available pulse rate has to be used. This can be realized by a copper vapor laser ($\nu_{\text{rep}} = 6 \text{ kHz}$, length of laser pulse = 20 ns , pulse power = 300 kW). It was shown in the case of Gd that the three-step photoionization can be saturated via an autoionizing state using a laser beam of 1 cm diameter [PEU 85]. The efficiency of the laser ion source is expected to be up to 40% [KLU85]. Apart from high efficiency the method has an inherent high selectivity against the ionization of other elements. This is due to the low atomic level density reached by allowed E1 transitions (1 state/eV) and the comparably small Doppler width (10^{-5} eV).

The magnet of an on-line mass separator will generally assure the selectivity in respect to different isotopes. Hence, the isobaric selectivity of laser ion sources is of primary interest, although isotopic selectivity might also be achieved by RIS using the HFS and IS, which differ from isotope to isotope.

Fig. 4: Right: Principle of resonance ionization spectroscopy. Three tunable pulsed Dye lasers are used to stepwise excite and ionize the atom. The effective cross-sections are indicated for the different transitions in cm^2 . Left: Layout of a laser ion source for on-line mass separators.

The time structure of the ion beam (every 150 μ s a pulse with a length of 15 ns) enables the improvement of many techniques such as the filling of ion traps, the injection into storage rings or accelerators, or, for example, the suppressing of the background of collinear laser spectroscopy with detection of fluorescence light. In the latter case an improvement by two orders of magnitude will be obtained with a 10^{-4} duty cycle.

5. OPTICAL SPECTROSCOPY

Several groups at ISOLDE are planning further improvements of their techniques. For each element the most appropriate experimental scheme has to be found. Today, collinear laser spectroscopy is the most general high-resolution and sensitive method for optical spectroscopy on radioactive beams delivered by on-line mass separators. Its sensitivity ranges from 10^4 - 10^6 atoms/s depending on the strength and multiplicity of the optical transitions.

Until now, the main goal of the measurements was systematic ground state studies in long isotopic chains. In the future, however, more experiments will aim for the investigation of a specific nucleus. According to Murphy's law, these nuclei are generally far away from the valley of stability or are produced with low yield. Hence a special version of the technique or an improvement of the scheme are required. Table 1 gives a survey of these attempts and summarizes at the same time the on-going programme of ground state studies by optical spectroscopy at ISOLDE.

6. ODD-EVEN STAGGERING

The IS's of nuclei far from stability turned out to be the most informative data obtained by optical spectroscopy. This is because the nuclear charge radius depends on collective as well as on single-particle effects. The integral IS's ($\delta\langle r^2 \rangle_{A,A'}$ with A' being a reference isotope) exhibit the gross behaviour of nuclear matter as a function of varying neutron number. These can be compared with predictions of macroscopic models like the Droplet Model [MEY83], which describes the overall trend quite well.

The differential IS's ($\delta\langle r^2 \rangle_{A,A+1}$ or $\delta\langle r^2 \rangle_{A,A+2}$) are measures of the radius change of the neighbouring nuclei and yield more clearly than the integral IS the effect of the addition of a neutron or a neutron pair. In this way, the increase or decrease of deformation is easily observable as a function of neutron number. A still more sensitive measure of the influence of an unpaired neutron on the charge radius is the odd-even staggering parameter γ introduced by H.H. Stroke [TOM64] and given by

$$\gamma^A = 2(\langle r^2 \rangle_{A-1} - \langle r^2 \rangle_{A+1}) / (\langle r^2 \rangle_{A+1} + \langle r^2 \rangle_{A-1})$$

TABLE 1: On-line techniques for Optical Spectroscopy at ISOLDE

BASIC TECHNIQUE	INCREASE OF SENSITIVITY BY	APPLICATION	STATUS	REF.*
COLLINEAR SPECTROSCOPY IN FAST ATOMIC AND IONIC BEAMS				
- Observation of optical fluorescence	-	rare earth, Rn, In	data taking	(M203) (P77)
- Observation of optical fluorescence, with frequency doubled CW dye laser	-	D ₂ line of Ra	first data taking Nov. 85	(IP-16)
- Observation of precession of optical polarization in a magnetic field	-	g _I of Ra isotopes	first data taking Dec. 85	(P76)
- Reionization by charge exchange after laser interaction	ion detection after charge exchange	Rn, Xe	tested	(M203)
- Resonant 3-photon ionization with pulsed laser (Cu-vapor pump laser)	ion detection after photo-ionization	rare earth	in preparation	(P78)
- Observation of fluorescence with pulsed ion beam	10 ⁻⁴ duty cycle of laser ion source	rare earth	in preparation	[KLU85]
- Two-step photo ionization with CW laser via Rydberg states	ion detection	In	tested	(P77)
- One-step photo ionization with CW laser via Rydberg states	ion detection	Fr, Cs	tested	(IP-17)
- Implantation of optically pumped beams in a crystal-observation of β asymmetry	asymmetry of β radiation	Li	first data taking Oct. 85	[BON84]
OPTICAL PUMPING IN RESONANCE CELLS				
- Polarization by spin exchange of optically pumped Rb observation of γ anisotropy	anisotropy of γ radiation	Rn	data taking	(P79)
RESONANCE IONIZATION SPECTROSCOPY IN THERMAL ATOMIC BEAMS				
- Resonant 3 photon ionization with pulsed laser, mass measurement of photo ions by time of flight	ion detection TOF	Au, Pt	first data taking Dec. 85	(IP-14)
- As above with pulsed thermal beam using laser	ion detection, TOF, duty cycle	Au	in preparation	[KLU84]

*) References in round parentheses give the CERN filing number of the proposal. Copies might be obtained by the ISOLDE Secretariat, EP Division, CERN.

Fig. 5: Odd-even staggering parameter of the isotopes around $N = 126$. The data on Rn, Fr, and Ra are obtained by the Mainz and Orsay groups and are preliminary.

$\gamma = 1$ indicates that the effect of adding an odd neutron is just half of the effect of adding a pair. Such a behaviour would be expected, e.g. by the Liquid Drop Model. The other extreme case ($\gamma = 0$) is obtained when the charge distribution of the nucleus with even N completely ignores the additional neutron. Generally, $\gamma < 1$ is obtained throughout the chart of nuclei. In some rare cases, $\gamma > 1$ is found. These exceptions can be associated with an irregularity of the IS of one of the 3 isotopes entering the calculation of γ . Fig. 5 shows the staggering parameter in the region around $N = 126$. With the exception of ^{199m}Hg , $\gamma < 1$ is found below $N = 126$ for all isotopes. In case of the $l = 13/2$ isomers of Hg, a smooth decrease of γ is found to about $\gamma = 0$ at $A = 185$. Many explanations have been tried to interpret the phenomenon: different shell filling in odd and even isotopes [TOM64], blocking of zero-point quadrupole vibration in the odd neutron isotope [REE71], different polarization of the core by the paired and unpaired neutron [TAL84], and the influence of the type of coupling in the particle-plus-rotor picture [STR79]. None of these interpretations gives a quantitative description of the staggering effect except for Ca and Pb [TAL84]. Nevertheless, $\gamma < 1$ is an empirical fact found for almost all isotopes. However, at $N = 133$ to 137 , $\gamma > 1$ is observed. This anomaly cannot be attributed to an irregularity of the IS of one individual isotope, but it is found for 7 nuclei of Rn, Fr, and Ra. Above $N = 137$, the usual $\gamma < 1$ is observed again.

A similar anomaly was found in the masses of the Ra isotopes in this region [LEA82], which stimulated the search for octupole deformation in these nuclei. Again, the results of mass measurements and of optical spectroscopy might be useful to fix the energy-deformation curve (now β_3 in addition). However, calculations are still missing. Perhaps the extended IBA model is the most appropriate way to calculate the effect of the additional or missing fermion on the charge radii of the paired neighbouring nuclei. The regular behaviour of the staggering parameter of the Hg isomers with their pure $i_{13/2}$ states eventually offers the key for solving the puzzle.

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