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NUCLEAR GROUND STATE PROPERTIES FROM OPTICAL INVESTIGATIONS

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Abstract

Recent progress in on-line techniques of laser spectroscopy applied to nuclei far off stability is reviewed. The results concern nuclear spins, moments and charge radii, determined from hyperfine structure and isotope shift of atomic transitions. Examples of large core polarizations in the Cd-In-Sn region, derived from isotope shifts, and the octupole deformation in the Ra region, derived from ground state spins and magnetic moments, are discussed.

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1. Introduction

My task is to review the experimental progress in the field of optical spectroscopy of unstable nuclei since the Groningen meeting, and to interpret some of the results in order to extract new information on nuclear structure off stability. The number of groups participating in the field as well as of methods they apply is increasing at a fast footing. Table 1 lists the elements for which results far off stability have been reported together with the methods and groups involved. The more recent results, marked by an asterisk, will be discussed in this paper.

2. Methodological Progress

The majority of results since 1980 has been obtained by the nowadays standard collinear technique /1/ (see Fig. 1). An on-line mass-separated beam of the isotope in question is merged collinearly into a laser beam and the fluorescence photons following resonant laser excitation are monitored downstream by a photomultiplier, viewing an extended interaction region by a suitable imaging system. In (most) cases, where resonance lines from the ionic ground state cannot be met by standard cw lasers, the beam is neutralized before, by passing a charge exchange cell containing alkali vapour. This technique is applicable to practically any element, even noble ones; because in the latter cases charge exchange favours the population of excited metastable states rather than of the tightly bound ground state. Resonance lines, starting from metastable states, lie in the accessible, visible range, noticeably. The limit of sensitivity is reached at beam intensities of 10^4 to 10^6 ions/s, depending on the complexity of the spectrum, and in particular on the multiplicity of fine structure and hfs levels populated.

Table 1

Present status of optical spectroscopy far off stability.

*) discussed in this review, **) discussed in ref. /6/ at this conference,
 ***) discussed in ref. /9/ at this conference.

Elements investigated	Methods applied	Groups
Sr	Collinear laser spectroscopy with photon tagging*)	Daresbury
In*), Sn*)	Collinear laser spectroscopy*)	GSI - Mainz
Ba, Ra*)	Collinear laser spectroscopy with spin-precession*)	ISOLDE - Lyon - Mainz - Orsay
Cd*), Au, Hg	Laser spectroscopy in resonance cells	ISOLDE - Mainz
In, Ba, Dy, Eu, Gd, Er, Yb, Hg, Tl, Rn**), Fr, Ra*)	Collinear laser spectroscopy*)	ISOLDE - Mainz
Li*)	Collinear RADOP laser spectroscopy*)	ISOLDE - Mainz
Kr	Collinear double charge exchange spectroscopy*)	ISOLDE - Mainz
Au***)	Resonance ionization mass spectroscopy***)	ISOLDE - Mainz
Na, K, Rb, Cs, Fr*)	Laser-induced optical pumping	ISOLDE - Orsay
Sn*), Ba, Pb	Atomic beam fluorescence (off-line)	Karlsruhe
Eu	Collinear laser spectroscopy	Leningrad - Marburg
Eu, Tm	Resonance ionization mass spectroscopy	Leningrad - Troitzk
Tl, (Pb)	Collinear laser spectroscopy	Oak Ridge

Fig.1. Standard set-up for collinear laser spectroscopy /1/.

The ISOLDE facility at CERN is offering beam intensities higher than these limits for many elements and for an isotopic range of typically 20 mass numbers for heavy elements. Thus this standard technique is perfectly suited for systematic survey measurements. So far they concentrated mainly on the rare-earth region from Ba to

Yb /1-4/ and on very heavy elements in the Ra region /5,6/. Fig. 2 gives a more recent example of scanning hfs transitions in ^{122}In /7/, showing strong signals of $I = 5$ and $I = 8$ isomers in addition to the $I = 1$ ground state.

Fig.2.
Scan of hfs of ^{122}In in the transition $5p\ 2P_{3/2} \rightarrow 6s\ 2S_{1/2}$, obtained by standard collinear laser spectroscopy /7/. The hfs components of the nuclear ground state [$I = 1$] and the two isomers are marked by their spin values.

In the case of refractory elements as well as at the very ends of the yield curve of the usual spallation reaction, however, one cannot hope for sufficient separation rates by using the present ISOLDE techniques. In these difficult regions of rates below $10^6/\text{s}$ fusion and transfer reactions by heavy ions compete. Most of the methodological development work concentrates, therefore, on the increase in sensitivity of the collinear technique. A very sensitive, completely different experimental ansatz is on-line multiphoton resonance ionization spectroscopy, performed by the Leningrad/Troitsk collaboration on Tm and Eu /8/. This method was also applied to a refractory daughter element (Au) of a primary separated ISOLDE beam (Hg) and will be presented at this conference /9/. I will confine myself in the following to the discussion of variants of the collinear technique.

a) Photon tagging: In the standard scheme the sensitivity is limited primarily by background from laser stray light, radioactivity, PM noise, etc. which add up to typically $10000/\text{s}$. The Daresbury group recently succeeded in suppressing this background by tagging true fluorescence photons with the coincidence signal of the incoming beam particle which was detected downstream by a channeltron (see Fig. 3a and b). This way they were able to measure the resonance transition of light Sr isotopes at a beam level as low as 100 ions/s /10/.

This elegant method requires, of course, a very clean beam. Contaminations by other isotopes or isobars will bury the signal in the background from accidental coincidences, especially, since the coincidence window has to be as wide as 100 ns. This is the time-of-flight of the particle through the observation region of the PM. In the Daresbury experiment this difficulty was surmounted by carefully conditioning the surface ionization source. The requirement may also be met by a mass-separator of high resolution, capable of separating isobars. Such an instrument will be installed e.g. at the ISOLDE-III facility. Another possibility of getting clean beams will be offered by laser ion sources in the near future. A prototype was

recently realized by the Troitzk group reaching 10 % total ionization efficiency for Sr /11/. Note that these laser ion sources are pulsed allowing triple coincidence between the times of ion birth (t_0) of fluorescence detection (t_1) and of ion stopping (t_2). The foregoing discussion evidences the great impact which the development of new, sophisticated ion source-separator combinations will have on the progress of on-line optical spectroscopy in the future.

Fig.3. a) Set-up for photon tagging experiment.
b) Ion photon coincidence signal when scanning the resonance transition of ^{80}Sr /10/.

b) Collinear double charge exchange spectroscopy: The two following methods aim to avoid the detection of fluorescence photons at all not only because it is so sensitive to background, but also for its low overall efficiency. The double charge exchange idea is due to R. Neugart and has been realized by him and collaborators at ISOLDE for the case of Kr /12/. The principle is shown in Fig. 4a to 4c. The Kr^+ beam is neutralized in a first charge exchange with an electro-positive gas, Cs or Na, into the metastable $5s[3/2]_2$ state bound by only 4 eV. This state is depopulated by laser excitation to the $5p[3/2]_2$ state the decay of which has a strong branching to the atomic ground state bound by 14 eV. In order to monitor this optical pumping process by non-optical means, a second charge exchange with an electro-negative gas (e.g. O_2 , SF_6) follows downstream. It reionizes the Kr beam with a large cross-section from the loosely bound metastable state, but hardly from the tightly bound ground state. The reionized fraction is then deflected electro-statically into an ion detector which shows a flop-out signal when the laser hits the resonance (Fig. 4c). As seen from the numbers given, this flop-out signal is a thousand times stronger than the simultaneously recorded fluorescence signal.

A similar idea was realized independently by Silverans in a reversed sense /13/. In his scheme Sr^+ ions were pumped from the $5s$ ground state via excitation to $6p$ and subsequent branching into the metastable $4d$ state. The pumping effect was monitored by the difference in neutralization probability of the ionic states in a subsequent charge exchange cell.

c) Collinear laser RADOP: This experiment applies the ideas of the old RADOP scheme (Radioactive Detection of Optical Pumping) /14/ to the new collinear technique (Fig. 5). A circularly polarized laser polarizes a fast beam of alkali atoms in flight by optical pumping. The beam is stopped in a suitable matrix exposed to an external field B. If relaxation times in this matrix are longer or at least comparable to the nuclear lifetime, the nuclear polarization P_I can

Fig.4. a) Set-up for double charge exchange spectroscopy.

b) Level scheme of Kr with charge exchange and pumping processes indicated.

c) Double charge exchange and fluorescence spectroscopy signal from a primary Kr^+ beam of $5 \cdot 10^{11}$ ions/s /12/.

Fig.5. Set-up for collinear RADOP laser spectroscopy /15/.

be detected by a pair of β -telescopes at 0° and 180° with respect to the axis of nuclear orientation. These detectors measure the decay asymmetry term $a = \pm P_I A$. The experiment was first conducted by J. Bonn and collaborators at our on-line facility at the Mainz-Triga reactor for the case of some short-lived neutron-rich Rb isotopes /15/. The method was then exported to the ISOLDE and applied to short-lived Li isotopes /16/. Fig. 6 shows the asymmetry signals of ^9Li ($T_{1/2} = 178$ ms) and ^{11}Li ($T_{1/2} = 8$ ms) when scanning over the hfs of the resonance line. Only the ground state splitting is resolved. The ^{11}Li current was 600/s. An asymmetry of only 0.4 % for ^9Li and 2.4 % for ^{11}Li was observed in several matrices, Au, LiF, pyrolytic graphit, although $P_I \approx 30$ % is reached in the beam before entering the transverse holding field. The asymmetry parameter of ^9Li is calculated to be 9 %. Some other effects, diminishing the asymmetry are discussed in /16/. Part of them may be overcome in another field geometry and by simultaneous pumping with two lasers on both hfs transitions. The results, $I = 3/2$ and $\mu_I = 3.73(12)$ n.m. (preliminary), close to the Schmidt value 3.79 characterize ^{11}Li as a spherical semi-magic nucleus in contrast to its isotone ^{11}Be whose $1/2^+$ ground state can only be explained by assuming a deformed shape.

Fig.6. β -asymmetry signal from ^9Li and ^{11}Li when scanning the hfs of the D_1 -resonance line (bottom) and corresponding level schemes (top) /16/.

d) g_I measurement by spin rotation: This variant of collinear laser spectroscopy makes also use of spin polarization of the beam induced by optical pumping in the section I, following charge exchange (see Fig. 7a). The pumping zone is then followed by a region of length l of a perpendicular magnetic field B_0 in which the oriented spins precess by an angle $\vartheta = \gamma B_0 l / v$, where v is the velocity of the beam. Note that B_0 is strong enough to decouple the atoms during the precession phase from interaction with the laser by Zeeman splitting. The precession angle can be measured downstream by the modulation of fluorescence, because excitation by a polarized laser beam (see Fig. 7b) strongly depends on the angle of orientation of the ground state spins via relative intensity rules of Zeeman components. If the atom in question has a diamagnetic ground state, as in the case of alkaline earths, it is the nuclear spin which precesses and the measurement of ϑ determines directly g_I .

Fig.7.

- a) Set-up for observation of spin precession in collinear laser spectroscopy /17/;
 I = pumping zone,
 II = precession zone,
 III = detection zone.

- b) Fluorescence intensity of ^{137}Ba observed in zone III as a function of field H_0 in zone II /17/.

The method described was developed by Vialle and collaborators at Orsay (now at Lyon) /17/ for the examples of Na and Ba. It is applied now at ISOLDE in collaboration with the Mainz group in order to determine for the first time directly a g_I -factor of Ra isotopes. Fig. 7b shows a test and calibration signal from stable ^{137}Ba , which is a homologue of Ra. During the week this conference was running, first (preliminary) results $g_I(^{213}\text{Ra}) = 1.226(4)$ and $g_I(^{225}\text{Ra}) = (-) 1.468(4)$ were obtained /18/. The measurement also serves to calibrate hyperfine fields in Ra spectra from measured A-factors /5/ and to compare them to Hartree Fock calculations for this highly relativistic case. The hyperfine field of the 7s ionic ground state has been determined in this way to be 1226 T in comparison to theoretical ones: 1293 T /19/, 1304 T /20/, 1266 T /21/. The simple semi-empirical Goudsmit-Fermi-Segre formula yields 1285 T. The theoretical values cluster about 5 % above the experimental one.

III. Isotope shift in the Cd-In-Sn region and the question of large core polarization

Out of the many contributions which optical investigations made to nuclear structure off stability, I will pick out here two interesting, recent questions, namely the interpretation of nuclear charge radii in the neutron shell $50 \leq N \leq 82$ close to the proton shell closure and the occurrence of octupole shaped nuclei in the Ra region, evidenced by ground state spins and magnetic moments (see Section IV).

Fig. 8 shows the course of $\delta\langle r^2 \rangle$ derived from the IS of Cd /22/, In /7/ and Sn /23, 24/, which cover most of the neutron shell $50 \leq N \leq 82$. It is very regular and similar in all three elements. Usually one decomposes $\delta\langle r^2 \rangle$ into a volume and a deformation part:

$$\delta\langle r^2 \rangle = \delta\langle r^2 \rangle_{\text{vol}} + \frac{5}{4\pi} \langle r^2 \rangle \delta\langle \beta^2 \rangle. \quad (1)$$

Fig.8.
 $\delta \langle r^2 \rangle$ for the isotopic chains of

- a) Cd /22/ ,
- b) In /7/ and
- c) Sn /23,24/.

The solid line represents the spherical droplet model, the broken one the result from a parabolic fit to the data.

The volume part is varying with $A^{1/3}$, i.e. practically linear in the limited range considered. It seems to be well described by Myers droplet model /25/. The deformation part depends on the shell structure. It can exhibit sharp shape transitions, but also a smooth N-dependence like observed in the Cd-Sn region in the neighbourhood of the $Z = 50$ proton shell closure. The $\delta\langle r^2 \rangle$ curve has obviously a parabolic shape with a tangent to the droplet line in the middle of the neutron shell around $N = 66$. The curvature and hence $\langle \beta^2 \rangle$ increase with the distance from the proton shell closure.

Talmi has recently applied a core polarization model to the similar case of the IS of Ca /26/. He shows that in a single (v_j^n) shell model configuration the polarization contribution is proportional to the number of particles (n) times the number of holes $(2j+1-n)$. The odd-even staggering of $\langle r^2 \rangle$ is contained in the model as a constant offset of the odd N isotopes. For semi-magic nuclei the model can be generalized also to a major N-shell; it then predicts $\delta\langle r^2 \rangle$ to be a general quadratic form in the particle number plus the odd-even staggering term. Looking to the data and from theoretical arguments it obviously makes sense to retain the symmetry in particles and holes also with respect to a major shell. This leads to a parametrization of (1) in the form /22/:

$$\delta\langle r^2 \rangle^{50,N} = a(N - 50) + b(N - 50)(82 - N) + (1/2)d(1 - (-1)^N). \quad (2)$$

The first term in (2) is now identified with the volume, the second with the deformation contribution.

Fitting (2) to the data, one yields $a(\text{Cd}) = 0.047 \text{ fm}^2$, $a(\text{In}) = 0.060 \text{ fm}^2$, $a(\text{Sn}) = 0.065 \text{ fm}^2$; the droplet model predicts $a = 0.055 \text{ fm}^2$ in fair agreement with the average of the data. The deformation part vanishes at the shell closures by definition of the model (2) and peaks in the center at $N = 66$. By fitting the parameter b one obtains the center deformations $\langle \beta^2 \rangle^{N=66} = 0.078, 0.048, 0.032$ for Cd /22/, In /23/, Sn /24,25/.

Fig. 9 compares for the case of Cd $\langle \beta^2 \rangle_{\text{IS}}$ derived from $\delta\langle r^2 \rangle$ through equations (1), (2) with those obtained from quadrupole strengths through the closure relation:

$$\langle \beta^2 \rangle_{\text{BE2}} = \left(\frac{4}{3ZR_0^2} \right)^2 \sum_i B(E2, 0^+ \rightarrow 2^+_1). \quad (3)$$

Fig.9.
 $\langle \beta^2 \rangle$ of Cd ground states from $\delta\langle r^2 \rangle$ analyzed by equ. (2) (full dots) compared to those derived from $B(E2, 0^+ \rightarrow 2^+_1)$ values (open circles) /22/.

For harmonic vibrators as well as rigid rotators the sum is exhausted by its first term. This truncation was also used in the Cd case. From Fig. 9 one reads that the deformation parameter as derived from $\delta\langle r^2 \rangle$ reaches the astonishing large value of $\langle \beta^2 \rangle_{IS}^{1/2} = 0.28$ whereas $\langle \beta^2 \rangle_{BE2}^{1/2}$ is in the familiar range of 0.18 to 0.20. The same proportion is observed in In between $\langle \beta^2 \rangle_{IS}^{1/2}$ and $\langle \beta \rangle_{Q_s}$, where the latter is derived from Q_s values projected to Q_0 in the strong coupling limit $\Omega = I$ and the relation

$$\langle \beta \rangle = \sqrt{5\pi} Q_0 / (4Zr_0^2 A^{2/3}) \quad (4)$$

with $r_0 = 1.2$ fm (compare Fig. 10).

Fig.10.
 $\langle \beta^2 \rangle^{1/2}$ values from $\delta\langle r^2 \rangle$ analyzed by equ. (2) (dotted line) in comparison with $\langle \beta \rangle$ values derived from Q_s values (dashed line) /7/. The error bars on $\langle \beta^2 \rangle^{1/2}$ increase towards the wings of the curve due to systematic scaling errors.

In both cases the IS reveals a much stronger collective contribution to $\langle r^2 \rangle$ than expected from the simple model of vibrational or static quadrupole deformation. In the latter case one could argue that the contribution of zero point motion to Q_s and hence to $\langle \beta \rangle_{Q_s}$ cancels. This is not the case in $\langle \beta^2 \rangle_{IS}$ and also not in $\langle \beta^2 \rangle_{BE2}$. The truncation of (3) is certainly unjustified in case of anharmonic vibration. Strong anharmonicity of a soft mode is postulated in the Jahn-Teller model of nuclear deformation /27/. Moreover, the question is open to what extent multipoles other than quadrupole may contribute to the ground-state collectivity. But they hardly make up for the whole discrepancy.

IV. Spins and moments in the Ra region indicating nuclear octupole shapes

At the Groningen meeting the first measurements of spins and moments in a series of Ra isotopes were reported /5/. In the meantime these numbers have become cornerstones (besides results from nuclear spectroscopy) in the discussion on the existence of stable octupole deformation in this region. How can these single particle properties be so decisive for that particular collective phenomenon of nuclear structure?

Per definition the nuclear potential energy surface must be symmetric in the collective octupole coordinate β_3 , since change of sign is equivalent to a rotation of the nucleus by 180° . If the central barrier at $\beta_3 = 0$ is high enough, the collective wave function

localizes around the two potential minima at $\pm\beta_{3\min}$ and forms a symmetric (positive parity) and an antisymmetric (negative parity) state with respect to reflexion. These two states form an (almost) degenerate doublet of opposite parity which is the characteristic spectroscopic feature of asymmetric shapes, as is well known from molecular physics. The famous maser transition in NH_3 , for instance, is just this doublet transition. If the doublet splitting is very small as compared to other excitations, one can speak of a "stable" octupole deformation; because the time for which the collective wave function can be localized at one side of the barrier, say at $+\beta_{3\min}$, is given by the reciprocal of the transition frequency. This doublet structure is fairly well established in a number of cases in the Ra region (reviewed e.g. in ref. /28/). In an octupole potential single particle levels of opposite parity will get mixed, especially degenerated ones. Fig. 11a shows Nilsson levels for Ra as a function of the quadrupole deformation β_2 where the octupole deformation has been kept zero. One sees a number of level crossings of states with same spin but opposite parity. After switching on octupole deformation to $\beta_3 = 0.08$ (Fig. 11b), these crossings are removed by forming new single particle states, which now have a mixed intrinsic parity. In fact, these level crossings are the ones, which trigger the breakdown from quadrupole to octupole symmetry by residual octupole interaction with the core (reviewed e.g. in ref. /29/). In molecular or solid state physics one would call this spontaneous breakdown of shape symmetry a Jahn-Teller transition /27/.

For comparison with experiment it is important that the reshuffled level scheme shows another spin sequence as a function of neutron number than in the pure quadrupole core. For neutron numbers $133 \leq N \leq 141$ spins $1/2, 3/2, 3/2, 5/2, 5/2$ appear consecutively at the Fermi surface in the pure quadrupole case, whereas calculations including octupole reproduce the correct experimental sequence $5/2, 3/2, 1/2, 3/2, 5/2$. (β_2 increases in this range from 0.15 to 0.2).

Fig.11. Nilsson diagram of neutron levels in Ra as a function of β_2 ;
a) without octupole degree of freedom ($\beta_3 = 0$),
b) β_3 fixed to 0.08.

Moreover, the magnetic moment is very sensitive to the degree of intrinsic parity mixing in the hybridized single particle wave function. This is particularly evident, when states with opposite nucleon spin projection like $|n, n_z, \Lambda \uparrow\rangle$ and $|n+1, n_z+1, \Lambda-1 \uparrow\rangle$ mix, because the nucleon g-factor cancels in taking the sum. Table 2, taken from ref. /30/, shows in comparison with experiment magnetic moments calculated with and without octupole deformation. When in the octupole free case the theoretical ground state spin was not found to be the experimental one, the next neighbouring theoretical level, showing the correct spin parity assignment, was chosen for calculating μ_I . The Table definitely proves that only in the octupole case satisfactory agreement between theory and experiment can be achieved. Recently the Orsay group measured spins, moments and charge radii for Fr isotopes in the region in question /31/. The theoretical analysis of their data is still under way. The Mainz group measured corresponding Rn isotopes in the meantime /6/, which also await a theoretical analysis. All three elements, however, show the peculiarity of inverted odd-even staggering of the isotope shift in the critical region which is supposed to be characteristic for octupole deformation /32/ (compare also the discussion below).

Table 2
Spins and magnetic moments of some Ra-isotopes in comparison with theoretical calculations with and without octupole degree of freedom /30/.

Nucleus	I_{exp}^P	μ_{exp} (n.m.)	I_{th}^P	μ_{th} (n.m.)	β_3	Configuration
^{221}Ra	5/2	-0.18	5/2 ⁺	-0.13	0.1	[642]x[752]5/2
			5/2 ⁺	0.39	0	[633]5/2
^{223}Ra	3/2	0.27	3/2 ⁺	0.50	0.1	[642]3/2
			3/2 ⁺	0.03	0	[631]3/2
			3/2 ⁻	-0.06	0	[761]3/2
^{225}Ra	1/2 ⁺	-0.73	1/2 ⁺	-0.75	0.1	[640]1/2
			-	-	0	-
^{227}Ra	3/2 ⁺	-0.40	3/2 ⁺	-0.41	0.08	[631]3/2
			3/2 ⁺	-0.06	0	[631]3/2
^{229}Ra	5/2	0.50	5/2 ⁺	0.38	0.04	[633]5/2
			5/2 ⁺	0.61	0	[633]5/2
			5/2 ⁻	-0.29	0	[752]5/2

V. Summary

On-line laser spectroscopy is not only a fascinating experimental playground with toys from all kinds of physics: atomic physics, quantum optics and nuclear physics. It also produces abundant new information on nuclear structure off stability. The systematics of the data enhance and stabilize our knowledge on nuclear gross structure and in checking models, like the droplet model, or Hartree Fock calculations of nuclear matter. Local deviations from the average gross behaviour reveal shell closures, phase transitions and many other features of single particle or collective structure. On the experimental side the situation was characterized for the last few years mainly by extensive applications of the on-line methods developed in the late seventies. But recently methodological work restarted vigorously at several places, pushing the exploration of nuclear structure by optical means further off stability and to refractory elements. Since, in parallel new schemes of ion source and

separation techniques are coming on the floor, it is foreseeable that the knowledge of spins, moments and charge radii of nuclear ground states may be essentially completed in another decade.

References

- / 1/ A.C. Mueller, F. Buchinger, W. Klempt, E.W. Otten, R. Neugart, C. Ekström, and J. Heinemeier, Nucl. Phys. A403 (1983) 234
- / 2/ S.A. Ahmad, W. Klempt, C. Ekström, R. Neugart, and K. Wendt, Z. Physik A321 (1985) 35
- / 3/ R. Neugart, K. Wendt, S.A. Ahmad, W. Klempt, and C. Ekström, Hyperfine Interactions 15 (1983) 181
- / 4/ R. Neugart, Hyperfine Interactions 24 (1985) 159
- / 5/ S.A. Ahmad, W. Klempt, R. Neugart, E.W. Otten, K. Wendt, and C. Ekström, Phys. Lett. 133B (1983) 47
- / 6/ W. Borchers, R. Neugart, E.W. Otten, H.T. Duong, G. Ulm, K. Wendt, and the ISOLDE Collaboration, contributed paper to this conference
- / 7/ J. Eberz, U. Dinger, G. Huber, H. Lochmann, R. Menges, R. Neugart, R. Kirchner, O. Klepper, T. Kühl, D. Marx, G. Ulm, and K. Wendt, submitted to Nucl. Phys.
- / 8/ G.D. Alkhasov, A.E. Barzakh, E.E. Berlovich, V.P. Denisov, A.G. Dernityan, V.S. Ivanov, V.S. Letokhov, V.I. Mishin and V.N. Fedoseev, JETP Lett. (USA), 40 (1984) 836
- / 9/ K. Wallmeroth, G. Bollen, M.J.G. Borge, J. Campos, A. Dohn, P. Egelhof, J. Grüner, H.-J. Kluge, U. Krönert, R.B. Moore, A. Rodriguez, A. Venugopalan, and J. Wood, contribution to this conference
- /10/ D.A. Eastham, P.M. Walker, J.R.H. Smith, J.A.R. Griffith, D.E. Evans, S.A. Wells, M.J. Fawcett, and I.S. Grant, submitted to J. Phys. G. Nucl. Phys.
- /11/ S.V. Andreev, V.I. Mishin, and V.S. Letokhov, Optics Commun. 57 (1986) 317
- /12/ ref. /4/ and R. Neugart, W. Klempt, and K. Wendt, in print at Nucl. Instr. Meth.
- /13/ R.F. Silverans, G. Borghs, P. De Bisschop, and M. Van Hove, Hyperfine Interactions 24 (1985) 181
- /14/ U. Köpf, H.J. Besch, E.W. Otten, and Ch. v. Platen, Z. Physik 226 (1969) 297
- /15/ J. Bonn, Hyperfine Interactions 22 (1985) 57; Ch. Spath, thesis, Mainz 1985; R. Gegenwart, thesis, Mainz, 1986 and to be published
- /16/ E. Arnold, thesis, Mainz, 1986, and to be published
- /17/ N. Bendali, H.T. Duong, J.M. Saint-Jalm, and J.L. Vialle, Journal de Physique 45 (1984) 421; M. Carré, J. Lermé, and J.L. Vialle, J. Phys. B 19 (1986) 2853
- /18/ Lyon - Mainz - Orsay collaboration, J.L. Vialle, Lyon, private communication
- /19/ T.P. Das, contribution to this conference and to be published
- /20/ J.L. Heully and J.L. Martensson-Pendrill, Phys. Scr. 31 (1985) 169
- /21/ V.A. Dzuba, V.v. Flambaum, and O.P. Sushkov, Phys. Scr. 32 (1985) 507
- /22/ F. Buchinger, P. Dabkiewicz, H.-J. Kluge, A.C. Mueller, and E.W. Otten, Hyperfine Interactions 9 (1981) 165 and in print at Nucl. Phys.
- /23/ M. Anselment, K. Bekt, H. Hauser, H. Hoeffgen, G. Meisel, S. Göring, H. Rebel, and G. Schatz, in print at Phys. Rev. C
- /24/ H. Lochmann, U. Dinger, J. Eberz, G. Huber, G. Ulm, R. Kirchner, O. Klepper, T. Kühl, and D. Marx, submitted to Z. Physik
- /25/ W.D. Myers and K.H. Schmidt, Nucl. Phys. A410 (1983) 61
- /26/ I. Talmi, Nucl. Phys. A423 (1984) 189
- /27/ P.G. Reinhard and E.W. Otten, Nucl. Phys. A420 (1984) 173
- /28/ J. Żylicz, Proc. Int. Conf. Nucl. Structure, Reactions and Symmetries, Dubrovnik, 1986, in print, GSI preprint 86-29
- /29/ I. Ragnarsson, S.V. Nillson, and R.K. Sheline, Phys. Reports 45 (1978) 1
- /30/ G.A. Leander and R.K. Sheline, Nucl. Phys. A413 (1984) 375
- /31/ A. Coc, C. Thibault, F. Touchard, H.T. Duong, P. Juncar, S. Liberman, J. Pinard, M. Carré, J. Lermé, J.L. Vialle, S. Büttgenbach, A.C. Mueller, and A. Pesnelle, CERN preprint EP 86-109, submitted to Nucl. Phys.
- /32/ S.A. Ahmad, C. Ekström, W. Klempt, R. Neugart, E.W. Otten, and K. Wendt, Proc. of 7th Int. Conf. on Atomic Masses and Fundamental Constants (AMCO-7), Darmstadt-Seeheim, 1984, ed.: O. Klepper, p. 361