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Status Report

and

Request for Beam Time

Experiment IS 80:

STUDY OF NUCLEAR MOMENTS AND MEAN SQUARE CHARGE RADII BY COLLINEAR FAST-BEAM LASER SPECTROSCOPY

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1. Introduction

The experiment IS 80 has established the basis for extended collinear laser spectroscopy work at ISOLDE. The main goal is a systematic investigation of nuclear radii, spins and moments from the optical isotope shift and hyperfine structure. Since 1985 the original IS 80 programme has been joined by a number of more specific experiments performed in different collaborations and served by the IS 80 equipment to which various components have been added. These include the investigation of particular regions of nuclei like the near-spherical one around Z = 50 (IS 81), the Sr chain together with a new sensitive technique for alkaline-earth elements (IS 83-84), new developments like the laser ionization of rare-earth elements (IS 82), UV spectroscopy (IS01-11) and the direct g_I-factor measurement (IS01-c) on Ra, and a RADOP variant of collinear spectroscopy (IS01-9) which has been applied to ^{11}Li and offers promising applications also for solid-state physics.

Consequently, we had to find a balance within this programme and to delay partly the experiments envisaged in our last status report (PSCC/84-47/M203). These include

1) the invesitgations of moments and radii on either side of the neutron numbers N = 82 and N = 126, which reflect the transition from spherical to different types of deformed nuclear shape.
2) the development of the new technique of ion (instead of photon) detection which - for the rare gases - offers a gain in sensitivity by several orders of magnitude.

2. Experiments in 1985 - 87

2.1 Systematics in the Rare-Earth Region

For the rare-earth elements between Nd and Dy - i.e. around Z = 64 - the onset of deformation occurs in a sharp transition between N = 88 and 90. The systematics of moments and radii mainly covers the even-Z elements /1,2/ and europium /3-5/ of which the two stable isotopes happen to fall on these two neutron numbers. The measurements show that the shape transition is more pronounced for Z = 63 than for all even-Z neighbours. This is likely to be connected with the nearby Z = 64 subshell closure. From the results on even-Z elements one also concludes that holmium lies at the boundary between the sharp and the smooth onset of deformation. Therefore, measurements on holmium help to clarify the influence of the odd proton which for most of the isotopes can be found in a high-spin ground state or a low-spin isomer.

We have studied $^{151-165}Ho$ for which an adequate technique is the conventional photon-detected collinear laser spectroscopy. The experiment was performed in the transition $4f^{11}6s^2\ ^2F_{15/2} \rightarrow 4f^{11}6s6p\ (15/2,1)_{17/2}$ of neutral holmium at 4104 Å. The yields from spallation in a thick Ta-foil target were between 10^6 and 10^{10} atoms/s.

Fig. 1 gives the change in the mean square charge radii $\delta\langle r^2\rangle$ for $^{151-165}Ho$ in comparison with the curve for $^{140-156}Eu$ /4,5/, both evaluated from the isotope shift measurements. Despite the striking similarity the two curves indicate a remarkable difference in the structure of the N = 89 isotones: ^{152}Eu is strongly deformed in the I = 3 ground state, whereas in ^{156}Ho both the I = 4 ground state and the I = 1 isomer are on the near-spherical branch. Beyond N = 90 the initial deformation is smaller and continues to increase towards the heavier isotopes. A particularly interesting feature is the isomerism which gives rise to large shape differences between the I = 5 ground states and the I = 2 isomers in ^{158}Ho and ^{160}Ho. The isomer shifts below N = 90 are small. While the onset of deformation for the holmium ground states occurs suddenly between N = 88 and 90, the deformation for the isomeric states increases gradually with the neutron number.

The spins are readily deduced from the spectra, because the number of strong hyperfine structure components ($\Delta F = +1$), observed in the $J = 15/2 \rightarrow J = 17/2$ transition, is equal to (2I+1) for $I < 8$. In a few cases the spin values differ from earlier assignments. As an example we give in Fig. 2 the hyperfine structure of ^{156}Ho (N = 89) where the ground state spin is obviously I = 4 and the three small components of the I = 1 isomer are marked by arrows.

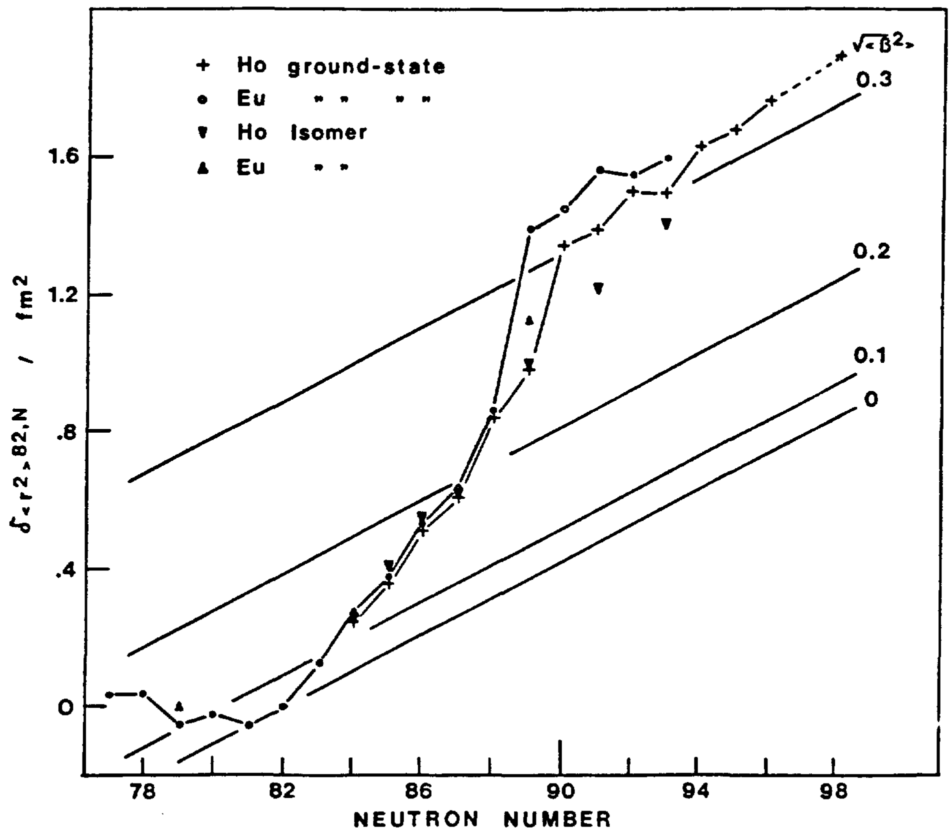

Fig. 1: Plot of $\delta\langle r^2\rangle^{82,N}$ for Eu and Ho. Lines of constant deformation are calculated from the droplet model.

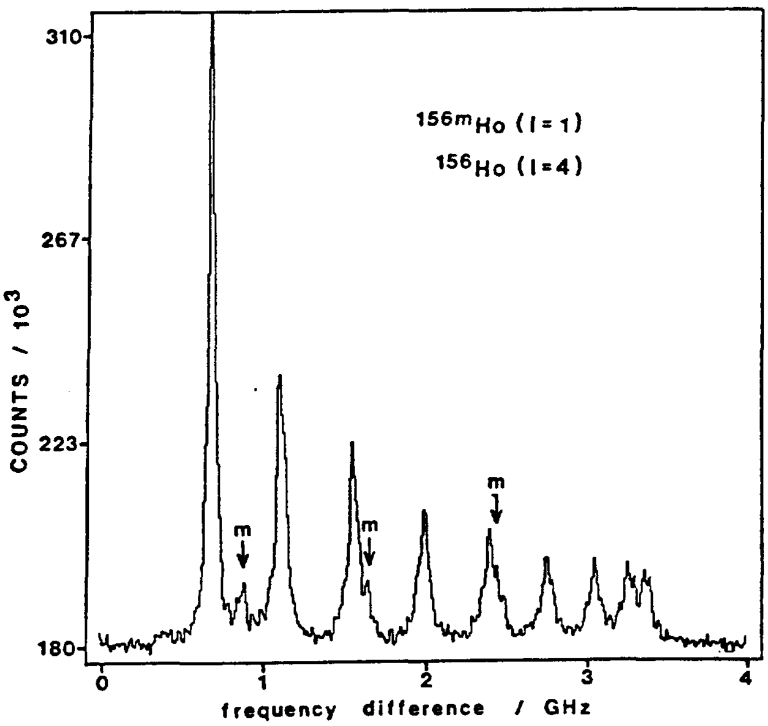

Fig. 2: Hyperfine spectrum for ^{156}Ho and ^{156m}Ho.

The interpretation of the proton configurations is straightforward for the odd-A isotopes whose moments are consistent with spherical shell model assignments of $\pi h_{11/2}$ and $\pi s_{1/2}$ for ^{151}Ho and ^{153}Ho, $\pi d_{5/2}$ for ^{155}Ho and the rather pure π[532 7/2] Nilsson configuration /6/ for the deformed $^{157-165}$Ho.

As the earlier measurements on gadolinium (Z = 64) isotopes suffered from unresolved hyperfine structures in the strongest atomic resonance line at 4226 Å, we have investigated a few other transitions which generally turned out to be inadequate for sensitive measurements on isotopes far from stability. We expect to solve this problem by UV spectroscopy on Gd^+ ions (see section 3.1).

2.2 Radon

The nuclear physics aspects of the measurements on radon isotopes are closely related to the previous investigations on radium: The heavier isotopes are expected to fall on the boundary of a region of pronounced octupole instability which is centered around the Ra-Th nuclei with $N \approx 136$. Mainly the spins and magnetic moments of these nuclei provide clues of reflection-asymmetric intrinsic shapes, because they are directly influenced by the parity mixing of the neutron orbitals. An indication of stabilized octupole-deformed shapes due to core polarization can be found in the inversion of the odd-even staggering effect of the radii (observed for Ra between N = 132 and 138).

We have performed the first measurements of hyperfine structures and isotope shifts in the radioactive element radon. They cover the isotopes $^{202-212}$Rn and $^{218-222}$Rn, and provide the basis for the determination of spins and moments in the odd-A isotopes. A calibration value for the magnetic moments, $\mu(^{209}$Rn), has been obtained by spin-exchange optical pumping in combination with γ-ray detected NMR (experiment IS 110 by F.P. Calaprice et al.). An interesting systematics of $f_{5/2}$ neutron moments can be studied in the near-spherical nuclei below N = 126. Fig. 3 shows a comparison of the mean square charge radii for Pb /7/, Rn and Ra /8/ from a preliminary evaluation of the isotope shifts.

These measurements were performed using the conventional fluorescence detected laser excitation from the metastable $7s[3/2]_2$ state which is populated in the charge transfer neutralization process. It is obvious from Fig. 3 that the measurements up to N = 136 do not cover the full range of neutron numbers which are relevant for octupole instability effects. An extension to the weakly produced isotopes $^{223-226}Rn$ has become possible by the new sensitive detection scheme of state-selective collisional ionization /9/.

2.3 Ion-Detected Spectroscopy on Rare Gases

It is a common feature of the rare-gas spectra that the ionization energy is more than 10 eV for the ground state and only about 4 eV for the metastable first excited state in which one electron is promoted from the closed np valence shell to the next higher (n+1)s shell. This involves a considerable difference in the cross-sections for electron stripping. Fig. 4 shows the relevant part of the energy level diagram for the example of radon. A fast beam of metastable atoms in the J = 2 state of the $6p^5 7s$ configuration - designated $7s[3/2]_2$ - is prepared in the charge-transfer neutralization of the original ion beam with caesium vapour. Laser excitation to $7p[3/2]_2$ at 705.5 nm depopulates the metastable level and pumps the atom via $7s[3/2]_1$ into the low-lying $^1S_0$ ground state. In passing the beam through a gas target, one can ionize predominantly the metastable atoms and thus detect the optical pumping as a flop-out signal on the ion current.

Fig. 5 gives a schematic view of the experimental setup used at ISOLDE. The front part including fluorescence detection is essentially identical with the standard apparatus that has been used extensively to study nuclear moments and radii. The differentially pumped stripping target has an effective thickness of 10 cm at a pressure of 10^{-3} to 10^{-2} mbar optimized for the individual gas. Ions created in this target are detected by a secondary-electron multiplier whose cathode is formed by a remote-controlled moveable metallic tape. This is indispensable for removing the considerable background from the radioactive decay of the nuclei collected on the detector during the experiment.

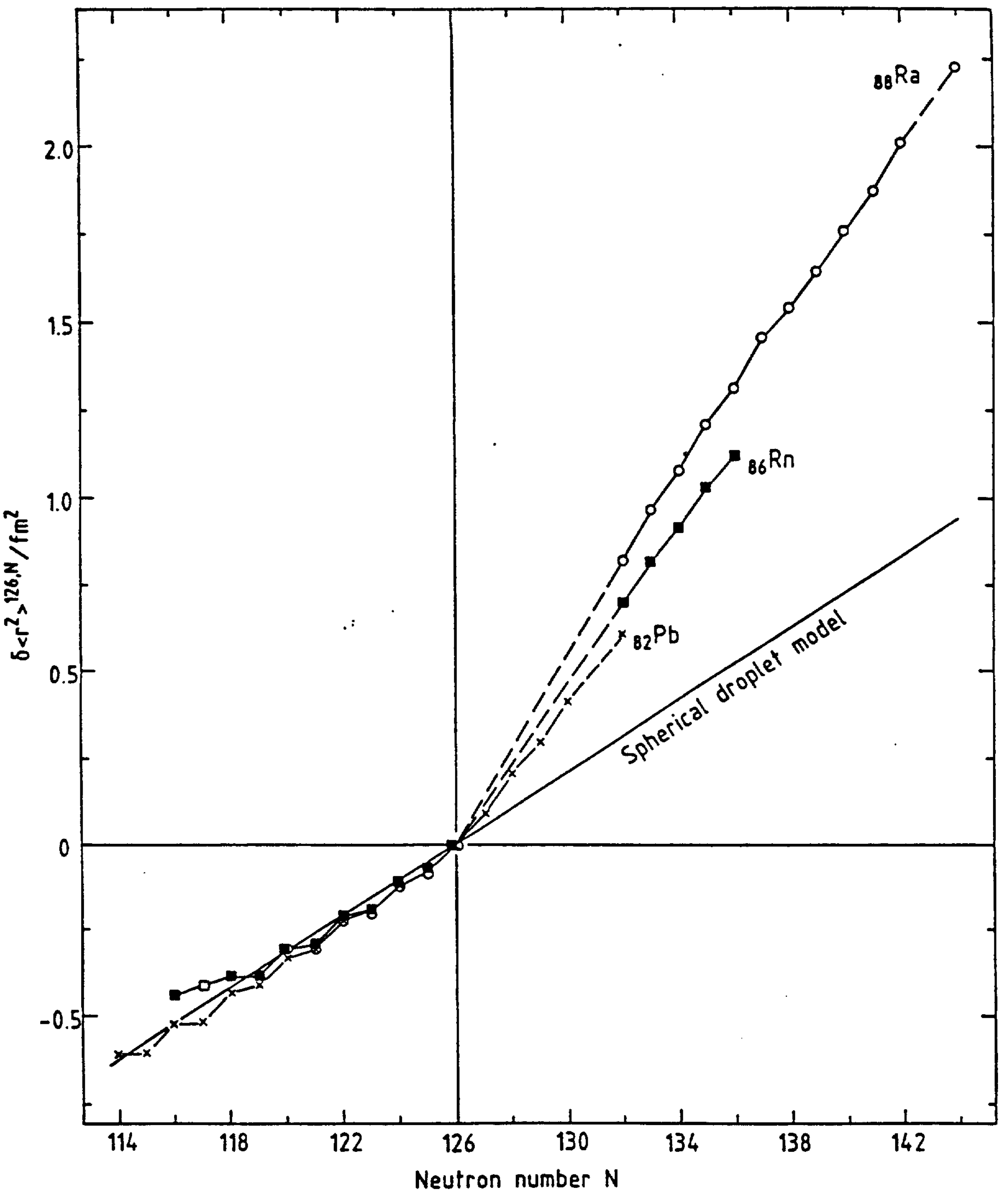

Fig. 3: Changes of the mean square charge radii in Pb (Z = 82), Rn (Z = 86) and Ra (Z = 88).

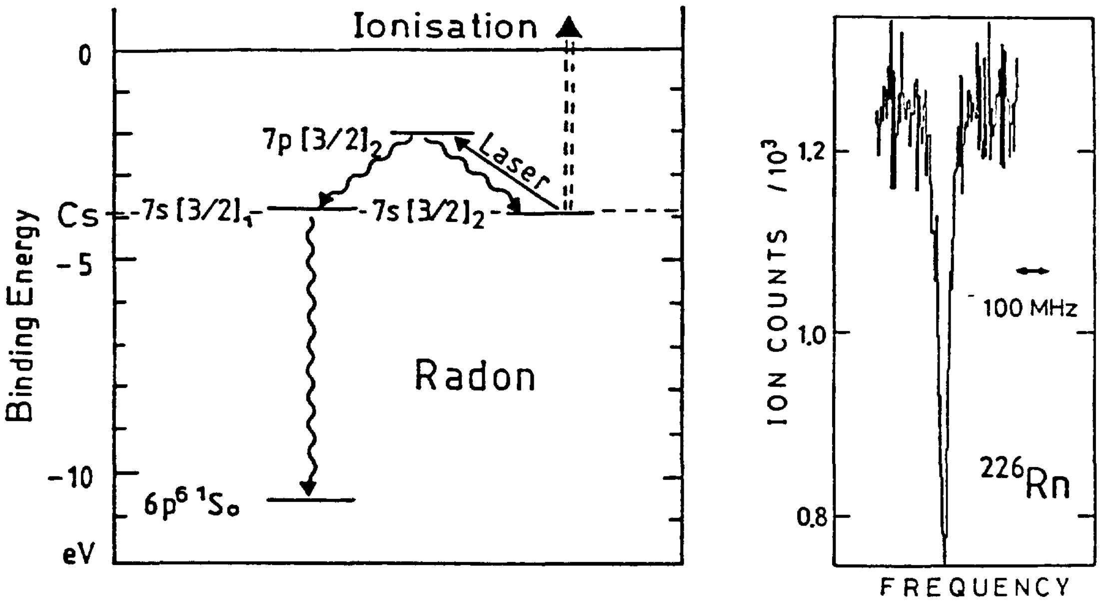

Fig. 4: a) Partial energy-level diagram of radon. The caesium ground-state energy is close to the metastable $7s[3/2]_2$ level.
b) Resonance signal of ^{226}Rn.

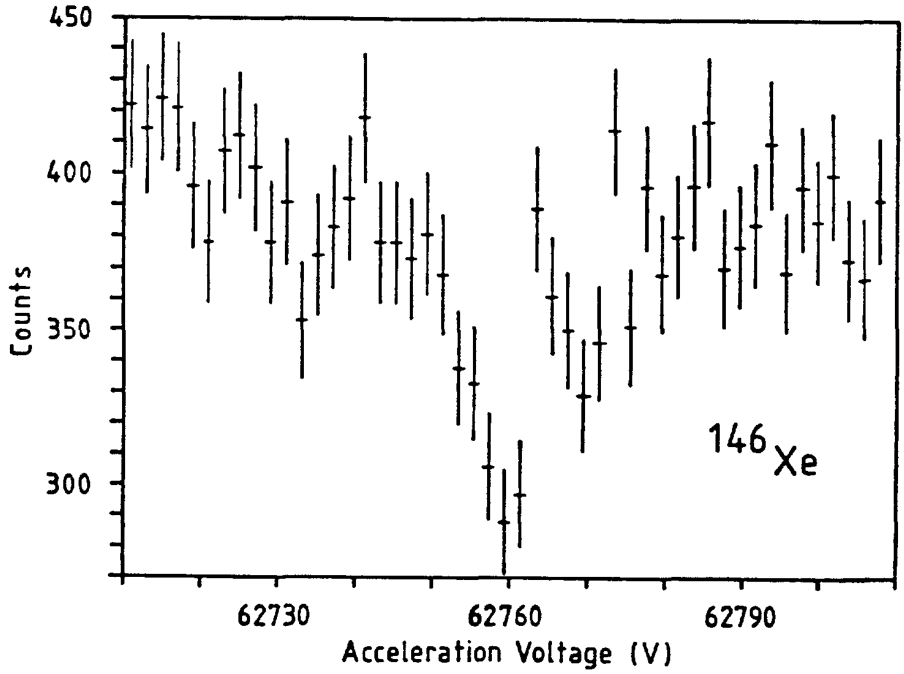

Fig. 6: Resonance signal of ^{146}Xe from a beam of originally 400 atoms/s.

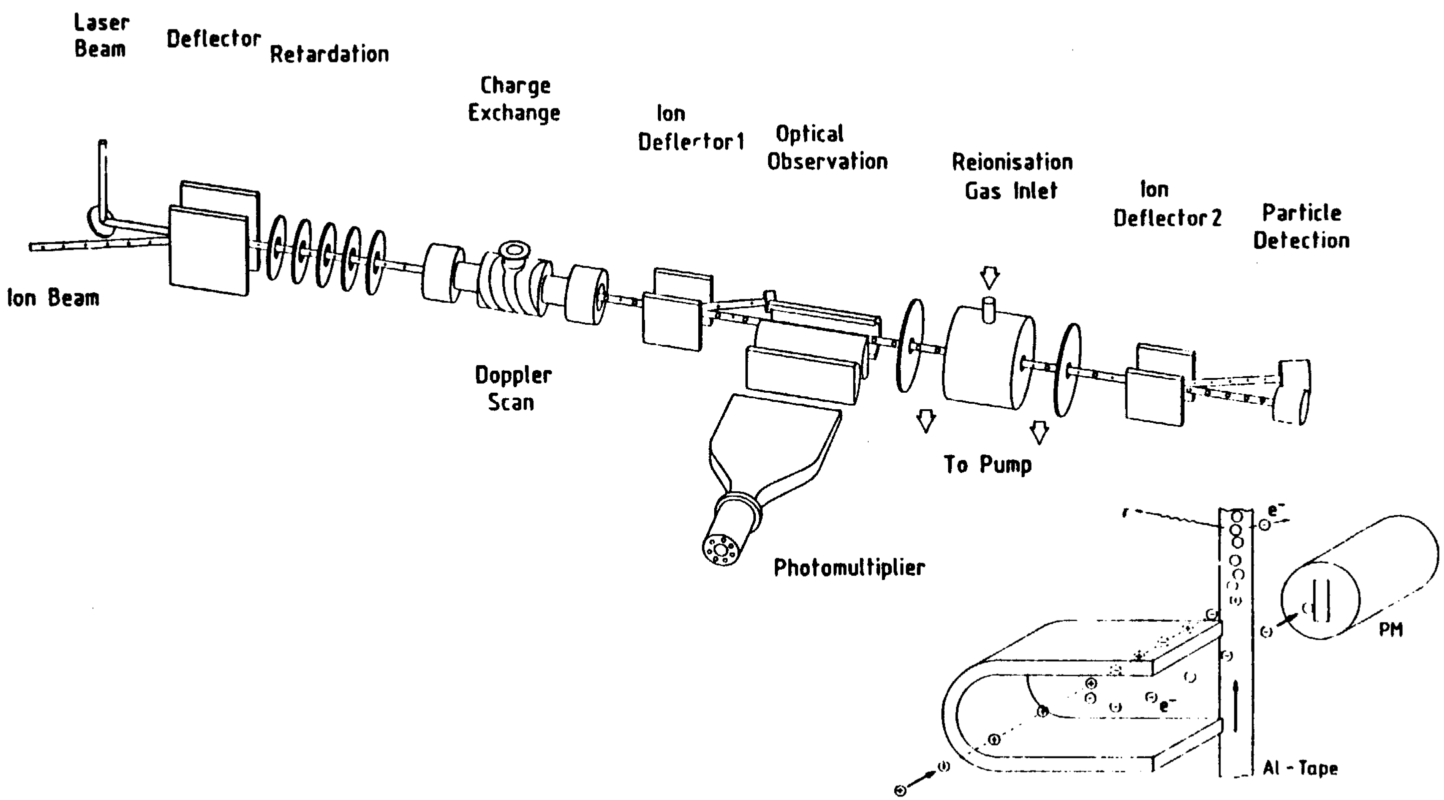

Fig. 5: Schematic view of the experimental setup. The ion detection system is shown in detail.

Another important source of background consists in the isobaric contaminations of the very weak beams of mass-separated radioactive atoms: Only to some extent the neutralization and ionization reactions are specific for the particular chemical element. For the "cold line" plasma ion source of ISOLDE we have found that after careful outgassing the beams of heavy Rn and Xe isotopes are very clean. Before we discuss some results of the initial experiments on $^{223-226}$Rn and $^{141-146}$Xe, we shall demonstrate the sensitivity for the example of the discovered new isotope, ^{146}Xe.

The resonance of Fig. 6 represents the transition $6s[3/2]_2$-$6p[3/2]_2$ for the I = 0 isotope ^{146}Xe, measured relative to ^{136}Xe thus yielding the isotope shift. The total measuring time over a 2.5 times larger scanning range was 35 min with a beam of about 400 atoms/s from ISOLDE. The signal efficiency is given by a 50 % total transmission of the beam line and our apparatus, 50 % charge exchange and 10 % ionization efficiencies and a 50 % flop-out signal on the ion current. These numbers refer to the $2x10^{-3}$ mbar Cl_2 target used in most of our experiments. A constant background of about 10 counts/s is ascribed to the general radioactivity level of the experimental area and should be removed by more careful shielding. It is obvious that even without significant improvements mass-separated beam intensities well below 100 atoms/s are sufficient for a measurement within reasonable time. This should be compared to the fluorescence detection limit for rare gases which is about 10^6 atoms/s in the far-red transitions that are accessible from the metastable state.

The results of the first runs on neutron-rich Rn and Xe isotopes are being analyzed. It seems that a significant change in the ground-state structure is reflected in the moments of ^{221,223,225}Rn which all have the spin I = 7/2. For ^{221}Rn this spin value is difficult to explain in combination with the almost zero magnetic moment and a small negative quadrupole moment. The key to such a state may be found in the transitional nature of this nucleus which should be soft in both the quadrupole and octupole degrees of freedom. On the other hand, ^{223}Rn and ^{225}Rn have nearly identical moments which can be accounted for by assuming a $7/2^-$ orbital based on the $j_{15/2}$ configuration. The isotones ^{225}Ra and ^{227}Ra, on the contrary, have I = 1/2 and I = 3/2 which are interpreted in the reflection-asymmetric scheme.

The recent xenon measurements include a few neutron-deficient test candidates and the systematically studied isotopes $^{136-146}Xe$ ($^{136-140}Xe$ from standard fluorescence spectroscopy). These neutron-rich nuclei with 82 $\leq$ N $\leq$ 92 belong to the classical region of transition from spherical to deformed nuclear shapes which is crossed by the stability line along the lighter rare-earth elements. xenon (Z = 54) is the element closest to the magic proton number Z = 50 for which isotopes around N = 90 can be reached, and it remains to be analyzed to what extent these nuclei still develop deformed shapes like the neighbouring barium (Z = 56) /10/.

3. Planned Experiments

3.1 Rare-Earth Region

Of the elements which have not been studied so far by laser spectroscopy, terbium (Z = 65) is particularly interesting because of the neighbourhood of the semi-magic proton number Z = 64. The investigation of ground-state properties will be complementary to the spectroscopy work of experiment IS 160 (P. Kleinheinz et al.). It can be expected that the interesting region around N = 82 - 90 will be accessible with fluorescence spectroscopy on neutralized beams.

For a continuation of the gadolinium and holmium experiments we expect significant progress from UV spectroscopy on singly-charged ions (which has been introduced recently by experiment IS01-11 for the case of Ra^+). We can thus avoid

1) the background from the decay of long-lived atomic states populated in the charge-exchange process, which is particularly serious because of the strong isobaric contaminations of all rare-earth beams;
2) the broad final-state distribution of the charge-exchange process which reduces the number of "useful" atoms.

The latter problem arises mainly on gadolinium where the electronic level structure is extremely complex. Here, we expect also clearly resolved hyperfine structures for the resonance transitions in the ion.

3.2 Rare-Gas Elements

With the ion detection described in section 2.3 we have a unique tool of spectroscopy on the rare-gas isotopes. This we want to exploit for measurements on the isotopes in the very neutron-rich and neutron-deficient wings of the ISOLDE yield curves. Only in some special mass regions we encounter problems from isobaric contaminations of the very weak beams. For example, it is difficult to avoid strong Hg beams around A = 200, together with the lightest Rn isotopes produced in the same ThC_2 target. In some lighter mass regions one finds contaminants from ion source materials and the rest gas. We hope to overcome these problems step by step in collaboration with H. Ravn and his target development group.

Tests on the existing target units have shown that most Xe and Kr isotopes are available under very clean conditions. Therefore, we would like to complete the Xe measurements and extend them to the neutron-deficient isotopes. In connection with the recent Sr experiment (IS 83) there is particular interest also in the neutron-deficient and neutron-rich Kr isotopes for which the deformation of the nuclei with $N \approx 40$ and $N \approx 100$ is being very much discussed (see also proposal IP 40 by K.-L. Kratz et al.).

3.3 Development of the Ionization Technique

From the atomic spectra it is obvious that rare-gas elements are the outstanding candidates for collisional ionization spectroscopy. Nevertheless, there may be a few other elements for which this scheme can be applied at a tolarable expense of sensitivity. A deeper understanding of the collision processes would certainly be useful to optimize the conditions. This is the subject of further investigations in our home laboratory. The final development will require radioactive beams from ISOLDE for studies of the background conditions of one or the other production target and ion source. A possible application may be the extension of the well investigated chains of Hg and Cd isotopes.

3.4 Thallium-207

We finally want to renew our interest in the magnetic moment of the 1.3 sec (11/2$^-$) isomer of ^{207}Tl (see status report PSCC/84-47/M203 and ref. /11/) which is of fundamental importance in connection with meson exchange currents. A sufficient production seems possible with the new high-intensity ^{3}He beam. In this connection we would also like to investigate the possibilities of studying some lighter Tl isotopes as a complementary programme to extensive classical optical measurements the laser spectroscopy work at UNISOR /12/ and possibly at GSI. First steps in this direction were taken together with the earlier measurement of the ^{207}Tl (1/2$^+$) ground-state moment /11/.

4. Beam Time Request

As in the past we are ready to coordinate the beam time of IS 80 and the other experiments using essentially the same apparatus. Therefore, the present programme will cover at least two years. The situation should improve after the installation of a new ISOLDE-III collinear laser spectroscopy setup.

We request for the work on

- Rare-earth elements (Gd, Tb, Ho) - Ta target, hot surface ion source -	15 shifts
Rare-gas elements (Xe, Kr, Rn) - ThC_2 target, La target, Nb target, plasma ion source with cold line -	25 shifts
Small experiments, radioactive test beams (e.g. Hg, Tl, ionization tests) - target to be defined -	10 shifts
	50 shifts

Although we have installed a new test apparatus at Mainz, we shall occasionally need stable beams from ISOLDE for tests and calibration (estimated time about 20 shifts).

Most of this programme will be performed at ISOLDE-II. Later we may take advantage from isobar separation capabilities of ISOLDE-III for the ionization experiments.

References

/1/ R. Neugart, in Lasers in Nuclear Physics (C.E. Bemis, jr., and H.K. Carter), Nuclear Science Research Conf. Series, Vol. 3 (Harwood, Chur - London - New York, 1982), p. 231

/2/ R. Neugart, K. Wendt, S.A. Ahmad, W. Klempt and C. Ekström, Hyperfine Interactions 15/16 (1983) 181

/3/ V.N. Fedoseev, V.S. Letokhov, V.I. Mishin, G.D. Alkhazov, A.E. Barzakh, V.P. Denisov, A.G. Dernyatin and V.S. Ivanov, Optics Commun. 52 (1984) 24

/4/ K. Dörschel, W. Heddrich, H. Hühnermann, E.W. Peau, W. Wagner, G.D. Alkhazov, E.Ye. Berlovich, V.P. Denisov, V.N. Panteleev and A.G. Polyakov, Z. Phys. A317 (1984) 233

/5/ S.A. Ahmad, W. Klempt, C. Ekström, R. Neugart and K. Wendt, Z. Phys. A321 (1985) 35

/6/ C. Ekström and I.-L. Lamm, Physica Scripta 7 (1973) 31

/7/ M. Anselment, W. Faubel, S. Göring, A. Hanser, G. Meisel, H. Rebel and G. schatz, Nucl. Phys. A451 (1986) 471

/8/ S.A. Ahmad, W. Klempt, R. Neugart, E.W. Otten, G. Ulm and K. Wendt, submitted to Nucl. Phys. A

/9/ R. Neugart, W. Klempt and K. Wendt, Nucl. Instr. Meth. B17 (1986) 354

/10/ A.C. Mueller, F. Buchinger, W. Klempt, E.W. Otten, R. Neugart, C. Ekström and J. Heinemeier, Nucl. Phys. A403 (1983) 234

/11/ R. Neugart, H.H. Stroke, S.A. Ahmad, H.T. Duong, H.L. Ravn and K. Wendt, Phys. Rev. Lett. 55 (1985) 1559

/12/ J.A. Bounds, C.R. Bingham, P. Juncar, H.K. Carter, G.A. Leander, R.L. Mlekodaj, E.H. Spejewski and W.M. Fairbank, jr., Phys. Rev. Lett. 55 (1985) 2269

Publications of IS 80 Work

1985 - 1987

S.A. Ahmad, W. Klempt, C. Ekström, R. Neugart, K. Wendt, Z. Phys. A321, 35 (1985)

R. Neugart, H.H. Stroke, S.A. Ahmad, H.T. Duong, H.L. Ravn and K. Wendt, Phys. Rev. Lett. 55, 1559 (1985)

R. Neugart, W. Klempt and K. Wendt, Nucl. Instr. Meth. B17, 354 (1986)

G. Ulm, S.K. Bhattacherjee, P. Dabkiewicz, G. Huber, H.J. Kluge, T. Kühl, H. Lochmann, E.W. Otten, K. Wendt, S.A. Ahmad, W. Klempt, R. Neugart, Z. Phys. A325, 247 (1986)

W. Borchers, R. Neugart, E.W. Otten, H.T. Duong, G. Ulm and K. Wendt, Hyp. Int. 34, 25 (1987)

H.T. Duong, P. Juncar, S. Liberman, A.C. Mueller, R. Neugart, E.W. Otten, B. Peuse, J. Pinard, H.H. Stroke, C. Thibault, F. Touchard, J.L. Vialle, K. Wendt, Europhys. Lett. 3, 175 (1987)

K. Wendt, S.A. Ahmad, W. Klempt, R. Neugart, E.W. Otten, H.H. Stroke, Z. Phys. D4, 227 (1987)

S.A. Ahmad, W. Klempt, R. Neugart, E.-W. Otten, G. Ulm and K. Wendt, subm. to Nucl. Phys. A (Nuclear mean square charge radii of $^{208-232}$Ra and octupole deformation around A=224)

K. Wendt, S.A. Ahmad, W. Klempt, R. Neugart and E.W. Otten, subm. to Z. Phys. A (HFS and IS of the neutron rich barium isotopes $^{139-146}$Ba and ^{148}Ba)

R. Neugart, E. Arnold, W. Borchers, W. Neu, G. Ulm and K. Wendt, Proc. 5th Int. Conf. on Nuclei far from Stability, Rosseau Lake, Canada, 1987