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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PROPOSAL TO THE ISOLDE COMMITTEE

HYPERFINE SPECTROSCOPY OF UNSTABLE EU+ ISOTOPES IN AN ION TRAP

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SUMMARY

Radioactive Eu isotopes produced at the ISOLDE facility shall be collected on metal foils. A total number of 10^{11} - 10^{12} particles is sufficient to perform off line experiments: After surface ionisation the ions are confined in a r.f. ion trap for extended periods of time. In laser-microwave double resonance experiments precision values of hyperfine separations and nuclear moments can be obtained. This leads to reliable and accurate hyperfine anomalies, which may be useful for a more detailed understanding of the distribution of magnetization over the nuclear volume, if they are available for chains of isotopes. In similar measurements on stable Eu+ isotopes magnetic dipole interaction constants A have been obtained with 10^{-8} precision and moreover electric quadrupole, magnetic octupole and electric hexadecapole interactions have been observed.

Keyword: Paul-Trap

I. Physics Motivation

The measurement of spins, nuclear magnetic moments and isotope shifts in a large number of particles produced by high energy reactions on accelerators and nuclear reactors during the past years has substantially increased our knowledge of nuclear properties in the region outside the valley of stability. A variety of methods has been employed in these experiments like Doppler limited fluorescences spectroscopy [1], atomic beam magnetic resonance [2], laser optical pumping and magnetic state selection [3], and collinear laser spectroscopy [4]. In these experiments the beam intensity of the shortlived isotopes was in some cases as low as 10^5 atoms per second.

We propose, to make use of the favourable properties of ion traps to extend this kind of investigations to precise measurements of hyperfine separations and nuclear moments of chains of isotopes. Experiments of hyperfine-splittings of stable ions using the ion storage method resulted in uncertainties as low as a few parts in 10^{11} [5] and nuclear magnetic moments can be expected to become known to better than 1 part in 10^6. A determination of these quantities in different isotopes would yield accurate values of differential hyperfine anomalies.

These arise from the deviation of a measured magnetic hfs coupling constant A from the calculated value A' for a point like nucleus

$$A = A'(1+\varepsilon)$$

$$A' = \frac{16}{3} \pi \, g_I \, \mu_B \, |\psi(o)|^2$$

It follows

$$\frac{A_1}{A_2} = \frac{g_{I1}}{g_{I2}} \frac{(1+\varepsilon_1)}{(1+\varepsilon_2)} \approx \frac{g_{I1}}{g_{I2}} (1+{}^1\Delta^2)$$

where the subscripts 1,2 refer to two different isotopes. Here the change in the electronic wavefunction ψ for the two isotopes (Breit-Rosenthal-effect) has been neglected. The physical origin of ${}^1\Delta^2$ is the change in the distribution of magnetization over the nuclear volume (Bohr-Weisskopf-effect) [6,7].

The experimental and theoretical status of the magnetic hfs anomaly has been most recently reviewed by Büttgenbach [8]. ${}^1\Delta^2$ has been determined with reasonable accuracy ($\leq 10\%$) for the pairs of odd stable nuclei and some unstable ones by measurements in neutral atoms, sometimes in different atomic states. It ranges typically between 10^{-2} and 10^{-4}. A general model to understand these data does not exist so far. An empirical rule by Moskowitz and Lombardi [9]

$$\varepsilon = \alpha/\mu_I,$$

where α is a parameter of the order of 10^{-2} μ_N, depending on the element, gives reasonable results near doubly closed shell nuclei. Nuclear models like the single particle shell model |10|, the core excitation model for non-deformed odd nuclei |11|, or the collective Nilsson model for strongly deformed odd nuclei |12| give predictions in selected areas of the nuclear chart.

A contribution to a better understanding might be a systematic study of the Bohr-Weisskopf effect in a long chain of isotopes with accuracies in the 1% range. This is the subject of this proposal. It aims for a determination of magnetic hfs splitting constants A and nuclear g-values with 10^{-6} precision, which would be sufficient to determine small (10^{-4}) values of Δ with 1% accuracy. A similar approach, using the atom beam resonance method on alkali atoms, is presently under way at ISOLDE |13|.

II. Status of Research

(a) Hyperfine Structure measurements in ion traps

For a number of stable isotopes precision hyperfine measurements have been performed using the ion trap technique. These experiments use lasers for optical pumping and microwaves to drive hyperfine transitions. Due to the virtual absence of perturbations and the long observation times (> 1 h) in traps spectral resolutions up to $1 \cdot 10^{11}$ have been obtained, limited sometimes only by the available frequency reference. Results of ion traps experiments, performed at Boulder, Sendai and Mainz, are given in Table 1. They have been restricted in the past to alkali-like systems. A first attempt to extend the measurements to unstable isotopes |14| was succesful in the cases of $^{133}Ba^+$ ($\tau_{1/2} = 10a$) and $^{131}Ba^+$ ($\tau_{1/2} = 11d$) where the results are of the same order in precision as with the stable ones and in any case superseedes the required precision of 10^{-6}.

Ion	Hyperfine separation [Hz]		Reference
$^9Be^+$	1 250 017 674.096	(0.008)	J.J. Bollinger et al., Laser Spectr. VI, Springer 1983,
$^{25}Mg^+$	1 788 763 128	(162)	W.M. Itano and D.J. Wineland, Phys.Rev. A24, 1364(1981)
$^{87}Sr^+$	5 002 368 354	(24)	H. Sanaoshi et al., Abstr. IX. Int. Conf. on Hyperf. Interactions, (Osaka 1992)
$^{131}Ba^+$	9 107 913 698.97	(0.50)	H. Knab, M. Schupp and G. Werth, Europhys.Lett. 4, 1361(1987)
$^{133}Ba^+$	9 925 453 554.59	(0.10)	H. Knab, M. Schupp and G. Werth, Europhys.Lett. 4, 1361(1987)
$^{135}Ba^+$	7 183 340 234.90	(0.57)	W. Becker and G. Werth, Z. Phys. A311, 41(1983)
$^{137}Ba^+$	8 037 741 667.69	(0.36)	R. Blatt and G. Werth, Phys.Rev. A25, 1476(1982)
$^{171}Yb^+$	12 642 812 124.3	(1.4)	R. Blatt, H. Schnatz and G. Werth, Z.Phys. A312, 143(1983)
$^{173}Yb^+$	10 491 720 239.55	(0.09)	A. Münch, M. Berkler and G. Werth, Phys.Rev. A35, 4147(1987)
$^{199}Hg^+$	40 507 347 997.8	(1.0)	F.G. Major and G. Werth, Phys.Rev.Lett. 30, 1155(1977)
$^{207}Pb^+$	12 968 180 601.61	(0.22)	X. Feng, G.Z. Li and G. Werth, Phys.Rev.A (in press)

Table 1: Hyperfine splitting of ionic ground states measured ion traps.

Most recently we have extended our measurements to the stable Eu^+ isotopes, which have a rather complex level structure |15|. The ground state is split into many hyperfine sublevels due to the coupling of the electronic total angular momentum J = 4 to the nuclear spin of I = 5/2. Many long living metastable states exist, where population trapping of the ions occurs, which reduces the signal-to-noise ratio. In spite of this difficulties the complete hyperfine structure has been resolved including the Zeeman splitting in a residual stray field of 270 mG in our trap. Fig. 1 shows an example of the measurement. From the measured frequencies and extended second order hfs correction we derived the coupling constant A for the magnetic dipole interaction and moreover those for the electric quadrupole (B), the magnetic octupole (C) and the electric hexadecupole (D) interactions. The results are listed in table 2.

hfs constant	$^{151}Eu^+$ [Hz]	$^{153}Eu^+$ [Hz]	$\dfrac{^{151}Eu^+}{^{153}Eu^+}$
A	1 540 297 394(13)	684 565 993(9)	2.2500349(6)
B	-660 862(231)	-1 752 868(84)	0.37702(19)
C	26(23)	3(7)	9(28)
D	-6(5)	-5(2)	1.2(1.2)

Table 2: The hfs coupling constants for the magnetic dipole (A), electric quadrupole (B), magnetic octupole (C) and electric hexadecapole (D) interaction in the ground state $4f^7(^8S)6s$; $^9S_4$ of the two stabile isotopes $^{151}Eu^+$ and $^{153}Eu^+$.

Eu^+ seems to be an interesting candidate for the proposed investigations. The two stable isotopes of mass 151 and 153 are a prominent example of a nuclear shape transition which manifest itself in an exceptionally large isotope shift and in a large difference in nuclear magnetic dipole and electric quadrupole moments |16|. It has a chain of 9 different isotpes with non-zero nuclear spin, which live longer than a few days (table 3). These isotopes may be subject to our measurements off line from the production area.

A first attempt to extend the measurements to unstable isotopes was partially succesful. We collected about 10^{12} $^{150}Eu^+$ at Isolde and observed the optical spectrum with sufficient resolution (fig. 2). Due to isotope contamination with ^{151}Eu and due to failure of our laser system we could not perform the microwave induced hyperfine transitions, but we have demonstrated the feasibility of the experimental prerequisits.

(b) g_I-factor measurements

The g_I-factors of the unstable isotopes are not known with sufficient accuracy. We plan to measure them by observation of the nuclear Zeeman-effect in a Penning-trap experiment. At present we study the Zeeman-effect on Ba^+ ions in such a trap, located in a 6 Tesla B-field. We have measured the

Zeeman splitting of the electronic groundstate of the even isotopes at 163 GHz with an uncertainty of $3 \cdot 10^{-8}$ (fig. 3). The B-field strength at the ions position was determined by a measurement of the cyclotron frequency of electrons stored in the same trap. The total accuracy of the g_J-value is $5 \cdot 10^{-7}$ |17|. We expect a similar precision in the g_I-factor determination, which is under preparation.

III. Experimental Method

Ions are implanted on metal foils which then are placed inside an aperture of an ion trap electrode. Surface ionisation, sputtering or laser desorbtion produces a cloud of low energetic ions, which are slowed down by buffer gas collisions at about 10^{-5} mbar. Trapping efficiencies of $10^{-4} - 10^{-5}$ have been obtained. The storage time in many cases exceeds several hours. A hyperfine transition, driven by a microwave field after optical pumping by a laser beam is observed by the change in fluorescence intensity from the ions, which is monitored through a mesh electrode, an interference filter and an optical system, amplified by a photomultipliertube and counted in a multichannel analyzer. Fig. 4 shows the experimental setup

Table 3

Isotopes	Nuclear Spin	Lifetime	ISOLDE yield
$^{145}Eu^+$	5/2	5.6d	$7 \cdot 10^8\ s^{-1}$
$^{146}Eu^+$	4	4.6d	$5 \cdot 10^8\ s^{-1}$
$^{147}Eu^+$	5/2	24.6d	$3 \cdot 10^8\ s^{-1}$
$^{148}Eu^+$	5	54d	$5 \cdot 10^8\ s^{-1}$
$^{149}Eu^+$	5/2	93.1d	$5 \cdot 10^8\ s^{-1}$
$^{150}Eu^+$	5	36a	$5 \cdot 10^8\ s^{-1}$
$^{151}Eu^+$	5/2	stable	
$^{152}Eu^+$	3	13a	$3 \cdot 10^8\ s^{-1}$
$^{153}Eu^+$	5/2	stable	
$^{154}Eu^+$	3	8.8a	$2 \cdot 10^8\ s^{-1}$
$^{155}Eu^+$	5/2	4.9a	

The number of atoms required for such an experiment can be estimated: About 10^5 ions in a trap is at present the minimum number for an uncooled ion cloud to get sufficient high signal-to-noise ratio. A trapping efficiency of 10^{-4} then would require a total number of 10^9 atoms per trap filling. We estimate that about 100 trap fillings are needed to complete the measurements for one isotope, which gives a minimum of 10^{11} collected atoms at ISOLDE.

The minimum lifetime is given by the fact, that the isotopes have to be transported to Mainz and implanted into an UHV-apparatus, which requires a few days of bakeout. Previous experiments on radioactive $^{131}Ba^+$ ions |14| showed, that 10 days lifetime is sufficient to complete an experiment with high precision.

IV. Support from ISOLDE

In the first stage of the experiments for hyperfine measurements isotopes with lifetime extending several days would be investigated after collection on a foil at ISOLDE and transport to Mainz. The support from ISOLDE would be restricted to the production of the resp. isotope separated beam. In case of approval we would ask for beam time of two shifts per unstable isotope, which gives a total of 14 shifts over a period of two years.

Target requirements:

Beam	Min. Intensity	Target Material	Ion source	Shifts
$^{155}Eu^+$.....$^{147}Eu^+$	10^8	Ta-foil	W-surface	2 each
			Sum:	14

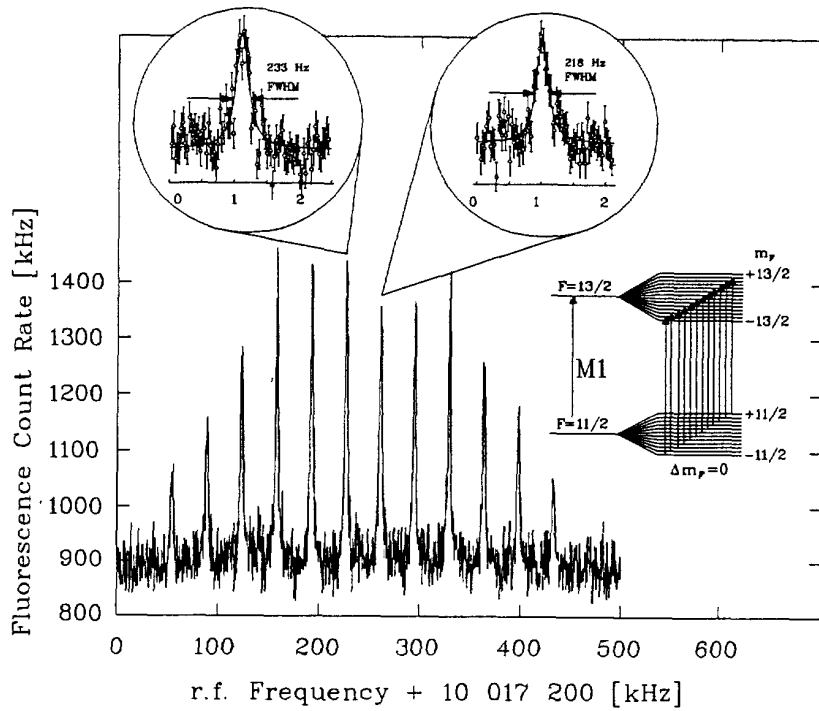**Fig. 1:**

$\Delta m_F=0$ part of the Zeeman transitions between the F=13/2 and F'=11/2 ground state hyperfine level in $^{151}Eu^+$. The residual magnetic field at ions position was 270 mG. The inset shows the two innermost Zeeman-resonances with higher resolution.

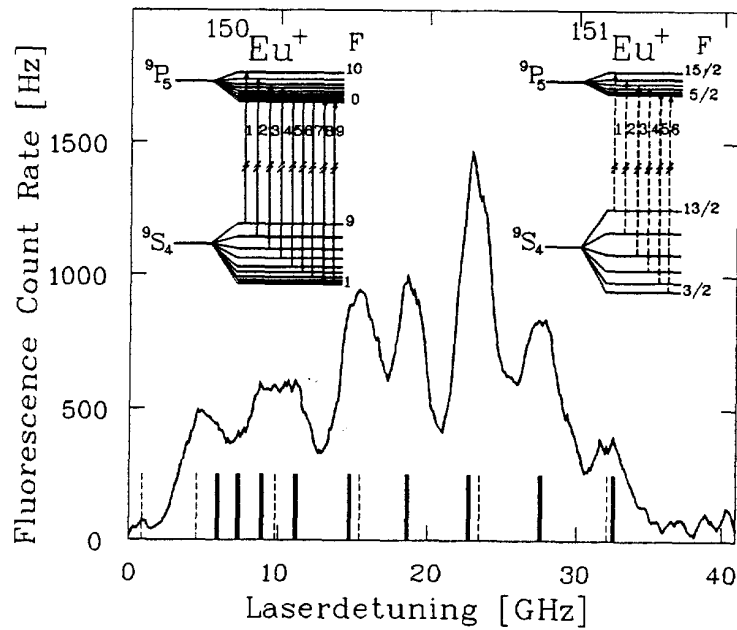**Fig. 2**

Optical $^9S_4$-$^9P_5$ exitation spectrum of a mixture of $^{150}Eu^+$ and $^{151}Eu^+$ ions. The positions of the different hyperfine components are indicated by thick ($^{150}Eu^+$) and thin dashed ($^{151}Eu^+$) bars.
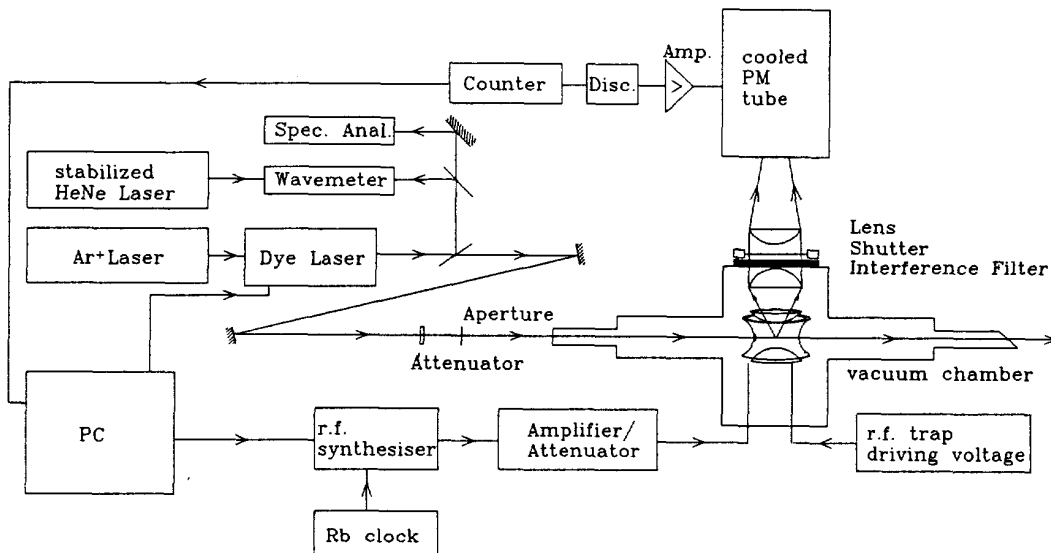
Fig. 3

Setup for laser-microwave double resonance experiment on Eu^+ in a Paul ion trap.
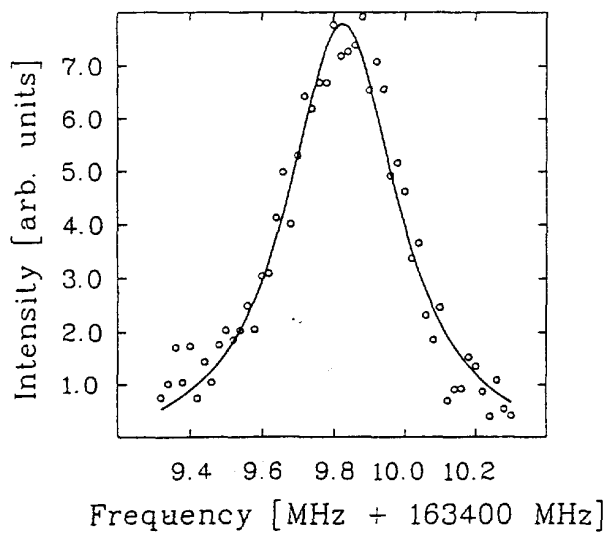

Fig. 4

Microwave inducees $\Delta m_J=1$ transition between groundstate Zeeman levels in Ba^+ in a 6 T magnetic field

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