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STUDY OF SHORT-LIVED BROMINE ISOTOPES

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and the NICOLE and ISOLDE collaborations

ABSTRACT

First experiments in the systematic study of the structure of ground states and isomeric states of Br isotopes as function of neutron number at ISOLDE, CERN are reported. The isotopes $^{74g, 74m, 77, 78, 84g, 84m}$Br have been implanted into iron and studied with the techniques of low temperature nuclear orientation and nuclear magnetic resonance of oriented nuclei (NMR/ON). The experiments were performed with the NICOLE on-line nuclear orientation set-up using the isotope separator ISOLDE-3. NMR/ON experiments were successful for ^{74m}Br with continuous on-line implantation and for ^{77}Br. Using as value of the hyperfine field B_{hf}(BrFe) = +81.35(3)T we obtain $|g(^{74m}Br)|$ = 0.455 (3) and $|g(^{77}Br)|$ = 0.6492 (3). Static nuclear orientation data have been measured for all above mentioned isotopes. From these data we drive $|\mu\ (^{78}Br, I = 1)|$ = 0.13 (3) and $|\mu\ (^{84g}Br, I=2)|$ = 1.9 (7). The results are discussed within the systematics of the bromine isotopes.

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First experiments in the systematic study of the structure of ground states and isomeric states of Br isotopes as function of neutron number at ISOLDE, CERN are reported. The isotopes ^{74g,74m,77,78,84g,84m}Br have been implanted into iron and studied with the techniques of low temperature nuclear orientation and nuclear magnetic resonance of oriented nuclei (NMR/ON). The experiments were performed with the NICOLE on-line nuclear orientation set-up using the isotope separator ISOLDE-3. NMR/ON experiments were successful for ^{74m}Br with continuous on-line implantation and for ^{77}Br. Using as value of the hyperfine field B_{hf}(Br**Fe**) = +81.35(3) T we obtain $|g(^{74m}Br)| = 0.455(3)$ and $|g(^{77}Br)| = 0.6492(3)$. Static nuclear orientation data have been measured for all above mentioned isotopes. From these data we derive $|\mu(^{78}Br, I=1)| = 0.13(3)$ and $|\mu(^{84g}Br, I=2)| = 1.9(7)$. The results are discussed within the systematics of the bromine isotopes.

1. Introduction

Nuclei with proton number around Z = 38 and masses in a large range around A = 80 have been studied extensively in the last years (e.g. /1/). Because the single particle level density in this mass region is considerably lower than e.g. in the A = 160 mass region shell-structure effects manifest themselves in a rather intensive way. They lead in particular to a strong variation of nuclear shape with particle number and to shape coexistence effects /2/ and generally to a richness of nuclear structure phenomena which explains the interest of both experimentalists and theoreticians in this mass region. The Br nuclei have Z = 35, three protons less than the deformed subshell gap number 38, which (enforced for N = 38) leads to strong nuclear deformation. Experimentally deformation has been found in light Br isotopes /3/. Deformation should vanish when crossing the magic neutron number N = 50 at ^{85}Br and it is interesting to follow the structure beyond this neutron shell closure in the direction to N = 56 where also for the low proton number Z = 36 i.e. Kr a subshell gap has been proved to exist /4/. Around neutron number N = 56 theoretical calculations predict octupole softness for $Z \approx 34$ /5/.
In this paper we report on first experiments of a project to measure precise values of the electromagnetic moments of the ground states and for odd-odd isotopes also of long-lived isomeric states of a series of Br isotopes in the range $72 \le A \le 89$ to study systematically the structure of these nuclei as function of neutron number. Especially the odd isotopes are interesting because here precise magnetic dipole moments give information on the proton-neutron coupling schemes which occur in the particular nuclei. On the neutron deficient side of the Br isotopes static low temperature nuclear orientation experiments have been performed in the past in host iron to determine magnetic moments. The moment of ^{77}Br has been derived reasonably precisely in Bonn and Oxford /6/. The

magnetic moment of the shorter lived ground states of ^{75}Br and ^{72}Br and isomeric states of ^{74}Br and ^{72}Br have been measured in on-line nuclear orientation (NO) experiments at Daresbury Laboratory /7/. The experimental values of these latter moments had rather large experimental errors which incorporate uncertainties due to model assumptions in the data evaluation.

The group in Bonn has in the past studied intensely the implantation behaviour of Br in iron /8, 9, 10, 11/. Successful nuclear magnetic resonance on oriented nuclei (NMR/ON) experiments have been performed with the isotope ^{82}Br using the FOLBIS set-up. Therefore it is intended to apply wherever possible the precision method of NMR/ON for the determination of the magnetic moments of Br isotopes. For isotopes where too little information on moment and decay is available from literature a static NO experiment must be performed before any NMR/ON attempt, to find γ-lines with good anisotropy and narrow down the resonance search range. For the latter purpose the experience in meaningful evaluation of static NO data for the system Br**Fe**, gained in the systematic studies of implantation behaviour /8, 9, 10, 11/, helps.

The experiments have been and are planned to be performed at the isotope separation facility ISOLDE at CERN, Geneva, Switzerland. This facility provides good yields of Br isotopes in the mass range $72 \leq A \leq 89$.

2. Experiments and results

2.1 Experimental details and methods

The experiments described in this paper have been performed with the ^3He-^4He dilution refrigerator of the collaboration NICOLE at CERN. The refrigerator was operated on-line to the isotope separator ISOLDE-3, which is well known for its high yields in radioactive isotopes far from stability. A short description of the experimental set-up can be found e.g. in ref. /12/.

In all cases, besides ^{77}Br, samples were prepared by on-line implantation of bromine isotopes. The isotopes were produced by irradiation of a niobium powder target with 600 MeV protons from the CERN synchrocyclotron /13/. After negative surface ionization the nuclei were implanted with 60 keV into an iron foil on the cold-finger of the refrigerator. The experiment was the first one using negative ions on the separator ISOLDE-3 and showed the full suitability for such experiments.

The sample of ^{77}Br**Fe** was produced off-line at the separator ISOLDE-2. The precursor isotope ^{77}Kr was implanted into an iron foil at room temperature and left to decay ($T_{1/2} = 1.24$ h) to ^{77}Br. For the measurements the sample was top-loaded into the cryostat and cooled to low temperatures.

The iron foils for the experiments were prepared by rolling highly pure iron (99.998%) bulk material to foils. After careful mechanical polishing of the surfaces the foils were annealed in high vacuum at about 900°C. This production process provides excellent quality of surface which is necessary for reasonably reproducible results with a high percentage of implanted nuclei in "good sites".

Data of static nuclear orientation measurements were interpreted in terms of a "two frequency" model /10, 14/ which was shown to be necessary for a meaningful evaluation of data of ^{82}Br**Fe**. In this model it is assumed that a fraction f of the nuclei experience a magnetic interaction with the NMR frequency while the rest (1-f) is oriented by a weaker but collinear magnetic interaction with frequency ν_{low}. Then the γ-intensity in direction ϑ relativ to the orientation axis at temperature T is:

$$W(\vartheta, T) = f\, W(\vartheta, T, \nu_{nmr}) + (1-f)\, W(\vartheta, T, \nu_{low}) \qquad (1)$$

with $$W(\vartheta, T, \nu) = 1 + \sum_k B_k(\nu/kT)\, U_k A_k Q_k P_k(\cos\vartheta) \qquad (2)$$

Here the coefficents B_k describe the orientation of the nuclear state with magnetic hyperfine interaction frequency ν. The coefficients U_k take account of the deorientation by unobserved intermediate nuclear transitions and A_k are the usual angular distribution coefficients of the observed γ-transition. The Q_k correct for finite detector size and the P_k are Legendre polynomials /15/.
Before the NMR/ON measurements the eddy current heating as a function of rf-frequency in the cryostat was carefully investigated. Precise knowledge of the "power pattern" allowed us for the NMR/ON measurements to dispense with carrier wave counts and measure only with frequency modulation switched on to avoid waste of beam-time.

2.2 Measurements and results

Measurements were performed with the isotopes $^{74g,m}Br$, ^{77}Br, ^{78}Br and $^{84g,m}Br$.

$^{74g,m}Br$

The resonance search range for ^{74m}Br ($T_{1/2}$ = 46 m) was estimated from NO data of experiments at Daresbury /7/ and Louvain-la-Neuve /16 /. In fig.1 the ratio of count rates at 0° and 90° against the orientation axis, respectively, is shown for the frequency region of interest. The width of the frequency modulation was ± 1 MHz; the center frequency was varied in steps of 2 MHz. The measurement was performed with continuous implantation of $^{74g,m}Br$. A clear resonance signal is observed. A single Gaussian line with linear background was fitted to the data, solid line in fig.1. The center frequency obtained corrected for the external field of B_{ext} = 0.1 T is given in table 1. The g-factor of ^{74m}Br listed also in table 1 was derived using as value for the hyperfine field at the nuclear site of bromine in iron /8/

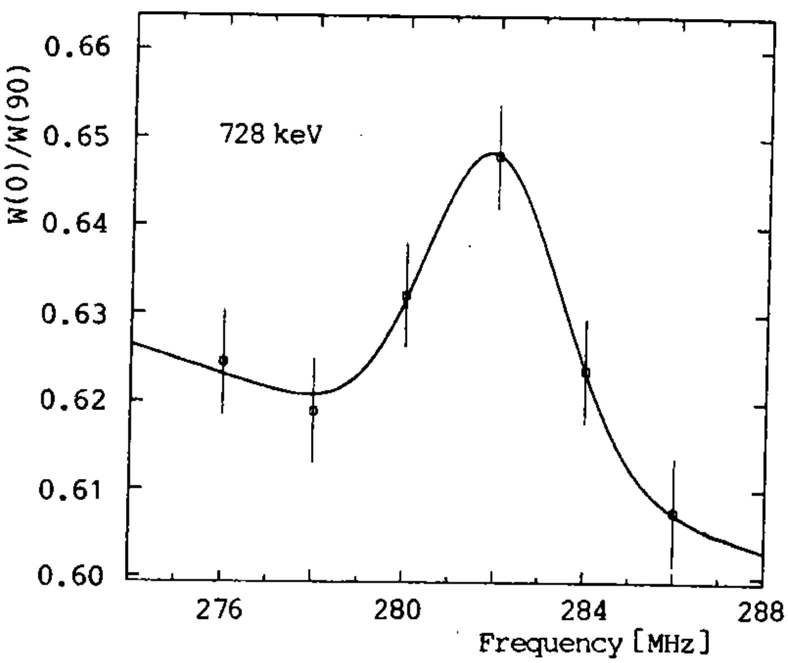

Fig 1. Ratio of the normalized count rates at 0° and 90° W(0°)/W(90°) of the 728 keV γ-line in the decay of ^{74m}Br versus frequency. The solid line represents the result of a fit of a single gaussian line with linear background to the data.

$$B_{HF}(BrFe) = +81.35(3)\ T.$$

In fig.2 static NO data for the 728 keV γ-line emitted exclusively in the decay of ^{74m}Br measured also with continuous implantation of $^{74g,m}Br$ are displayed. The solid line represents the result of a least-squares fit of the theoretical anisotropy ratio [W(0)/W(90) - 1] in the two frequency model, see sect.2.1, to the data. Numerical results

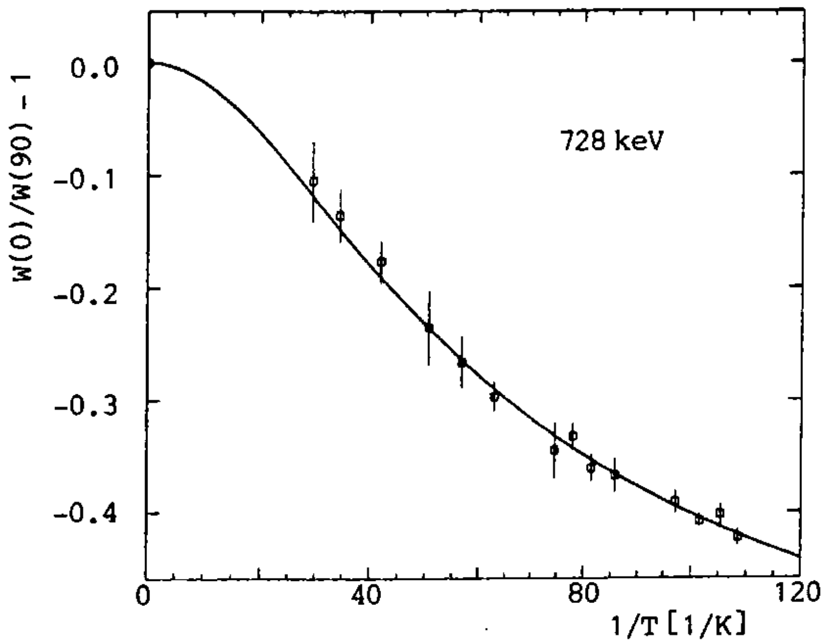

Fig.2 Anisotropy ratio $W(0^0)/W(90^0) - 1$ of 728 keV γ-line in the decay of ^{74m}Br versus inverse temperature

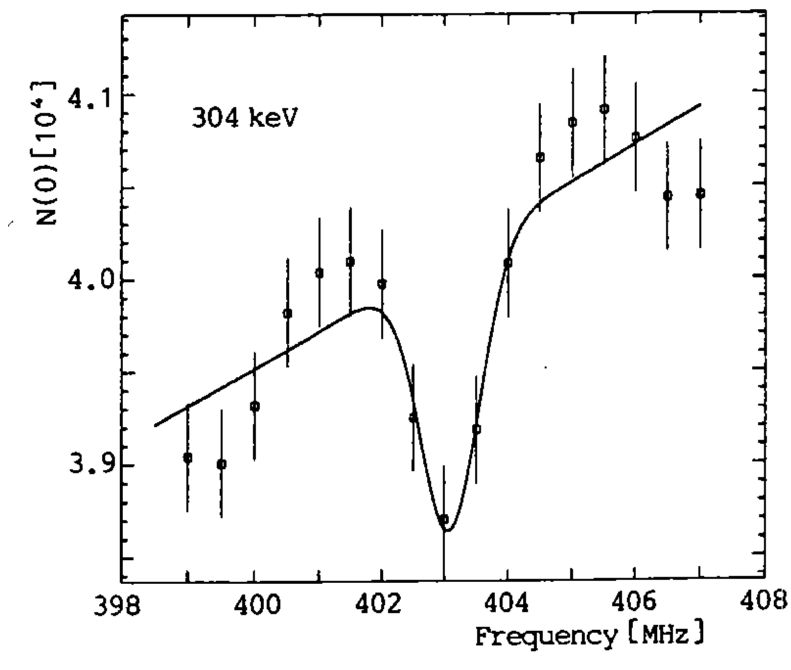

Fig.3 Count rate of the 304 keV γ-line in the decay of ^{77}Br at 0^0 with respect to the orientation axis versus frequency

are listed in table 2. In the fit only the fraction f of nuclei in NMR/ON field sites and the A_kU_k coefficients were varied. The magnetic hyperfine field at the second site was fixed at $B_{low} = 24.6$ T derived from systematic investigations on ^{82}Br**Fe** /8/. The quality of fit derived is excellent, if one takes into account that the two interaction frequencies were kept fixed. The rather large error in the fraction f results from a parameter correlation between f and the A_kU_k coefficients.

A careful inspection of the γ-spectra which were measured up to about 4 MeV γ-energy revealed that no γ-line with reasonable anisotropy emitted in the decay of ^{74g}Br alone could be found. In fact it turned out that in the production of bromine with 600 MeV protons on niobium the ground state of ^{74}Br was populated at least a factor of 10 less than the isomeric state.

^{77}Br

As described above the ^{77}Br**Fe** sample was prepared by implantation of ^{77}Kr with the ISOLDE-2 separator. From former experiments in Bonn /8/ and Daresbury /7/ a search range between 350 MHz and 422 MHz was scanned. The frequency was varied in steps of 0.5 MHz with a modulation width of ±0.5 MHz. In fig.3 the count rate of the 304 keV γ-transition versus frequency is shown in the region where the resonance signal was found. Again a single Gaussian line with linear background was fitted to the data points. Numerical results are listed in table 1. Static NO data were measured down to a temperature of 6.7 mK. They are displayed for the 304 keV γ-line in fig.4. The dashed lines represent a fit of the simple 2-site model /10, 14/ to the data, where the frequency was

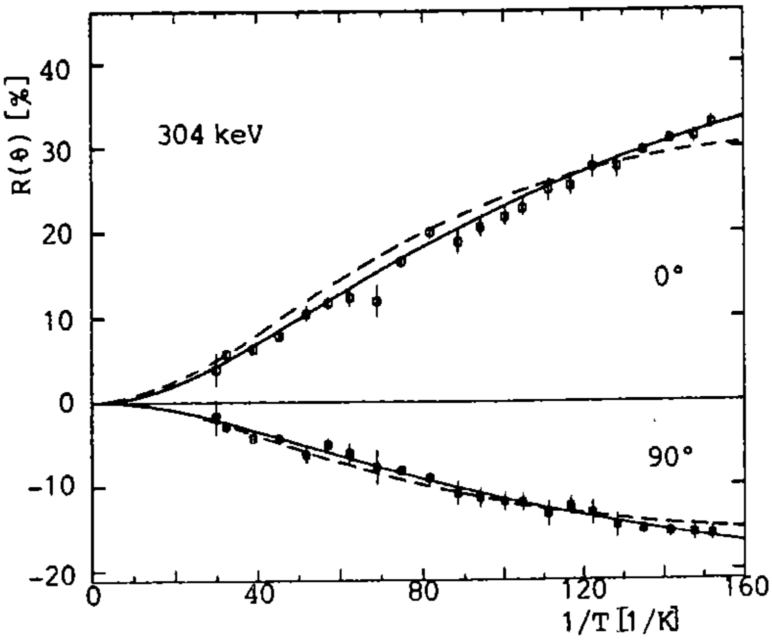

Fig.4 Anisotropy R = W(ϑ) − 1 of the 304 keV γ-line in the decay of ^{77}Br for ϑ = 0° and 90° versus inverse temperature. The dashed lines result from a fit of theoretical anisotropies in the 2-site model to the data. The solid lines are from a fit in the 2-frequency model. For details see text.

fixed to the NMR/ON result. Again it is demonstrated visibly that this model is not applicable to the system BrFe. The solid lines in fig. 4 represent the result of a fit of the two frequency model, see section 2.1, to the data. Here the first frequency was that obtained from NMR/ON, the second corresponded to a hyperfine field of 24.6 T, see above for ^{74m}Br. It can be seen that in this model the data are well reproduced in contrast to the simple 2-site model. Numerical results are listed in table 2.

Table 1: Results of NMR/ON experiments

Isotope	I	$\nu(B_{ext}=0)$ [MHz]	FWHM [MHz]	|g-factor| [a]	|μ [n.m.]|	|μ [n.m.]| ref. /7/
^{74m}Br	4	281.3(9)	2(1)	0.455(3)	1.82(1)	1.68(18)
^{77}Br	3/2	402.6(1)	1.0(3)	0.6492(3)	0.9738(5)	0.92(5)

[a] no hyperfine anomaly taken into account

^{78}Br

Since no experimental information on the magnetic moment was known, a static NO experiment was performed to make an estimate, in which frequency region the nuclear magnetic resonance should be searched for. Two separate measurements, one with a ^{60}CoCo (hcp), the other with a ^{54}MnNi thermometer, were carried out. The combined data for the 614 keV γ-line, which is the only strong line in the decay of ^{78}Br are shown in fig.5. Only a very small anisotropy was observed down to a temperature of about 10 mK. A theoretical function using the 2-frequency model was fitted to the data (solid line in fig.5). For the fit L = 1 was assumed for the β-decay to the 614 keV state of ^{78}Se. With this assumption the $A_k U_k$ coefficients are known. B_{low} was set to the same value as for ^{74,77}Br. Contrary to the above described evaluations of NO data the value of the magnetic moment was varied and the fraction f was fixed at f = 0.5 as suggested by the ^{74,82}Br NO data /8/. A very small magnetic moment, see table 2, was derived. For such a small moment the spin-lattice-relaxation time would become comparable in size to the half-life of $T_{1/2}$ = 6.46 min of ^{78}Br. This would cause a reduction

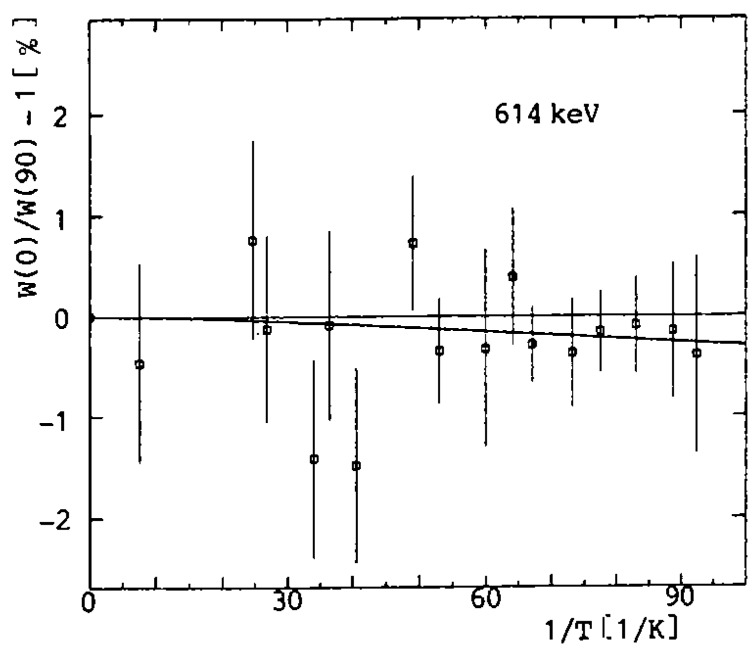

Fig.5 Anisotropy ratio W(0°)/W(90°) - 1 versus inverse temperature for the 614 keV γ-line in the decay of ^{78}Br, for details see text.

of the anisotropy through incomplete relaxation, see sect. 3, below.

^{84g,m}Br

On the neutron rich side the Nb target gives still good yields for ^{84g,m}Br. Therefore a short NO measurement at this mass number was performed to get information on anisotropies etc. Both isomers were produced and implanted with comparable intensity. Because of technical reasons data could be taken only for one fixed temperature T ≈ 8.5 mK. For ^{84g}Br the anisotropy of the 3927 keV transition was used for evaluation. Under the assumption of L = 1 for the β-decay to the 3927 keV level (I = 1) we derive for fixed f = 0.5 a value of the magnetic moment as given in table 2. The spin of ^{84m}Br is not known / 17 /. However for both spin values I = 5, 6 suggested in / 17 / and pure E1-multipolarity of the 424 keV transition the experimental anisotropy of this transition is larger than the theoretical expectation with reasonable assumptions on the fraction f. An admixture of M2-multipolarity in the 424 keV transition with mixing parameter δ (M2 / E1) < 0 could e.g. explain the large anisotropy. Since, however, no information is available we list in table 2 only the experimental anisotropy ratio. No other lines with reasonable intensity are emitted exclusively in the decay of ^{84m} Br, to yield further information / 17 /.

Table 2: Results of evaluation of static NO data in the two frequency model

Isotope	I	|μ [n.m.]|	f	B_{low}[T]	Remarks
^{74m}Br	4	1.82	0.49(14)	24.6	
^{77}Br	3/2	0.9738	0.44(4)	24.6	^{77}Kr implanted
^{78}Br	1	0.08 (4)	0.5	24.6	f fixed, μ varied in fit, full relaxation assumed
	1	0.13(3)	0.5	24.6	incomplete relaxation taken into account, preliminary
^{82}Br	5	1.6270	0.48	24.2	warm implantation ref./ 8 /
			0.54	25.0	cold implantation ref./ 8 /
^{84g}Br	2	1.9 (7)	0.5	24.6	W(0)/W(90)-1=0.59(6) at 8.5mK 3927 keV γ-line
^{84m}Br	(6)				W(0)/W(90)-1=0.53(1) at 8.5mK 424 keV γ-line

3. Discussion

The NMR/ON measurements described in this paper result in very accurate values for the magnetic moments of ^{74m}Br and ^{77}Br. The absolute values are in fact more than 5% larger than the moments adopted in ref./7/ from an evaluation of static NO data in the two frequency model, see columns 6 and 7 of table 1. It can be seen from table 2 of ref./7/ that the value f of the fraction in NMR/ON field sites is rather correlated with the absolute value of the magnetic moment and the assumption of too big a value for f automatically results in a magnetic moment which is too small. On the other side the value of f will depend on the technique of iron foil preparation. All experiments of the Bonn group with Br isotopes have been performed with identically prepared foils ensuring good reproducibility of experimental conditions.

The intrinsic width of the resonance line for ^{74m}Br is difficult to estimate since the frequency steps and modulation width had to be chosen rather wide. The FWHM of the resonance for ^{77}Br, column 4 of table 1 is comparable with the relative width which was obtained with samples prepared by implantation of ^{82}Br at room temperature /10/. This shows that a sample prepared by room temperature implantation of ^{77}Kr and subsequent β-decay to ^{77}Br is of similar quality as a sample prepared directly by implantation of Br.

The fractions in NMR/ON field sites obtained from the static NO data of ^{74m}Br and ^{77}Br, see column 4 of table 2 are not much different within errors and equal to the values which one would have expected from the systematics /10/. This makes us to believe that fixing f to the same value for the evaluation of static NO data for ^{78}Br and ^{84g,m}Br will not cause larger systematic errors.

The measured NO data for ^{78}Br in iron do not completely exclude the possibility that the spin of ^{78}Br is I=0. If, however, we assume the assignment I=1 to be correct /18,19/, the small moment derived from a data evaluation under the assumption of full thermal relaxation of the ^{78}Br nuclei before decay, indicates that relaxation will be slow and therefore has to be taken into account, resulting in a somewhat bigger absolute value of the moment. We have evaluated the data including relaxation in the high temperature limit /20/. In this evaluation the Korringa constant was scaled using experimental results for ^{82}Br**Fe** /8/. The result is given in line 4 of table 2.

The small absolute value of the magnetic moment of ^{78}Br is only slightly larger than the moment measured for ^{80}Rb /21/ which is isotonic to ^{78}Br. The moment of ^{80}Rb has been explained by Ekström et al. /22/ in the deformed nuclear model as due to a $\left[\pi[312]3/2 * \nu[301]1/2\right]1^+$ configuration. Our experimental result favours assignment of the same configuration to the isotone ^{78}Br, showing that a small magnetic moment of ^{78}Br is in accord with theoretical expectation. The $[312]3/2$ proton orbital should also be the ground state of ^{77}Br indicated by the experimental magnetic moment. The same configuration was assigned by Ekström et al. /22/ to ^{77}Rb which has two neutrons less and a similar magnetic moment.

^{84}Br with neutron number N=49 should have nearly spherical shape. T.Hattula et al. /23/ have proposed a $\left[\pi(f\,5/2)^3 * \nu(g\,9/2)^{-1}\right]2^-$ configuration for the ground state and a $\left[\pi(p\,3/2)^{-1} * \nu(g\,9/2)^{-1}\right]6^-$ configuration for the isomeric state of ^{84}Br. The magnetic moment calculated in the shell model for the first configuration assuming $g_s = 0.6\,g_s^{free}$ is $\mu = -2.0\,\mu_N$. This value is in good agreement with the experimental value of $|\mu| = 1.9(7)\mu_N$. The precision of the experimental value is unfortunately rather low because the temperature could not be varied in the experiment. The magnetic moment for the above configuration of the isomeric state is for $g_s = 0.6\,g_s^{free}$ $\mu = +1.52\mu_N$. This value would be large enough to explain the experimentally observed large anisotropy if decay parameters are assumed as proposed in sect. 2.2. A more quantitative comparison of experimental magnetic moments of Br isotopes with theoretical predictions will be given in a future paper. For such a comparison precise measurements of as many moments as possible are desirable which is the purpose of our bromine project at CERN.

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