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NUCLEAR SPINS OF THE BROMINE ISOTOPES $^{74}(\text{m})$, 75 , $^{77\text{m}}$, ^{78}Br

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ABSTRACT

The nuclear spins of some neutron-deficient bromine isotopes have been measured by on-line atomic-beam magnetic resonance techniques at the ISOLDE facility at CERN. The following results have been obtained : $^{74}(\text{m})\text{Br}$ (41.5 min) $I = 4$, ^{75}Br (1.6 h) $I = 3/2$, $^{77\text{m}}\text{Br}$ (4.3 min) $I = 9/2$ and ^{78}Br (6.5 min) $I = 1$. The spin values are discussed briefly in terms of the strong-coupling model.

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1. INTRODUCTION

In our previous work on spin and moment measurements in the light rubidium isotopes [1], strong collective effects were shown to be present towards the center of the region $28 < (N,Z) < 50$ of the nuclear chart. It is therefore of great interest to extend this kind of experiments to nuclides of the neighbouring elements in an attempt to map the systematic trends. We here report on the measurements of nuclear spins of some neutron-deficient isotopes of bromine, located two proton numbers below rubidium.

During the late fifties and early sixties, the atomic-beam group at Berkeley performed a series of spin and moments measurements on radioactive nuclides of bromine [2]. Following cyclotron or reactor irradiation, the bromine was chemically separated from the target material. The atomic-beam was subsequently obtained by dissociation of a mixture of active and natural bromine in a discharge tube. For natural reasons, this experimental procedure was restricted to the study of nuclides with half-lives longer than some hours.

The study of more short-lived species requires some kind of on-line technique. In this particular experiment, we have made use of the atomic-beam magnetic resonance (ABMR) apparatus, connected on-line with the ISOLDE isotope separator at CERN [3].

2. EXPERIMENTAL PROCEDURE

At the ISOLDE isotope separator, a number of radioactive products are formed in spallation reactions when irradiating a target of niobium powder with 600 MeV protons from the CERN synchro-cyclotron. The most volatile products diffuse into the ion source of the separator. In this particular case of bromine, the element selectivity was ensured by making use of the high electron affinity of bromine to produce negative ions by ionization on a surface of lanthanum hexaboride having a low work function [4]. After mass separation, the radioactive beam of negative bromine ions of a preselected mass number was directed to the oven section of the atomic-beam apparatus, where it was collected on the on-line oven foil. The foil was kept at a temperature of about 1500°C by resistance heating in order to directly reevaporate the collected activity in the form of free atoms into the main chamber of the ABMR apparatus. The atomic-beam production requires a foil material with a high surface work function in order to avoid negative ions to be emitted. The procedure is thus opposite to the negative ion production in the ion source of the separator. We tried a number of different oven foil materials before choosing rhenium. This material was shown to be efficient for evaporation of atomic bromine, reproducible and mechanically stable.

It may be of interest to note that in our previous experiments on the alkalis (cf. e.g. ref. [5]), having very low ionization potentials, the situation was

reversed with respect to the present one. Then, the positive ion production in the separator required a surface with a high work function and the atomic-beam production in the ABMR apparatus an oven foil material with extremely low surface work function.

Using a target of 162 g niobium powder bombarded with a 1.4 μ A proton beam, the production yield curve of bromine from the separator showed a maximum of 5×10^9 ions/s at the masses $A = 76-77$. The nuclides studied in this experiment, $A = 74-78$, are located close to this maximum.

The experiments were performed in the $^2P_{3/2}$ electronic ground state of bromine, having a splitting factor $g_J = 1.3335(6)$ [6,7]. The excited state $^2P_{1/2}$ is located too high in energy to interfere with our measurements. External magnetic fields ranging between $\mu_B B/h = 1.3 - 3.6$ MHz were used. At these weak field strengths, the linear Zeeman effect for the hyperfine structure is expected to prevail. Then, the frequencies of allowed transitions within one hyperfine level are given by :

$$\nu_{\text{res}} = g_J \frac{\mu_B B}{h} \frac{F(F+1) - I(I+1) + J(J+1)}{2F(F+1)}$$

neglecting a small term including the nuclear g-factor. It is immediately seen that the observation of a resonance signal gives information on the nuclear spin I , once the external magnetic field is known. In our case, the field was measured before and after each run by observing the standard calibration transition in ^{39}K . In order to ensure the experimental spin values, we recorded for each nucleus resonance signals in at least two settings of the external magnetic field and/or in different hyperfine levels, characterized by the quantum number F .

The atoms transmitted through the ABMR apparatus were collected on aluminium foils and subsequently measured by thin plastic scintillators detecting the β^+ -decay, except in the case of $^{77\text{m}}\text{Br}$ where the 106 keV isomeric transition was detected by a NaI(Tl) crystal.

3. EXPERIMENTAL RESULTS

Below, the experimental results on the nuclides $^{74}(\text{m}), ^{75}, ^{77\text{m}}, ^{78}\text{Br}$ will be discussed separately. A summary of the results is given in Table 1.

3.1 The nuclide $^{74}(\text{m})\text{Br}$

The experiments on the bromine isotope with mass number $A = 74$ were made in an external magnetic field of $\mu_B B/h = 2.1$ MHz. A 30 min collection and counting of samples exposed by frequencies corresponding to the integer nuclear spin values $I = 0-5$ gave resonance signals only for the spin value $I = 4$. The signals were reproducibly observed in the hyperfine levels $F = 11/2$ and $F = 9/2$. The results

are shown in Fig. 1. The radioactive decay curves of the signals had a half-life of 41.5 min which ascribes a nuclear spin $I = 4$ to the long-lived isomer in ^{74}Br . No resonance signals were observed which could be assigned to the more short-lived, $T_{1/2} = 25.4$ min, isomer in ^{74}Br . This fact is explained by the low production yield of this isomer in the spallation reaction. An analysis of the decay curve of an $A = 74$ sample showed that the 25.4 min component is suppressed by at least a factor 30. It is not known which of the two isomers represents the ground state in ^{74}Br .

3.2 The nuclide ^{75}Br

The first experiments on the 1.6 h nuclide ^{75}Br were made in an intermittent running procedure using samples of bromine obtained as daughter products of krypton. Strong signals were observed for the nuclear spin $I = 3/2$ while the $I = 1/2, 5/2$ and $7/2$ intensities were equal to the apparatus background. The strong signal is due to the particular combination of $I = J = 3/2$, giving coinciding resonance frequencies for all hyperfine levels. This experiment, made in an external field of $\mu_B B/h = 1.3$ MHz, was subsequently repeated in the field of $\mu_B B/h = 2.1$ MHz. Here, we exposed two collectors alternately for 5 min periods, in total 2 h, at the spin $I = 3/2$ and $I = 1/2$ frequencies. This procedure reduced errors due to fluctuations in the beam intensity during the long exposure period. The same experiment was made for combinations of spin $I = 3/2$ with the nuclear spin values $I = 5/2$ and $I = 9/2$. In all cases, a high intensity was obtained at the spin $I = 3/2$ frequency compared to those of the other spin values.

3.3 The nuclide ^{77}Br

The nuclear spin of the 57 h ground state in ^{77}Br has previously been measured with the result $I = 3/2$ [2]. Therefore, our experiment was concentrated to the 4.3 min isomer, decaying by an 106 keV isomeric transition to the ground state. The spin search consisted of 10 min collection and counting of samples exposed by frequencies corresponding to the half-integer nuclear spins $I = 1/2 - 9/2$ in the field $\mu_B B/h = 2.1$ MHz. The results from this spin search are shown in Fig. 2. A significant signal is there observed for the nuclear spin $I = 9/2$, while those of the other spin values are equal to the apparatus background. The same results were obtained in a subsequent experiment at $\mu_B B/h = 3.6$ MHz.

3.4 The nuclide ^{78}Br

The resonance signals observed in the 6.5 min nuclide ^{78}Br were strong enough to allow a reduction of the collection and counting periods to 5 min. Experiments made in the external fields $\mu_B B/h = 1.6, 2.1$ and 3.6 MHz ensured a nuclear spin $I = 1$ to ^{78}Br . The resonances were observed in the hyperfine levels $F = 5/2$ and $F = 3/2$. Furthermore, no resonance signals were observed at the frequencies corresponding to the integer spin values $I = 0, 2-6$.

4. DISCUSSION

The present discussion of the nuclear properties of the light bromine isotopes follows closely the corresponding one given for the light rubidium isotopes in ref. [1], to which frequent references will be given.

According to the systematics of the 2^+ energies in the even nuclides in the present region, the nuclear deformation of the bromine isotopes is expected to show a slight maximum at neutron number $N = 42$, while in rubidium, a gradual increase in deformation is expected with decreasing mass number, at least down to the nuclide ${}^{76}_{39}\text{Rb}$ (cf. Fig. 5 of ref. [1]). The bromine nuclides with mass number $A = 74-78$ ($N = 39-43$), studied in this work, should exhibit nuclear deformations of about $\epsilon = 0.3$. Therefore, an interpretation of the nuclear properties in terms of the strong-coupling model will be attempted. The appropriate single-particle energy diagram for odd protons, calculated within the modified oscillator model [8], is given as Fig. 6 of ref. [1].

In bromine, the odd- A nuclides in the mass range $A = 75-81$ are now shown to exhibit $I = 3/2$ ground states; the nuclides ${}^{79}\text{Br}$ and ${}^{81}\text{Br}$ with magnetic moments corresponding to those of the orbital $[301\ 3/2]$. The orbital assignments in ${}^{75}\text{Br}$ and ${}^{77}\text{Br}$ are, however, not evident. Comparing the situation in rubidium [1], a change from $[301\ 3/2]$ to $[312\ 3/2]$ is apparent when going from ${}^{81}\text{Rb}$ to ${}^{77}\text{Rb}$ (the nuclide ${}^{79}\text{Rb}$ has a ground state with $I^\pi = 5/2^+$). Also, the proton orbital $[312\ 3/2]$ has to be involved to explain the small magnetic moment in the doubly-odd rubidium isotope ${}^{80}\text{Rb}$ [1]. An indication that a similar change occurs in bromine is the magnetic moment of ${}^{76}\text{Br}$, $\mu = -0.5482(1)$ n.m. [2], which is well reproduced by the configuration $1^-[p\ [312\ 3/2]\ n[422\ 5/2]]$, $\mu = -0.57$ n.m., while the configuration $1^-[p\ [301\ 3/2]\ n[422\ 5/2]]$ gives a value $\mu = -1.47$ n.m., far from the experimental one. The theoretical moments were calculated using the $A = 78$ potential parameters [9] $\kappa_p = 0.0695$, $\mu_p = 0.425$ and $\kappa_n = 0.0720$, $\mu_n = 0.320$. A nuclear deformation of $\epsilon = 0.30$ was chosen, as well as an effective g_s -factor of $0.6\ g_s^{\text{free}}$. The orbital assignment $[422\ 5/2]$ to the 41st neutron in ${}^{76}\text{Br}$ is suggested by the $5/2^+$ ground states of the neighbouring nuclides ${}^{75}\text{Se}$ and ${}^{77}\text{Kr}$, and the experimental magnetic moment in ${}^{75}\text{Se}$, $\mu = (-)0.67(4)$ [10], which is close to the one predicted by the neutron orbital $[422\ 5/2]$.

Since bromine has two protons less than rubidium, the proton orbital $[312\ 3/2]$ is occupied at deformations smaller than those required for rubidium (cf. Fig. 6 of ref. [1]). This argument further supports the assignment of a $[312\ 3/2]$ proton orbital to the ground states in ${}^{75}\text{Br}$ and ${}^{77}\text{Br}$, and to the proton part of the doubly-odd nuclides ${}^{76}\text{Br}$ and ${}^{78}\text{Br}$. The latter nuclide thus should exhibit properties similar to those of the isotone ${}^{80}\text{Rb}$.

Spectroscopic works [11-13] on the bromine nuclide ${}^{74}\text{Br}$ have established two

isomers; a low-spin isomer, fed in the decay of ^{74}Kr , with a half-life of 25.3 min and a high-spin isomer with a half-life of 41.5 min. The spin-parity assignments $I^\pi = 0^-, 1^-$ and $I^\pi = 4^-$, respectively, have been proposed, of which the latter is confirmed by the present direct measurement. Without the knowledge of the magnetic moment of the spin $I = 4$ isomer, it is difficult to draw any firm conclusion about the configuration assignment. Possible candidates are $4^-\{p[312 \ 3/2] \ n[422 \ 5/2]\}$ and $4^-\{p[301 \ 3/2] \ n[422 \ 5/2]\}$, having theoretical moments of $\mu = 0.24$ n.m. and $\mu = 1.71$ n.m., respectively. The calculations were made using the parameter set given above for ^{76}Br .

Positive parity states associated with the $g_{9/2}$ shell appear at low energies in odd-proton as well as odd-neutron nuclei in the present region. For instance, the ground state bands in the $N = 41$ nuclides ^{75}Se and ^{77}Kr , discussed above, are due mainly to the neutron orbital $[422 \ 5/2]$ [14-16]. In these cases, the Fermi level lies in the middle of the $g_{9/2}$ shell. The odd-proton nuclides of bromine and rubidium, with proton numbers $Z = 35$ and $Z = 37$, respectively, have, on the other hand, a Fermi level closer to the lowest level of the $g_{9/2}$ system, i.e. $[400 \ 1/2]$. The positive parity level structure in ^{77}Br [17], of which, in this work, the band-head spin has been measured directly to be $I = 9/2$, is well reproduced within a particle-rotor model [16] assuming the deformation parameters $\epsilon = 0.30$ and $\gamma = 20^\circ$ [18]. The location of the $I = 5/2$ level below $I = 9/2$ in the ground state band of ^{79}Rb [1], is an indication of a still stronger deformation. In this case, the orbital $[412 \ 3/2]$ contributes to the nuclear wave function, in addition to $[400 \ 1/2]$. It is of interest to note the great similarity between the positive parity system due to $g_{9/2}$ in ^{79}Rb [1,19] and the negative parity system due to $h_{9/2}$ in ^{185}Au [20-22], both being associated with particle states occupying, at strong deformations, the low- Ω levels from high-spin shell model states.

In a recent paper, Kreiner and Mariscotti [23] explain the rotational structure built on the $I^\pi = 4^+$ isomer in the doubly-odd nuclide ^{76}Br in terms of a configuration with both proton and neutron contributions having $g_{9/2}$ parentage.

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Table 1

Results from the spin measurements

Isotope	$T_{1/2}$	Measured spin I
$^{74}(\text{m})\text{Br}$	41.5 min	4
^{75}Br	1.6 h	$3/2$
$^{77\text{m}}\text{Br}$	4.3 min	$9/2$
^{78}Br	6.5 min	1

FIGURE CAPTIONS

Fig. 1 : Results from a spin search in ^{74}Br . The ion-beam intensity decreased gradually during the experiment, as shown by the upper hatched line, giving the apparatus background. Above this line, the spin $I = 4$ resonances are observed; the central one recorded in the hyperfine level $F = 9/2$ and the other two in $F = 11/2$. The detector background counting rate, given by the lower hatched line, amounted to 15 cpm.

Fig. 2 : Results from a spin search in $^{77\text{m}}\text{Br}$. The count rates of the spin $I = 1/2-7/2$ samples are equal to the apparatus background, above which the spin $I = 9/2$ resonance is observed. This resonance is the sum of 3 recordings in the hyperfine level $F = 6$. The detector background, given by the lower hatched line, amounted to 3 cpm.

Fig. 1

Fig. 2

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