Magnetic moment of the 2_1^+ state in ^{98}Sr

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The g factor of the 2_1^+ state in ^{98}Sr was measured by the perturbed angular correlation method at a fission product on-line separator. The result, $g=0.38(7)$, is discussed in the framework of the proton-neutron interacting boson approximation and in relation to $g(2_1^+)$ values for two other $N=60$ isotones, ^{100}Zr and ^{102}Mo.

I. INTRODUCTION

Neutron-rich nuclei around $A=100$ are known to exhibit a sharp transition from vibrational to rotational structure. This transition is caused by the onset of deformation that takes place at about $N=60$ and is thought to be due to the proton-neutron interaction between high-j orbits.[1] A considerable amount of experimental information on energy levels, transition probabilities, and decay schemes exists for nuclei in this region and supports the above interpretation. However, little is known about nuclear moments in these nuclei although they are of particular importance for a detailed understanding of the structural changes. Magnetic moments of 2_1^+ states are of special interest in that they are determined by the collective properties of the nucleus and should provide valuable information for transitional nuclei. To date, only two $g(2_1^+)$ values are known in this region, i.e., for ^{100}Zr (Ref. 2) and ^{102}Mo (Ref. 3). These are $N=60$ isotones and therefore are situated at the transition line.

The purpose of this paper is to report the result of a measurement of the g factor of the 2_1^+ state in another $N=60$ isotone, ^{98}Sr. This result will be discussed in the framework of the proton-neutron interacting boson approximation (IBA-2) and in relation to a recent systematic study[4] of g factors in the range $A=70-200$.

II. EXPERIMENTAL TECHNIQUE AND RESULTS

^{98}Sr has an excess of ten neutrons with respect to the stable ^{88}Sr isotope and is therefore very far from stability. The only way in which it can be reached is by fission of actinides like ^{235}U, which have a large neutron excess. This excess is preserved in the fragments, and thus the fission process gives access to a large variety of neutron-rich isotopes situated mainly in the $A<100$ and $A<150$ region. In order to study these isotopes, mass separators are used, usually on-line to reactors which can provide the intense neutron exposure necessary to produce sufficient quantities of these rare isotopes.

The present experiment was performed at the TRISTAN fission product separator[5] which operates on-line at the High Flux Beam Reactor at Brookhaven National Laboratory. A flux of about 1.5×10^{10} neutrons/cm^2 sec is incident upon a 5 g target of highly enriched ^{235}U. The target is part of an integrated target-ion source system. A variety of ion sources is available, the choice depending on the specific elements to be studied. The fission products are ionized in the ion source, extracted and accelerated to 50 keV, and then mass separated in a 90° magnet. The resulting beam of radioactive atoms is deposited on an aluminized plastic tape, which carries it to the desired counting position.

For magnetic moment measurements,[6] the counting position is in the center of a superconducting magnet capable of providing magnetic fields of up to 6.25 T. The magnet is of the split-coil type and was designed in such a way as to provide minimum γ-ray absorption between the source and the detectors. Since the present experiment focuses on the decay of ^{98}Rb to levels of ^{98}Sr, a thermal ion source[5] which is known to provide high activities of Rb was used. The half-life of ^{98}Rb is 0.11 sec, so the transport time for the distance of 20 cm from the deposition point to the counting position had to be kept as short as possible. In practice, a transport time as short as about 0.25 sec could be used routinely, but nevertheless more than a factor of 4 of the ^{98}Rb activity was lost in transport.

Since the half-life of the 144 keV 2_1^+ state in ^{98}Sr is $T_{1/2}=2.7(1)$ nsec,[7] an external magnetic field of 1.7 T is sufficient to determine the magnetic moment using the integral perturbed angular correlation method. Four hyperpure Ge detectors were placed around the superconducting magnet at about 9.5 cm from the center. The electronics and data acquisition system were set to record coincidence events between any pair of the four detectors. Thus six angles were measured simultaneously. To determine the magnetic moment, the double ratio can be calculated:

$$R^2(\theta)=\frac{I(\theta,B)}{I(\theta,-B)}\Big/\frac{I(-\theta,B)}{I(-\theta,-B)}\ , \qquad (1)$$

where $I(\theta,\pm B)$ is the number of coincidence counts at angle θ between the γ transition feeding and depopulating the 2_1^+ level, with field up (+) or down (−). $R(\theta)$ depends on the product $gT_{1/2}B$, on the angle θ, and on the anisotropy of the angular correlation.[8] As in previous measurements of this type,[9] a 0^+-2^+-0^+ cascade was used to determine the value of $g(2_1^+)$. For this type of cascade, $R(\theta)$ has a maximum at $\theta=150°$, so the detectors were set in such a way that three pairs were at 150°, two pairs at 120°, and one pair at 90°.

The first excited 0^+ state in ^{98}Sr is at 215 keV,[10] so the cascade of interest was 71–144 keV. The low energy of the 0^+-2^+ γ transition caused serious difficulties because of the following: (a) the absorption between the source and the detectors was large (about 50% at 71 keV) and (b) the energies of lead x rays, produced in the shielding, are very close to 71 keV.

In order to minimize the lead x rays, a copper lining, about 5 mm thick, was placed between the lead shielding blocks and the detectors. This considerably reduced the x-ray intensity and made it possible to obtain a relatively clean low-energy spectrum. In Fig. 1 the spectra obtained at $\theta=+150°$ with field up and down during a run of about four weeks duration for one pair of detectors, with the gate set on the 144 keV, 2^+-0^+ transition is shown. For this pair of detectors (with the highest efficiency) the intensity of the 71 keV line was reasonable. However, in other cases, this line was quite weak, and spectra from different pairs with the same θ were summed together in order to obtain better statistics. This procedure may introduce an error because different pairs have slightly different solid angle correction factors. In practice, the solid angle correction factors were calculated from the tables of Camp and Van Lehn[11] and since all the detectors used were quite large, and similar in size and shape, the differences in the correction factors for the various pairs were of the order of 2% for A_{22} and 7% for A_{44}. The different correction factors were taken into account in calculating the g factor. The error introduced by this procedure in the final $g(2_1^+)$ value was estimated to be less than 3%.

The magnetic field at the site of the Sr nuclei stopped in the aluminized tape was taken to be equal to the applied magnetic field. This is a good assumption due to the cubic structure of aluminum. A large number of unperturbed angular correlations were measured to date using the samd kind of tape (e.g., Refs. 12 and 13) and good agreement with theoretical values was found. This indicates that extranuclear perturbations, if at all present, are smaller than the statistical errors. Also, a time-dependent perturbed correlation experiment[14] for an excited state in ^{97}Zr ($T_{1/2}=102$ nsec) did not show any significant attenuation of the correlation due to extranuclear effects.

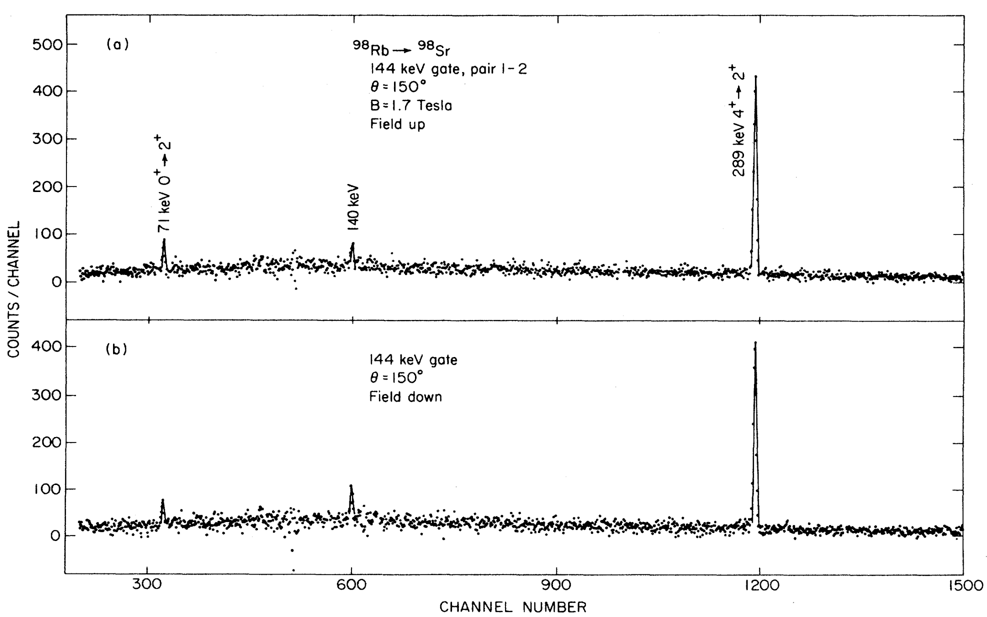

FIG. 1. Low-energy part of the γ-ray spectrum at $\theta=150°$, in one pair of detectors, with field up and field down. The coincidence gate was set on the 2^+-0^+, 144 keV line. The 140 keV γ ray is a transition in ^{98}Sr in coincidence with the 2^+-0^+ transition.

TABLE I. The double ratio $R(\theta)$ for the 71-144 keV and 289-144 keV cascades in ^{98}Sr for $\theta=90°$, 120°, and 150°.

Cascade (keV)	Spin sequence	$R(150°)$	$R(120°)$	$R(90°)$
71-144	0^+-2^+-0^+	1.47(9)	0.9(3)	1.2(5)
289-144	4^+-2^+-0^+	1.06(3)	1.05(5)	0.96(7)

In Table I the values of $R(\theta)$ for the 0^+-2^+-0^+ and 4^+-2^+-0^+ cascades in ^{98}Sr are presented. From $R(150°)$ for the 0^+-2^+-0^+ cascade we obtain

$$g(2_1^+)=0.38(7) . \quad (2)$$

For this g factor, the 289-144 keV, $4_1^+\rightarrow 2_1^+\rightarrow 0_1^+$ cascade should give $R(150°)=1.03$, and the experimental result in Table I is consistent with this value. $R(120°)$ should be close to 1.00 for both cascades, while $R(90°)$ is expected to be exactly 1.00. The results in Table I are consistent with these expectations, within the experimental errors. This provides a good check against systematic errors.

III. DISCUSSION

The $g(2_1^+)$ values for the three $N=60$ isotones ^{98}Sr, ^{100}Zr, and ^{102}Mo are presented in Table II. All three results were obtained by the perturbed angular correlation method. The half-lives used to determine the respective g factors are also given in Table II. Recently, the half-life of the 2_1^+ state in ^{100}Zr was measured[15] using a β-γ-γ triple coincidence technique. The new result [$T_{1/2}=0.55(2)$ nsec] is significantly lower than the previously adopted value[16] [$T_{1/2}=0.67(8)$ nsec]. In Table II we included the weighted average of the new result and the previous results[16] for this half-life. The value of $g(2_1^+)$ for ^{100}Zr was obtained using the previous experimentally determined value [$g=0.22(5)$] from Ref. 2 and correcting for the new $T_{1/2}$. The resulting value of g is larger, but overlaps with the uncertainties of the previous measurement.

We will first compare the experimental data with Greiner's predictions[17] for magnetic moments of vibrational and rotational nuclei. Essentially, these predictions are based on the hydrodynamical expectation value of Z/A for the g factor, with corrections which take into account the different pairing forces of protons and neutrons. In this approach, one assumes of course that all the nucleons contribute to the collective motion. The resulting values are given in Table II. We see that the experimental results for ^{98}Sr and ^{102}Mo are higher than the calculated values, and very close to Z/A. The value for ^{100}Zr, after correction for the newly measured half-life, is consistent within the error with Greiner's prediction.

Now we turn to a discussion of the data in terms of the neutron-proton version of the interacting boson approximation. This model provides us with a simple formula for $g(2_1^+)$ states that are completely symmetrical in the proton, neutron degrees of freedom:[18]

$$g(2_1^+)=g_\pi N_\pi/N_t+g_\nu N_\nu/N_t , \quad (3)$$

where N_π (N_ν) are the numbers of proton (neutron) bosons, $N_t=N_\pi+N_\nu$, and g_π (g_ν) are the respective boson g factors. In contrast to the hydrodynamical model, IBA-2 is a valence particle model, which assumes that only the valence particles contribute to the collective properties of the nucleus. A recent systematic analysis[4] of $g(2_1^+)$ values for 65 nuclei in the range $A=70-200$ has shown that Eq. (3) gives a good description of the experimental data. From this analysis, values of g_π and g_ν were obtained for various regions of the Periodic Table. In the $A=100$ region it was found that $g_\pi=0.48(12)$, $g_\nu=0.33(5)$, i.e., very different from $g_\pi=1.0$, $g_\nu=0.0$, which are to be expected if there were only orbital contributions to the boson g factors. The reason for the reduced g_π and enhanced g_ν is not clear. It may very well be due to spin contributions from specific proton and neutron configurations. In order to calculate $g(2_1^+)$ for the isotopes in Table II within the IBA-2 model, we use Eq. (3) and the values of g_π and g_ν mentioned above for the $A=100$ region. For N_π and N_ν we take the normal numbers of bosons in the respective major shells (28–50 for protons and 50–82 for neutrons). The resulting values are also given in Table II. For ^{98}Sr and ^{102}Mo the agreement between experimental data is very good. However, the result for ^{100}Zr is significantly lower, 0.26(6), and is more than two standard deviations lower than the calculated number.

A comparison of the two different models used in Table II shows that for two isotopes (^{98}Sr and ^{102}Mo), IBA-2 gives a better prediction than the hydrodynamical model.

TABLE II. The experimental values of $g(2_1^+)$ for ^{98}Sr, ^{100}Zr, and ^{102}Mo compared with theoretical calculations (see text).

Isotope	$T_{1/2}(2_1^+)$ (nsec)	Experimental $g(2_1^+)$	Hydrodynamical model	Z/A	IBA-2
^{98}Sr	2.7(1)[a]	0.38(7)	0.30	0.39	0.41(6)
^{100}Zr	0.61(8)[b]	0.26(6)[d]	0.31	0.40	0.41(6)
^{102}Mo	0.114(13)[c]	0.42(7)[e]	0.32	0.41	0.40(6)

[a]From Ref. 7.
[b]Weighted average of new result (Ref. 15) and data in Ref. 16.
[c]From Ref. 16.
[d]See text.
[e]From Ref. 3.

A similar result was recently reported[19] for the neutron-rich ^{142,144,146}Ba isotopes where the $g(2_1^+)$ dependence on mass number was found to be much stronger than expected from the Z/A dependence, and in good agreement with IBA-2. The g factor for ^{100}Zr, while in better agreement with the hydrodynamic model, can still be understood in terms of IBA-2 if we consider the fact that in this nucleus the $Z=38/40$ subshell may still be active, thus reducing the effective number of proton bosons (N_π). According to Eq. (3), a reduced N_π would give a corresponding reduction of $g(2_1^+)$ and thus account for the lower experimental value. In fact, if we assume $N_\pi=0$ for ^{100}Zr, then the IBA-2 prediction for this nucleus is $g(2_1^+)=g_\nu=0.33(5)$, which is close to the hydrodynamical value and about one standard deviation larger than the experimental result.

In conclusion, we have measured $g(2_1^+)$ for ^{98}Sr and found a value which is in good agreement with the IBA-2 predictions obtained from the systematics[4] of $g(2_1^+)$ data in the $A=100$ region. The new result, when compared with existing data for other $N=60$ isotones, shows the following: (a) IBA-2 and even the simple Z/A estimate give a better description of $g(2_1^+)$ than the hydrodynamical model with Greiner's corrections and (b) the value for ^{100}Zr is anomalously low, suggesting that the dissipation of the $Z=38$ subshell here is less complete than in ^{98}Sr and ^{102}Mo. The reason for this behavior of ^{100}Zr is unclear at present and warrants further investigation.

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