TRISTAN RESEARCH ON NEUTRON RICH NUCLEI:
MAGNETIC MOMENTS AND NUCLEAR STRUCTUREBNL--40316
DE88 002122A. Wolf*, R. F. Casten, and R. L. Gill
Brookhaven National Laboratory, Upton, New York, 11973, USAD. S. Brenner and H. Mach
Clark University, Worcester, Massachusetts, 01610, USAJohn C. Hill, F. K. Wohn, and J. A. Winger
Ames Laboratory, Iowa State University, Ames, Iowa, 50011, USA

ABSTRACT

The TRISTAN research program is briefly outlined. The discussion then turns to the measurements of magnetic moments of excited states in neutron-rich fission product nuclei using the perturbed angular correlation method. The results for 2^+_{11} states are analyzed in light of the systematics of magnetic moments in the $A=70-200$ region, and in relation to collective nuclear models.

INTRODUCTION

TRISTAN, an isotope separator on-line to the Brookhaven National Laboratory High Flux Beam Reactor, is used to study neutron-rich fission product nuclei far from stability. With an array of excellent ion sources, it provides access to about 400 isotopes far from stability. The facility currently operates as a joint BNL-Ames Laboratory-Clark University collaboration. The four main (inter-related) areas of research (and recent results) are:

- Study of phase transitions, collectivity, and the onset of deformation in nuclei, with special emphasis on the crucial role of the p-n interaction.

Results: a) Development of the $N_p N_n$ scheme and the related idea of the P-factor¹. This approach to nuclear systematics simplifies the interpretation of each transitional region, unifies the interpretation of different regions, provides quantitative "rules" for the onset of deformation and clearly distinguishes the monopole and quadrupole components of the p-n interaction. Recent work on nuclear masses in this scheme is also promising and seems to have predictive power. b) $g(2^+_{11})$ -factor measurements near $A=100, 150$ providing quantitative empirically-based information on the effective numbers of valence protons and neutrons and on the evolution of shell gap structure²⁻³. c) Spectroscopy near $A=100, 150$ leading to further information on the nature, mixing and co-existence of spherical and deformed states⁴, and on the possibility of pairing free rotations⁵. d) New techniques for lifetime measurements in the 100 psec range⁶.

*On leave from Nuclear Research Center Negev, Beer Sheva, Israel

- Symmetries in Nuclei

Results: Discovery of the first good example (30 years after its proposal) of a vibrational nucleus, namely ^{118}Cd , in which Aprahamian and co-workers⁷ discovered the complete 3-phonon quintuplet and possible evidence for higher phonon excitations.

- New Magic Regions

Results: Spectroscopy and g-factor studies near ^{78}Ni (^{82}Ge and ^{83}As) and ^{132}Sn (^{136}Xe , ^{138}Ba , and ^{132}Te).⁸⁻⁹ Recent shell model calculations indicate ^{132}Sn to be a valid doubly magic core, but are not as successful for the $A=50$ isotones above ^{78}Ni .

- Astrophysics Related to r-process Nucleosynthesis

Results: Half-life, Q_β value and decay scheme for ^{80}Zn ,¹⁰ one of the three crucial "waiting point" nuclei whose properties provide key constraints on the stellar supernova "exposure time" for r-process nucleosynthesis. New isotopes near the r-process path at $A=130$ are currently under study.

In this report we will primarily concentrate on the presentation of the results of magnetic moment measurements which were undertaken five years ago at TRISTAN, and have so far provided data for neutron-rich nuclei far from stability. These data could not be obtained by techniques other than mass separation of fission products. The results will be discussed in light of a systematic analysis of g-factors of 2^+_1 excited states in 65 nuclei in the range $A=70-200$, and the existing $B(E2)$ data for these nuclei. Fine structure effects in the $g(2^+_1)$ vs. A dependence were observed in the $A=100, 150$, and 170 regions. These effects can be related to the underlying shell structure, and, in the case of the neutron-rich Er and Yb isotopes, to a "saturation" in the proton-neutron interaction which takes place towards the middle of the $N = 82-126$ shell.

EXPERIMENTAL TECHNIQUES AND RESULTS

The TRISTAN ISOL facility was described in some detail in previous publications¹¹. It provides intense beams of short-lived neutron-rich nuclei produced by thermal neutron fission induced by a $3 \times 10^{10} \text{ n}_{\text{th}}/\text{cm}^2\text{-sec}$ neutron beam incident on a $5\text{g } ^{235}\text{U}$ target. During the past six years, several ion sources have been developed, each of which is best suited to producing certain elements: a) the surface ionization source¹² mainly produces high activities of Rb and Cs isotopes; b) the thermal source¹³ was designed to optimize the yield of rare-earth elements; c) the high-temperature plasma source¹¹ produces a large variety of elements (e.g., Zn, Ga, Ge, Ag, In, I, Xe) with relatively high yields. Typically, most yields at the output of the separator are of the order of 10^3 - 10^8 atoms/sec depending on mass number, half-life, and type of source used. The radioactive beam is deposited on an aluminized plastic tape, and the accumulated activity is subsequently transported to the desired counting

position. For the magnetic moment measurements, the counting position is in the center of a superconducting magnet capable of providing a field of up to 6.25 Tesla with inhomogeneity <1% in a volume of about 1 cm³.

Four large (80-120 cm³) hyperpure Ge detectors are set at about 10 cm from the center of the magnet to detect gamma radiations from the source. The magnet was specially designed so that the absorption between the source and the detector is minimal. This is particularly important for very deformed nuclei, where the transitions between low-lying levels have relatively low energy.

The electronics and data acquisition system associated with the four detector system has been described previously¹⁴. It is capable of recording coincidence events between any two detectors. Thus, six angles are measured simultaneously. To determine a magnetic moment, we use the integral perturbed angular correlation method (IPAC) and calculate the double ratio:

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

where $I(\theta, \pm B)$ is the actual number of coincidence events in the specific $\gamma\text{-}\gamma$ cascade, at angle θ , with magnetic field up or down. In general, it is convenient to use $0^+ \rightarrow 2^+ \rightarrow 0^+$ cascades, which have a very large anisotropy and give large effects. For these cascades, $R(\theta)$ has a maximum at about 150°. Consequently, three of the six angles were set at 150°, two at 120°, and one at 90°. The effect is also strongly dependent on the g-factor, the applied magnetic field, and the half-life of the intermediate state. The maximum available field (6.25T) imposes the limitation $T_{1/2} > 0.05$ nsec for excited states that can be investigated using the IPAC technique. In Fig. 1 we

Fig. 1. Results of PAC measurement for ¹⁴²Ba.

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Table I Experimental g-factors measured at TRISTAN

Isotope	Level Energy (keV)	J^π	g_{exp}
^{97}Zr	1264	$7/2^+$	0.39(4)
^{98}Sr	144	2^+	0.38(7)
^{132}Te	1775	6^+	0.79(9)
^{136}Xe	1694	4^+	0.80(15)
^{138}Ba	1899	4^+	0.80(14)
^{142}Ba	359	2^+	0.426(48)
^{144}Ba	199	2^+	0.33(5)
^{146}Ba	181	2^+	0.27(7)
^{146}Ce	259	2^+	0.24(5)
^{148}Ce	158	2^+	0.37(6)

present the perturbed angular correlation recently measured with field up and field down for two $0^+ \rightarrow 2^+ \rightarrow 0^+$ cascades in ^{142}Ba . The results for the two cascades were summed to improve statistics. The solid (dashed) lines were calculated for field up (down) using $g(2^+_1) = 0.42$. The experimental errors are smaller than the size of the points. In this case, $T_{1/2}(2^+_1) = 0.066$ nsec and the effect at 150° was quite small: $R(150^\circ) = 1.053(6)$. A much larger effect, $R(150^\circ) = 1.47(9)$, was obtained, for example, for the 71-144 keV, $0^+ \rightarrow 2^+ \rightarrow 0^+$ cascade in ^{98}Sr , with a field of only 1.7T, mainly because in that case $T_{1/2}(2^+_1) = 2.7$ nsec.

In Table I we present g-factor values that have been measured at TRISTAN. In the following discussion we will concentrate only on the $g(2^+_1)$ data and present an analysis in the context of systematics of magnetic moments across the periodic table.

SYSTEMATICS OF g-FACTORS OF 2^+_1 STATES IN THE RANGE A=70-200

The simplest prediction for the g-factor of the lowest-lying 2^+ state in a collective (vibrational or rotational) nucleus is just Z/A . This is the hydrodynamical approach, which assumes that all, and only, the protons contribute to the magnetic moment. A correction to this model was suggested by Greiner¹⁵, who took into account the different pairing forces between protons and neutrons. This effect causes a reduction of the g-factors by about 15-20%. The experimental data does indeed show such a reduction. However, in many cases, deviations from the simple Z/A dependence have been observed¹⁶. An alternative approach, which gives a much more accurate prediction of $g(2^+_1)$ in many nuclei, is provided by the neutron-proton version of the Interacting Boson Approximation (IBA-2). In this model, $g(2^+_1)$ is given by the simple relation¹⁶:

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

Fig. 2. Systematics of $g(2^+_{11})$ data for six groups of nuclei in $A=70-200$ mass range. The lines are linear fits of $g(2^+_{11}) \times N_t/N_v$ vs N_π/N_v .

for totally symmetric states in the proton, neutron degrees of freedom. $g_\pi(g_v)$ are the proton (neutron) boson g-factors, $N_\pi(N_v)$ are the respective numbers of bosons, and $N_t = N_\pi + N_v$. The essential difference between this IBA expression (2) and the hydrodynamic model does not depend specifically on the boson assumption or on the detailed IBA Hamiltonian but rather resides in the fact that the former assumes that the g-factor, and indeed all collective properties, arise from the valence nucleons whereas the hydrodynamic approach assumes that the entire nucleus participates equally. The difference is thus that between geometric and core plus valence particle pictures. In order to test to what extent the experimental data indeed follows the above linear relation, we analyzed¹⁷ $g(2^+_{11})$ values for 65 nuclei in the range $A=70-200$, using equation 2. In order not to obscure gross variations of g_π, g_v with mass number, the data was divided into six groups, following the major proton and neutron shells. Nuclei in the immediate vicinity of closed shells were not included in the analysis. For each group, a linear fit was made, assuming g_π, g_v are constant for all nuclei in the group. The linear fits (Fig. 2) clearly show that equation 2 gives a good description of the data. Quantitatively, values of g_π, g_v were obtained for each group. In general, a smooth behavior of g_π, g_v vs A is observed¹⁷, with g_π slightly increasing and g_v decreasing for the heavier nuclei. For nuclei with $A > 130$, we obtain $g_\pi = 0.5-0.7$, $g_v = 0.05-0.15$. These results are in contradiction with the simple expectation $g_\pi = 1.0$, $g_v = 0.0$, based on the assumption that there are only orbital contributions to the collective g-factors.

A significant deviation from the smooth dependence of g_{π}, g_{ν} vs A occurs for the neutron-rich Er, Yb isotopes. This is evident from Fig. 2e, where the slope of the line is much smaller, and the intercept much larger ($g_{\pi} = 0.30$, $g_{\nu} = 0.35$), than those in 2c (Ba-Dy) and 2f (Hf-Pt), which contain deformed nuclei with similar structure. This anomalous behavior will be discussed in a following section.

Now we proceed to discuss the TRISTAN results in light of the systematics presented above.

$g(2^+_1)$ DATA IN THE A=100 REGION (in collaboration with K. Sistemich)

The latest result from TRISTAN in this mass region is $g(2^+_1) = 0.38(7)$ for ^{98}Sr . Two other g-factor values for N=60 isotones are known to date: $g(2^+_1) = 0.22(5)$ for ^{100}Zr ,¹⁸ and $g(2^+_1) = 0.42(7)$ for ^{102}Mo .¹⁹ The values for Sr, Mo fit well in the systematics of Fig. 2d. In fact, if we use $g_{\pi} = g_{\nu} \approx 0.4$ for A=100 nuclei¹⁷, we obtain $g(2^+_1) = 0.4$, in excellent agreement with the experimental data. The reason for these particular values of g_{π}, g_{ν} is unclear at present. They may be due to the underlying shell structure in this region.

The strongly reduced value for ^{100}Zr can not be explained with the above values of g_{π}, g_{ν} . It has been suggested¹⁹ that the Z=38 subshell is still active in this nucleus, thus reducing the effective number of valence protons, and consequently the g-factor. However, when $g_{\pi} = g_{\nu}$, equation (2) reduces to $g(2^+_1) = g_{\pi}$, and thus the low value for ^{100}Zr is difficult to reconcile with the new result for ^{98}Sr and the systematics in the A=100 region. It might be possible to resolve this problem with a detailed shell model calculation in which the contributions of the different proton and neutron configurations are taken into account, but, at present it remains a puzzling experimental result.

DISSIPATION OF THE Z=64 SUBSHELL IN THE A=150 REGION

The existence of a proton subshell closure at Z=64 has been well established²⁰. It was found²¹ that this subshell is active for $N \leq 88$, but "disappears" when $N > 90$. Since in IBA-2, $g(2^+_1)$ depends on N_{π}, N_{ν} (equation (2)), we expect g-factor data in the A=150 region to be affected by the existence of the Z=64 subshell, due to a change in N_{π} of a given element when N changes around 90. Such an effect was observed experimentally²² for Ce, Nd, and Sm isotopes. This suggests that we can in fact use experimental $g(2^+_1)$ data to extract the number of valence protons using equation (2), and thus follow the dissipation of the Z=64 subshell. In order to do this we need: a) to obtain a set of g_{π}, g_{ν} values; b) to make an assumption about the values of N_{ν} , or use a second equation so as to calculate both N_{π} and N_{ν} simultaneously.

g_{π}, g_{ν} can be deduced from our systematic analysis (Fig. 2). For the A=150 region we have: $g_{\pi} = 0.63$, $g_{\nu} = 0.05$. These values were obtained from a linear fit (Fig. 2c) in which isotopes with $N \leq 88$ have not been included. Although it is reasonable to assume that N_{ν} can be simply counted in the major N=82-126 shell,

Fig. 3. Effective numbers of valence protons and neutrons in $A=150$ region, extracted from $g(2^+_1)$ and $B(E2)$ data.

we will take here a different approach²³. Namely, we will use $B(E2)$ data for the 2^+_1 states involved, in addition to $g(2^+_1)$ data, so that both N_π and N_ν can be obtained. This procedure involves the use of analytical formulas for the $B(E2)$ transition probabilities. We used the expression:

$$B(E2:0^+ \rightarrow 2^+) = 5/N_t (e_\pi N_\pi + e_\nu N_\nu)^2 \quad (3)$$

for the vibrational nuclei²⁴ in the $A=150$ region, and:

$$B(E2:0^+ \rightarrow 2^+) = 0.05 (1 + 1/N_t)^2 (e_\pi N_\pi + e_\nu N_\nu)^2 \quad (4)$$

for the deformed nuclei²⁵. Both formulas are based on the IBA. The effective charges e_π, e_ν were deduced by linear fits to experimental data, similarly to the calculation of g_π, g_ν . Then, we used the $g(2^+_1)$ data from Table I for Ba, Ce isotopes, in addition to $g(2^+_1)$ values for Nd, Sm,²⁶ and $B(E2)$ data from the recent compilation of Raman et al.²⁷, and extracted the effective numbers of valence protons and neutrons, N_p^{eff} , N_n^{eff} , by solving equations (2) and (3) or (2) and (4). The results are given in Fig. 3. We see that while N_n^{eff} follows very closely the values we would obtain by "normal" counting in the 82-126 shell, N_p^{eff} for Ce, Nd, and Sm exhibits a significant drop for $N < 88$. This behavior is consistent with the existence of a $Z=64$ subshell, and shows that the dissipation is gradual in the region $N=86-92$. Moreover, the Ba isotopes do not show any change in N_p^{eff} , as expected since $Z=56$ is below midshell for both 50-64 and 50-82 shells.

Fig. 4. Experimental $g(2^+_1)$ data for $^{142,144,146}\text{Ba}$ isotopes.

COMPARISON BETWEEN IBA AND HYDRODYNAMICAL MODELS FOR $^{142,144,146}\text{Ba}$ ISOTOPES

As we mentioned in a previous section, both IBA-2 and the hydrodynamical models give reasonable predictions for the gross mass dependence of $g(2^+_1)$. Therefore, in order to differentiate between these models, fine structure effects should be investigated. One example is the N -dependence of $g(2^+_1)$ for the transitional nuclei in the $A=150$ region which was discussed above. We saw that the valence particles play a major role in determining the g -factors, in good agreement with the IBA. Another example is the mass dependence of $g(2^+_1)$ for the neutron-rich $^{142,144,146}\text{Ba}$ isotopes. These g -factors were measured at TRISTAN (see Table I), and the results are plotted in Fig. 4 vs neutron number. Also shown in the figure are the Z/A line, the curves that include Greiner's correction¹⁵ for vibrational and rotational nuclei, and the IBA-2 curve based on equation 2. We used $g_\pi = 0.63$, $g_v = 0.05$ in equation 2. From Fig. 4 we see that: a) the mass dependence of $g(2^+_1)$ is very different from Z/A , but in good agreement with IBA-2; b) for ^{142}Ba , $g(2^+_1)$ is about two standard deviations larger than the hydrodynamical value which includes Greiner's correction. These results illustrate clearly that accurate g -factor measurements can help to distinguish between different nuclear models.

ANOMALOUS g_π, g_v IN NEUTRON-RICH Er, Yb ISOTOPES

In the systematic analysis presented earlier we noticed that in the Er, Yb region $g_\pi = 0.30$, $g_v = 0.35$, i.e., very different from $g_\pi \approx 0.6-0.7$ and $g_v \approx 0.05-0.10$ which were observed for the deformed nuclei in the $A=150-200$ region (see Figs. 2c, 2e, 2f). This is rather surprising in view of the fact that the neutron-rich Er, Yb

Fig. 5. Effective numbers of valence particles in neutron-rich Er, Yb isotopes, extracted from $g(2^+_{11})$ and $B(E2)$ data.

isotopes considered are not very different in structure from the neighboring Gd, Dy, Hf, and W isotopes. A possible interpretation of this anomaly is that, like the $A=150$ region discussed earlier, there is a change here in the effective N_π, N_ν , with respect to "normal" counting. In order to follow this assumption quantitatively, we will assume "normal" g_π, g_ν values ($g_\pi = 0.65$, $g_\nu = 0.08$) and calculate N_p^{eff} , N_n^{eff} from the experimental data. Again, we use $B(E2)$ data and relation (4) as a second equation in addition to $g(2^+_{11})$ data and relation (2). The results are shown in Fig. 5. We see that while N_p^{eff} for both Er and Yb are quite close to the "normal" values of 14 and 12, respectively, the N_n^{eff} values tend to "saturate" for $N > 100$, and are about 20-30% below "normal". This reduction can be explained in terms of a "saturation" in the integrated proton-neutron interaction near midshell as the protons and neutrons fill orbits with varying spatial overlap. That is, the p-n interaction summed over all occupied orbits no longer scales with $N_p N_n$. This can be expressed in terms of lower "effective" $N_p N_n$ values and is reflected in the present approach to the data in terms of reduced effective N_n values. A quantitative calculation²⁸ of the proton-neutron interaction in a deformed field supports this argument and clearly shows a "saturation" of $(N_p N_n)^{\text{eff}}$ for $N \geq 100$.

CONCLUSIONS

The results presented in this work show that magnetic moments of excited states in neutron-rich nuclei provide valuable nuclear structure information. In this paper we concentrated only on the

significance of $g(2^+_1)$ data and its relation to collective nuclear models. The results for other than 2^+_1 states (Table I) were found to be of importance for understanding the shell structure of the respective nuclei. In the future we plan to do more experiments in odd-mass nuclei and also to study higher spin states in even-even nuclei, particularly around the double-magic ^{132}Sn nucleus.

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