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Striking harmony between the nuclear shell model and new experimental g factors and $B(E2)$ values of even Ni isotopes

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High precision g factors and $B(E2)$ values were obtained in measurements of the first 2^+ states of $^{58-64}$Ni using the technique of projectile Coulomb excitation in combination with transient magnetic fields. The new results are well explained by large-scale shell model calculations in which, for $^{58-62}$Ni, up to $t=5$ nucleons are excited from the $f_{7/2}$ shell into the remaining fp shell orbits. A complete calculation was carried out for ^{64}Ni. The g factor of ^{58}Ni is particularly surprising as it is small but definitely positive, a result which was not expected and therefore not considered in several earlier calculations. This observation can be explained by strong coupling of valence particles to an excited ^{56}Ni core in accordance with recent Monte Carlo shell model calculations.

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The study of fp shell nuclei has become of major interest since large scale shell model calculations are now available to describe microscopically the competition between single particle and collective excitations in the full fp configuration space [1–3]. The great success of such complete calculations has been recently demonstrated for the lighter ^{50,52}Cr nuclei which reproduce the very precise g factors of the first 2^+ and 4^+ states [4,5]. On the other hand, the same quality of agreement between theory and experiment was not achieved for the ^{46,48,50}Ti isotopes where the calculations generally underestimated both the measured g factors and the $B(E2)$ values [4,5]. Similar discrepancies were found, in the interpretation of g factors of the first 2^+ states of the $N=28$ even-A isotones ^{50}Ti, ^{52}Cr, and ^{54}Fe [7] relative to those of the odd-A neighbors, which was discussed in the context of core polarization. Such distinct differences in the description of the microscopic structure of these nuclei are not expected and the reasons for the observed deviations are not fully understood. It was suggested that disregarding contributions from the sd shell core ^{40}Ca and deficits in the effective interactions commonly used in the calculations might be responsible for the uneven agreement.

For heavier fp shell nuclei in the iron, cobalt, and nickel region, shell model calculations have been attempted by several groups [8–10] to reproduce extensive experimental data. As emphasized earlier, for example in [9], the excitation of both protons and neutrons from the $f_{7/2}$ shell to higher orbitals across the energy gap at $Z,N=28$ is essential for this endeavor. The experimental situation for the Ni isotopes is sparse. Magnetic moments of the first 2^+ states of all stable even-A isotopes were determined with moderate accuracy [15], whereas the g factors of the $3/2^-$ ground states and $5/2^-$ excited states of the odd isotopes were obtained with much higher precision [16]. It is well known that the accuracy of g-factor measurements often depends on the nuclear state lifetime: high precision resonance techniques were applied for the long-lived states of the odd Ni isotopes while only the technique of transient magnetic fields can be used for the 2_1^+ states of the even isotopes with picosecond lifetimes. The shell model interpretation of the odd nuclei suggests distinct single neutron configurations, $p_{3/2}$ and $f_{5/2}$, in the wave function of the states which are responsible for the observed negative g factors of the $3/2^-$ and positive g factors of the $5/2^-$ states, respectively. This picture changes completely for the 2_1^+ states of the even isotopes: the experimental g factors rise from a possibly negative g factor for ^{58}Ni to positive values for the heavier isotopes, an effect which was attributed to a plausible increase of collectivity toward $g=Z/A=0.44$.

In view of the large experimental errors and the importance for a better nuclear structure understanding, a redetermination of the g factors of the 2_1^+ states of all even Ni isotopes under improved experimental conditions was highly desirable. This goal was achieved by the use of projectile Coulomb excitation in inverse kinematics in combination with the technique of transient magnetic fields. Beams of isotopically pure Ni provided by the ion source of the Munich Tandem accelerator were accelerated to energies of 155 MeV and 160 MeV with intensities of 1 pnA.

The multilayered target consisted of 0.45 mg/cm^2 ^{nat}C evaporated on a 3.82 mg/cm^2 gadolinium foil which had been vacuum deposited on a 1 mg/cm^2 tantalum foil and was backed by 3.5 mg/cm^2 of copper. The Ni beam ions were Coulomb excited to their first 2^+ states in the C layer. They subsequently traversed the ferromagnetic gadolinium layer where they experienced the transient field and were finally stopped in the hyperfine interaction free copper layer. For the nuclear spin precession measurements the target was cooled to liquid nitrogen temperature and magnetized to saturation by an external field of 0.06 T.

The γ rays emitted from the excited 2_1^+ states were measured in coincidence with the forward scattered carbon ions

TABLE I. Measured logarithmic slopes S of the angular correlations at $|\theta_\gamma|=65°$ and measured precession angles Φ^{exp}. The Φ^{lin}/g values were calculated using Eqs. (1)–(3). The last line refers to the measurement on ^{56}Fe with which the transient field was calibrated.

Nucleus	$E_x(2_1^+)$ [MeV]	$\|S(65°)\|$	Φ^{exp} [mrad]	$\frac{\Phi^{lin}}{g}$ [mrad]
		2.336(31)[a]	1.74(68)	28.2(2.5)
^{58}Ni	1.454	2.415(17)[b]	0.92(30)	28.4(2.5)
		2.482(21)[a,c]	1.12(38)	28.2(2.5)
^{60}Ni	1.333	2.381(45)	4.59(71)	28.9(2.5)
^{62}Ni	1.173	2.329(47)	5.10(60)	30.6(2.7)
^{64}Ni	1.346	2.413(46)	5.51(80)	29.8(2.6)
^{56}Fe	0.847	1.871(25)	19.36(1.34)	31.6(4.6)

[a]Beam energy 155 MeV.
[b]Beam energy is 160 MeV.
[c]Vertical mask in front of the particle detector.

using 9 cm×9 cm BaF_2 scintillators. Ions were detected in a Si counter with 100 μm nominal thickness placed at 0° and subtending an angle of 20°. The beam was stopped in a tantalum foil placed behind the target which, however, was thin enough for the carbon ions to pass through to be detected. A Ge detector at 0° to the beam direction served as a monitor for contaminant lines and for measuring the nuclear lifetimes by the Doppler-shift-attenuation method (DSAM). In order to reduce the background γ rays from nuclei produced in fusion reactions with the carbon target, the Si detector was operated at a low bias to separate light charged particles such as protons and α's, which do not stop completely, from the carbon ions. This procedure was successfully used in earlier similar experiments [5].

Particle-γ angular correlations $W(\theta_\gamma)$ were measured for the $2_1^+ \rightarrow 0_1^+$ transition in each nucleus in order to determine the logarithmic slopes at the angle θ_γ where the sensitivity of the precessions are optimal [5]. Precession angles Φ^{exp} were derived from double ratios of coincident counting rates with an external field applied perpendicular to the γ-detection plane, alternately in the ''up'' and ''down'' directions [4,5].

The nuclear g factor of the excited 2^+ state is extracted from

$$\Phi^{exp}=g\cdot\frac{\mu_N}{\hbar}\int_{t_{in}}^{t_{out}}B_{TF}(v_{ion}(t))\cdot e^{-t/\tau}\,dt, \qquad (1)$$

where B_{TF} is the transient field acting for the time $(t_{out}-t_{in})$ during which the ions traverse the gadolinium layer. The exponential accounts for the nuclear decay of the excited state with lifetime τ. The data are summarized in Table I. The accuracy of the $^{58}Ni(2_1^+)$ precession was improved by two additional measurements where in one run the beam energy was increased to 160 MeV with corresponding higher excitation cross section. Furthermore, the γ anisotropy was enhanced by inserting a vertical mask in front of the Si detector (see [6]).

The g factors (Table II) were derived from the experimental precessions, Φ^{exp}, by determining the effective transient field strength on the basis of the empirical linear parametrization [17]:

$$B_{TF}(v_{ion}) = G_{beam}\cdot B_{lin} \qquad (2)$$

with

$$B_{lin} = a(Gd)\cdot Z_{ion}\cdot\frac{v_{ion}}{v_0}, \qquad (3)$$

where the strength parameter $a(Gd)=17(1)$ T [5,18], $v_0=e^2/\hbar$, and $G_{beam}=0.69(6)$ is the attenuation factor accounting for dynamic demagnetization of gadolinium by the beam ions. The magnitude of G_{beam} was determined through a precession measurement on the first 2^+ state of ^{56}Fe whose g factor is known, $g=0.61(8)$ [16] (Table I). In this calibration experiment, where the same target was bombarded with ^{56}Fe beams of 155 MeV in conditions which are very similar to those pertaining to the Ni beams, an attenuation factor of $G_{beam}=0.69(10)$ was obtained. Its accuracy was improved by including other experimental data [18] which were taken in conditions similar to the present work.

The nuclear lifetimes of the 2^+ states of all Ni isotopes have been redetermined simultaneously with the precession measurements, using the DSAM technique on the spectra obtained with the 0° Ge detector. Maximum ion velocities between 0.040c and 0.048c implied high sensitivity for lifetimes in the picosecond range. The Doppler broadened lineshapes of the emitted γ-ray lines were fitted for the known reaction kinematics applying stopping powers to Monte Carlo simulations including the second order Doppler effect as well as the finite size and energy resolution of the Ge detector. The feeding from higher states was also taken into account. The computer code LINESHAPE [19] was used in the analysis. The measured lifetimes and the deduced

TABLE II. Comparison of the measured g factors, lifetimes, and $B(E2)$'s to earlier data and to results from large-scale shell model (SM) calculations in which $t=5$ nucleons were excited from the $f_{7/2}$ shell to the remaining fp shell orbits.

Nucleus	I^π	τ [ps]		$B(E2)$ [W.u.]		$g(2_1^+)$		
		[11–14]	present	present	$SM_{t=5}$	[15]	present	$SM_{t=5}$
^{58}Ni	2_1^+	0.96(4)	1.27(2)	7.40(10)	6.60	−0.06(12)	0.0378(85)	0.0350
^{60}Ni	2_1^+	1.03(2)	1.31(3)	10.60(23)	9.39	0.09(12)	0.158(28)	0.0975
^{62}Ni	2_1^+	2.09(3)	2.01(7)	12.54(44)	10.02	0.33(12)	0.167(24)	0.2050
^{64}Ni	2_1^+	1.27(4)	1.57(5)	7.74(25)	5.33	0.45(12)	0.184(31)	0.1405

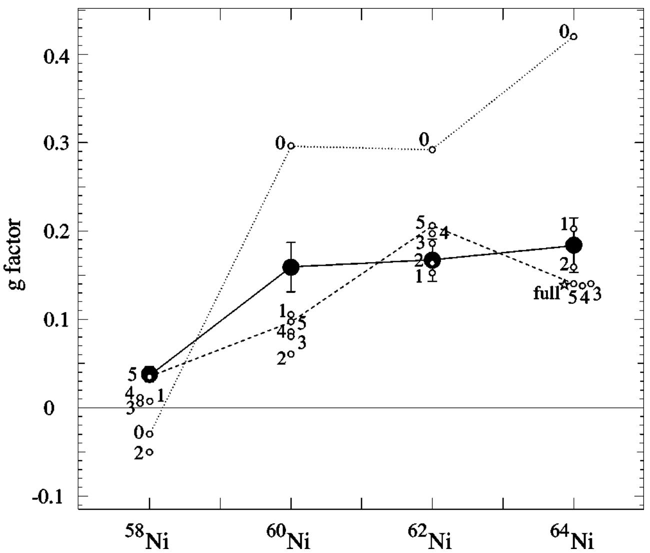

FIG. 1. Measured g factors (solid points) and results from shell model calculations in which the number t of nucleons excited from the $f_{7/2}$ shell into the remaining fp shell orbits (open points) is increased. The result of a full calculation for ^{64}Ni is marked by a star. Lines are drawn to guide the eye.

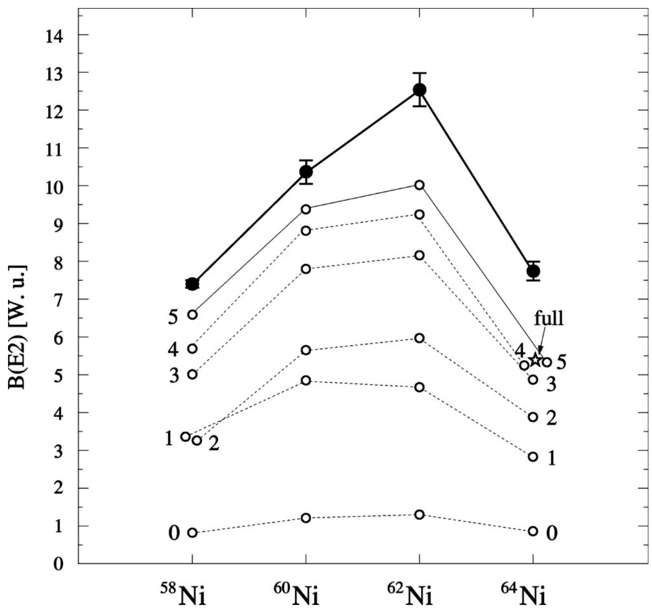

FIG. 2. Measured $B(E2)$'s in Weisskopf units (solid points) and results from shell model calculations in which the number t of nucleons excited from the $f_{7/2}$ shell into the remaining fp shell orbits (open points) is increased. The result of a full calculation for ^{64}Ni is marked by a star. Lines are drawn to guide the eye.

$B(E2)$'s are summarized in Table II. Significant differences between the present measurements and values quoted in the literature are found, in particular, for the ^{60}Ni(2_1^+) state, but in general all lifetimes are slightly longer than those quoted with the exception of ^{62}Ni where the known value was confirmed. Further experimental details will be presented in a forthcoming more extensive paper [20].

The resulting g factors and $B(E2)$'s were compared with large scale shell model calculations in the fp shell configuration space. These were carried out with the computer code ANTOINE [21] using a modified version of the Kuo-Brown interaction KB3 [1].

The general trends of g factors and $B(E2)$'s are well described by the calculations. As shown in Figs. 1 and 2, the agreement with the data is much improved with excitations of t nucleons from the $0f_{7/2}$ orbit to the $1p_{3/2}$, $0f_{5/2}$, and $1p_{1/2}$ orbits. The most striking result emerges for ^{58}Ni(2_1^+), with its small but definitely positive g factor, as the calculated g factors evolve from negative values for $t=0$ and $t=2$ excitations to positive values which finally converge for $t=5$ to precisely the experimental value (Table II). In all other isotopes the agreement between theory and the experimental data is nearly of the same quality, but, as the g factors are all positive, the dependence on the number of excited particles is much reduced and less dramatic than for ^{58}Ni. A full shell model calculation was carried out for ^{64}Ni(2_1^+) which agrees well with the $t=5$ result. It is also evident from Fig. 1 that for an inert $f_{7/2}$ shell ($t=0$), the calculations generally overestimate the g factors. This observation supports the presence of a strong coupling of valence particles to an excited ^{56}Ni core which needs to be taken into account for the description of nuclei around ^{56}Ni. The same conclusion has been drawn by Otsuka *et al.* [22] in Monte Carlo shell model calculations.

The $B(E2)$'s exhibit a similar behavior (Fig. 2). The magnitude of the $B(E2)$'s steadily increases with the number of particle-hole excitations but finally converges at $t \simeq 5$ as shown by the full calculation for ^{64}Ni. The missing strength at the $t=5$ level might be attributed to an underestimation of the effective charge for protons and neutrons used in the calculations, $e_{eff}(\pi)=1.5e$, $e_{eff}(\nu)=0.5e$, or to a lack of quadrupole strength in the residual interaction. As seen from the figure, the general trend of the $B(E2)$'s with increasing neutron number is well reproduced by the shell model calculations. It is noted that the new measurement for ^{60}Ni brings the experimental $B(E2)$ much closer to the calculated value.

Summarizing the experimental part of the present work, it has been shown that the new technique of projectile Coulomb excitation in inverse kinematics provides g factor and $B(E2)$ data of high precision and reliability. The latter is especially characterized by the fact that, in the measurements of series of isotopes, no change of targets is required and the tuning of the different beams in the operation of the accelerator is easily performed. The high precision achieved by this technique allows to measure fine effects in nuclear structure and to test critically large scale shell model calculations. Only with these experimental advantages was it possible to show that former calculations of the g factor of ^{58}Ni(2_1^+) did not agree with the data. The rather sophisticated calculations by Mooy and Glaudemans [8] and by Nakada *et al.* [10] yielded $g=-0.05$ and -0.09, respectively, clearly negative, and in disagreement with the present result.

Summarizing the theoretical situation, shell model calculations are now feasible in a rather large configuration space and therefore highly meaningful. In the present case both g

factors and $B(E2)$'s of the first 2^+ states of stable even Ni isotopes are well reproduced. The surrender of an inert ^{56}Ni core through the excitation of more than two particles from the $f_{7/2}$ shell is rather intriguing. This scenario is particularly striking for explaining the positive g factor of the $^{58}\mathrm{Ni}(2_1^+)$ state.

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[1] A. Poves and A. Zuker, Phys. Rep. **70**, 235 (1981).
[2] E. Caurier, J.L. Egido, G. Martinez-Pinedo, A. Poves, J. Retamosa, L.M. Robledo, and A.P. Zuker, Phys. Rev. Lett. **75**, 2466 (1995).
[3] G. Martinez-Pinedo, A. Poves, L.M. Robledo, E. Caurier, F. Nowacki, J. Retamosa, and A. Zuker, Phys. Rev. C **54**, R2150 (1996).
[4] R. Ernst, K.-H. Speidel, O. Kenn, U. Nachum, J. Gerber, P. Maier-Komor, N. Benczer-Koller, G. Jakob, G. Kumbartzki, L. Zamick, and F. Nowacki, Phys. Rev. Lett. **84**, 416 (2000).
[5] R. Ernst, K.-H. Speidel, O. Kenn, A. Gohla, U. Nachum, J. Gerber, P. Maier-Komor, N. Benczer-Koller, G. Kumbartzki, G. Jakob, L. Zamick, and F. Nowacki, Phys. Rev. C **62**, 024305 (2000).
[6] R.E. Horstman, J.L. Eberhardt, H.A. Doubt, C.M.E. Otten, and G. van Middelkoop, Nucl. Phys. **A248**, 291 (1975).
[7] K.-H. Speidel, R. Ernst, O. Kenn, J. Gerber, P. Maier-Komor, N. Benczer-Koller, G. Kumbartzki, L. Zamick, M.S. Fayache, and Y.Y. Sharon, Phys. Rev. C **62**, 031301(R) (2000).
[8] R.B.M. Mooy and P.W.M. Glaudemans, Z. Phys. A **312**, 59 (1983).
[9] T. Mizusaki, T. Otsuka, Y. Utsuno, M. Honma, and T. Sebe, Phys. Rev. C **59**, R1846 (1999).
[10] H. Nakada, T. Sebe, and T. Otsuka, Nucl. Phys. **A571**, 467 (1994).
[11] R. Bhat, Nucl. Data Sheets **80**, 789 (1997).
[12] M.M. King, Nucl. Data Sheets **69**, 1 (1993).
[13] M.M. King, Nucl. Data Sheets **60**, 337 (1990).
[14] Balraj Singh, Nucl. Data Sheets **78**, 395 (1996).
[15] M. Hass, N. Benczer-Koller, J.M. Brennan, H.T. King, and P. Goode, Phys. Rev. C **17**, 997 (1978).
[16] P. Raghavan, At. Data Nucl. Data Tables **42**, 189 (1989).
[17] J.L. Eberhardt and K. Dybdal, Hyperfine Interact. **7**, 387 (1979).
[18] G. Jakob, J. Cub, K.-H. Speidel, S. Kremeyer, H. Busch, U. Grabowy, A. Gohla, O. Jessensky, and J. Gerber, Z. Phys. D: At., Mol. Clusters **32**, 7 (1994), and references therein.
[19] J.C. Wells and N.R. Johnson, computer code LINESHAPE, ORNL, 1994.
[20] O. Kenn, K.-H. Speidel, R. Ernst, J. Gerber, N. Benczer-Koller, G. Kumbartzki, P. Maier-Komor, and F. Nowacki, Phys. Rev. C (to be published).
[21] E. Caurier, computer code ANTOINE, Strasbourg, 1989.
[22] T. Otsuka, M. Honma, and T. Mizusaki, Phys. Rev. Lett. **81**, 1588 (1998).