Gamow-Teller Strengths in the $A = 14$ Multiplet: A Challenge to the Shell Model

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A new experimental approach to the famous problem of the anomalously slow Gamow-Teller (GT) transitions in the β decay of the $A = 14$ multiplet is presented. The GT strength distributions to excited states in ^{14}C and ^{14}O were studied in high-resolution $(d, ^2\mathrm{He})$ and $(^3\mathrm{He}, t)$ charge-exchange reactions on ^{14}N. No-core shell-model calculations capable of reproducing the suppression of the β decays predict a selective excitation of $J^\pi = 2^+$ states. The experimental confirmation represents a validation of the assumptions about the underlying structure of the ^{14}N ground state wave function. However, the fragmentation of the GT strength over three 2^+ final states remains a fundamental issue not explained by the present no-core shell model using a $6\hbar\omega$ model space, suggesting possibly the need to include cluster structure in these light nuclei in a consistent way.

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The anomalously slow β decay in the $A = 14$ multiplet represents a very old, persistent puzzle. The ground state (g.s.) of the stable $N = Z$ nucleus ^{14}N is characterized by $J^\pi = 1^+$ and $T = 0$, while the unstable mirror nuclei ^{14}C and ^{14}O both have g.s.'s with $J^\pi = 0^+$, $T = 1$, suggesting that the g.s. $\rightarrow$ g.s. β decays can proceed through allowed transitions of the Gamow-Teller (GT) type. However, the measured lifetimes are several orders of magnitude longer than expected [1]. This anomaly has been known for many years, and the resulting long lifetime of ^{14}C enables dating techniques.

Numerous theoretical attempts were made to explain this anomaly in the framework of the shell model based on a special structure of the wave function of the ^{14}N g.s. [2–5]. In the simplest picture, the g.s.'s of the three nuclei are described as two holes in the $1p$ shell. It was emphasized that the suppression of the transitions can be correctly reproduced in an LS coupling scheme if the two holes would carry almost exclusively angular momentum $L = 2$ in the ^{14}N g.s. and $L = 0$ and 1 in the g.s.'s of ^{14}C and ^{14}O. In this case, the g.s. $\rightarrow$ g.s. transitions are suppressed because the GT operator does not change L. It was pointed out that this suppression could not be explained using only central and spin-orbit two-body interactions: Jancovich and Talmi [3] were the first to show that a reasonable tensor interaction could explain the suppression. Such a picture is supported, e.g., by a study of the $^{12}\mathrm{C}(^3\mathrm{He}, p)$ reaction, where the angular distributions for transitions to the g.s. and the 3.95 MeV state of ^{14}N were characterized by angular momentum transfers $\Delta L = 2$ and 0, respectively [6]. This idea was also investigated extensively by Genz *et al.* [7], who extracted phenomenological wave functions which were capable of describing many (but not all) features of the $A = 14$ multiplet simultaneously. García and Brown [8] found that by mixing the two lowest 1^+ states and adding $2\hbar\omega$ contributions they could reproduce the strength of the $M1$ transitions in ^{14}N and fit the $^{14}\mathrm{N}(e, e')$ data but could not account for the large asymmetry in the $\log ft$ values. Starting from the same shell-model calculations, but introducing renormalized axial-current operators, Towner and Hardy [9] were able to account for the β-decay data in the $A = 14$ nuclei.

At present, there is no theoretical framework in which all relevant spectroscopic information is consistently described. The strong retardation of the β decay makes contributions from the tensor part of the effective nucleon-

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nucleon interaction relevant [10,11], as well as processes such as meson-exchange currents, core polarization, or relativistic effects, usually neglected in calculations of GT transitions. New information is highly desirable, in particular, on the properties of the GT strengths and nuclear structure in the mass-14 system.

Here we try to shed light on this long-standing problem by studying GT transitions from the ^{14}N g.s. to *excited* states of ^{14}C and ^{14}O. Such information can be obtained from charge-exchange reactions on ^{14}N at energies of 100–400 MeV/nucleon, since at these energies the excitations are mediated at small momentum transfers by the spin-isospin term of the nucleon-nucleon interaction [10]. While such experiments cannot provide new insight into the suppressed g.s. transitions because of the complexity of the reaction mechanism (see, e.g., [12] and references therein), for strong GT transitions good agreement is found with β decay if the measured charge-exchange reaction cross sections are extrapolated to zero-momentum transfer [13]. The present work is also motivated by a recent no-core shell-model (NCSM) calculation of the GT strength in the mass-14 multiplet, which predicts a dominant excitation of $J^\pi = 2^+$ final states [14].

In the following, results obtained with the ^{14}N$(d, {}^2$He$)^{14}$C and ^{14}N$(^3$He$, t)^{14}$O reactions measured close to 0° are presented. Both reactions have been developed in recent years as high-resolution spectroscopic tools for the determination of B(GT)$^+$ and B(GT)$^-$ strengths, respectively [15,16]. The good energy resolution in both reactions allows one to resolve the GT strength distribution to individual excited states in the final nuclei. The ^{14}N$(^3$He$, t)^{14}$O reaction was already studied at 45 MeV ^{3}He beam energy [17], but at this energy no GT information could be extracted.

The ^{14}N$(d, {}^2$He$)^{14}$C reaction has been measured at Kernfysisch Versneller Instituut (KVI), Groningen. A deuteron beam was accelerated to 172 MeV by the Accelerateur Groningen-Orsay cyclotron. The outgoing particles were momentum analyzed and detected with the Big Bite Spectrometer [18] and the EuroSuperNova detection system [19]. The reaction product ^{2}He is an unbound system of two protons in a relative $^1S_0$ state. These were detected in coincidence. The limited momentum acceptance of the spectrometer restricts the relative energy of the two protons to $\epsilon < 1$ MeV, which guarantees that the two protons are in an $^1S_0$ state [20]. Melamine ($C_3H_3N_6$) targets of 4.5 and 9 mg/cm^2 thickness were used. Data were taken for angle settings $\theta = 0°, 3°, 5°$, and 7.8°. An energy resolution of $\Delta E \simeq 170$ keV [full width at half maximum (FWHM)] was achieved.

The ^{14}N$(^3$He$, t)^{14}$O reaction was measured at the West-South beam line and the Grand Raiden spectrometer of the Ring cyclotron at the Research Center for Nuclear Physics (RCNP), Osaka, using a 420 MeV ^{3}He beam [21]. Scattering angles were very accurately determined, and a resolution of $\Delta E = 33$ keV (FWHM) was obtained at very forward angles, as described in Ref. [22].

The B(GT) values were determined following a standard procedure (see, e.g., [23,24]). For this purpose, the cross sections deduced from spectra from Fig. 1 were extrapolated to zero-momentum transfer using distorted-wave Born approximation (DWBA) calculations [25,26]. Although not essential for most of our arguments below [that address mainly the B(GT) distribution], the absolute B(GT) values were evaluated starting from the assumption that the extrapolated cross sections are proportional to the B(GT) values [13]. We considered that the proportionality factor for ^{14}N and ^{12}C (^{12}C was observed as an impurity in our spectra) remains the same within ≈30% [13,24].

The angular distributions of transitions to excited states in ^{14}C and ^{14}O are presented in Fig. 2. They are used only to identify the $\Delta L = 0$ transitions, which are characterized by cross sections decreasing rapidly with increasing angle. The g.s. → g.s. transitions display an anomalous behavior, in particular, in the ^{14}N$(^3$He$, t)^{14}$O reaction. The B(GT) determination itself is independent from any fit to the experimental distributions, but, due to the rather poor agreement between the DWBA calculations and experimental results, the $\Delta L = 2$ contribution could not be reliably evaluated. However, all transitions to $J^\pi = 0^+, 1^+, 2^+$ excited states in both final nuclei are dominated by a $\Delta L = 0$ shape, and, therefore, we considered them all as pure GT transitions. A detailed description of the techniques and analysis procedures for both experiments can be found in Ref. [27].

In Fig. 3, we present the extracted B(GT) distributions and compare them with the predictions of Ref. [14]. The comparison points towards the presence of a mirror asymmetry not accounted for in the present calculations. Results of detailed studies, using more general potentials, will be discussed in a forthcoming paper. Also, the B(M1) tran-

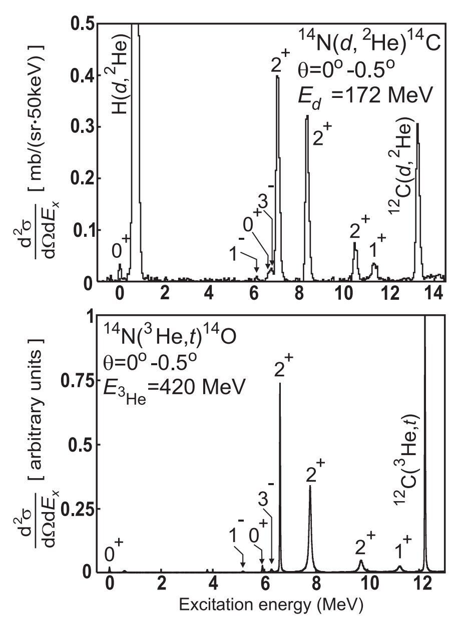

FIG. 1. The $(d, {}^2$He) and $(^2$He$, t)$ spectra of the melamine targets at very forward scattering angles.

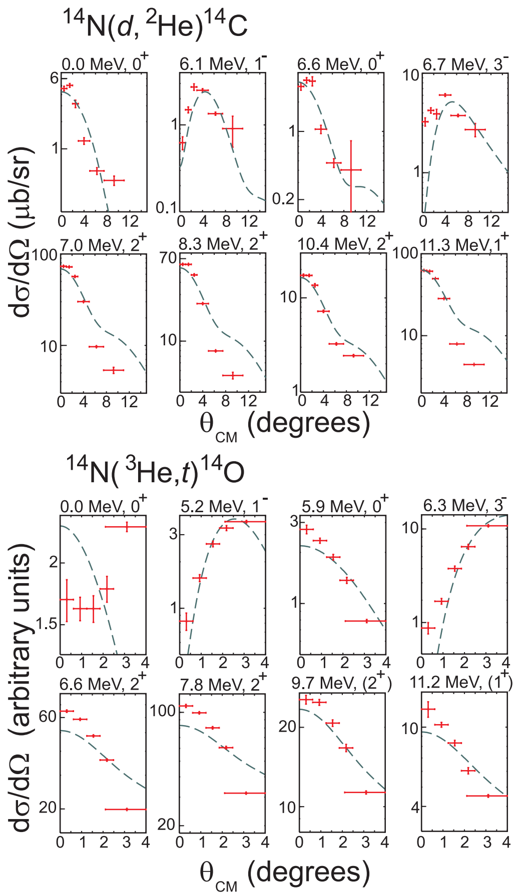

FIG. 2 (color online). Angular distributions for the ^{14}N(d, ^{2}He)^{14}C and ^{14}N(^{3}He, t)^{14}O reactions. The vertical error bars include only statistical contributions. The horizontal bars indicate merely the considered angular intervals. The dashed lines represent the DWBA calculations ($0\hbar\omega$) used for the extrapolation to zero-momentum transfer.

sition strength to the 1^+ isobaric analog state at $E_x = 13.75$ MeV in ^{14}N has been obtained in high-resolution electron scattering [28]. Assuming a pure spin nature of the transition, the corresponding strength B(GT) = 0.078(20) agrees with both values found in this work [0.072(27) for ^{14}C and 0.051(15) for ^{14}O]. The major part of the GT strength is clearly concentrated in transitions to the $J^\pi = 2^+$ final states in agreement with the shell-model result [14], which attributes this strength essentially to a single $(1p_{1/2}^{-1} \rightarrow 1p_{3/2}^{-1})$ transition. The preferential population of states with D-wave character independently confirms the arguments about a dominant D-wave component of the $J^\pi = 1^+$ ^{14}N g.s. wave function discussed above.

On the other hand, the elaborated NCSM calculations do not reproduce the observed fragmentation of the GT strength over three $J^\pi = 2^+$ final states or the first excited 0^+ state, even using a $6\hbar\omega$ model space. The existence of at least two 2^+ states in the low-excitation region of ^{14}O was already known [17]. It is interesting to note that simplified calculations using either a weak-coupling model [29] or considering the lowest 2 particle–4 hole configurations in ^{14}C made of a $^{12}\mathrm{C} \otimes 2n$ configuration, with the two neutrons in the $1d_{5/2}$ and $2s_{1/2}$ orbitals [30] or, more generally, considering a full $0 + 2\hbar\omega$ shell-model space [31] seem to be able to reproduce the experimental finding of a further 0^+ state and three 2^+ states in the excitation region of interest. However, these early studies were very phenomenological in scope (see also Ref. [32]), contrary to the shell-model calculations of Ref. [14]. On the other hand, Itagaki *et al.* [33], using cluster calculations, succeeded in producing three $J^\pi = 2^+$ states in the low-excitation region. There exists indeed recent experimental evidence for alpha-clustering effects in ^{14}C [34,35], but previous experiments indicated that these effects appear only at higher excitation energies, namely, above 15 MeV. Von Oertzen *et al.* [36] argue that two kinds of alpha clustering are possible in ^{14}C: a prolate shape, where the three clusters are aligned, and an oblate shape, where they form an equilateral triangle. This second possibility was investigated in Ref. [33], where a rather good description of the 0_2^+, 2_2^+, and 4_1^+ states forming a rotational band structure characteristic for a triangular shape is obtained. There appears, however, a serious problem with the excitation energy of the first 2^+ state, which exhibits mainly a $2n$ hole character of the $(1p_{1/2}^{-1}, 1p_{3/2}^{-1})_{2^+}$ type.

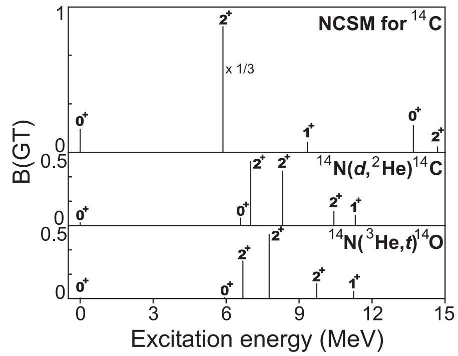

FIG. 3. Experimental B(GT) distributions, compared to the theoretical result of Aroua *et al.* [14], where the B(GT) to the 2^+ state was scaled down by a factor of 3.

One notices that the calculated GT strength to the 2^+ states $\sum$ B(GT) = 2.61 [14] is significantly larger than the experimentally found values: $\sum$ B(GT) = 0.92(33) (^{14}C) and 0.81(36) (^{14}O). This is most probably due to the fact that the structure of the 2^+ states is far too complex to be well reproduced even in a $6\hbar\omega$ NCSM calculation and using the bare GT operator. Also, three-body forces may be necessary to obtain better results. The better agreement between theory and experiment for B(GT) strength to 1^+ states is probably somewhat accidental, since the summed 1^+ strength doubles in going from a $4\hbar\omega$ to a $6\hbar\omega$ space, indicating lack of convergence. The important point is that the NCSM calculations correctly predict a strong summed B(GT) strength for the 2^+ states versus a weak value for the 1^+ states, a direct consequence of the nature of the nucleon-nucleon interaction. It is interesting to note that the early p-shell calculations of Cohen and Kurath [37] produced similar B(GT) values as the present nonconverged $6\hbar\omega$ NCSM calculations.

In conclusion, we have reported high-resolution studies of the $^{14}N(d, ^2He)$ and $^{14}N(^3He, t)$ reactions, exploring the GT distributions in the ^{14}O and ^{14}C final nuclei. In both cases, $J^\pi = 2^+$ final states are predominantly populated, a selectivity which independently confirms the peculiar D-wave nature of the two-hole pair of the $J^\pi = 1^+$ ^{14}N ground state in a shell-model picture put forward as a possible explanation of the anomalous β decay in the mass-14 multiplet. However, neither a reproduction of the total experimental B(GT) strength nor a detailed description of fragmentation into three final 2^+ states is possible with NCSM, even using very large ($6\hbar\omega$) model spaces. Cluster model calculations invoking specific configurations seem to be able to reproduce several of the 0^+ and 2^+ states below 12 MeV missing in the NCSM results. However, no B(GT) values have at present been calculated using cluster models.

This situation calls for a unified description combining typical shell-model and cluster-type configurations. At present, Green-function Monte Carlo calculations have gone up to $A = 12$, but no results for heavier masses are expected in the near future [38]. Another approach that might shed light on this problem uses fermionic molecular dynamics to generate correlated wave functions starting from realistic nucleon-nucleon potentials [39]. The experimental B(GT) distributions presented here might furthermore provide stringent tests of the mixing between the shell-model and cluster configurations.

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[1] F. Ajzenberg-Selove, J. H. Kelley, and C. D. Nesaraja, Nucl. Phys. **A523**, 1 (1991).
[2] D. R. Inglis, Rev. Mod. Phys. **25**, 390 (1953).
[3] B. Jancovich and I. Talmi, Phys. Rev. **95**, 289 (1954).
[4] L. Zamick, D. C. Zheng, and M. Fayache, Phys. Rev. C **51**, 1253 (1995).
[5] M. Fayache, L. Zamick, and H. Müther, Phys. Rev. C **60**, 067305 (1999).
[6] C. H. Holbrow, R. Middleton, and W. Focht, Phys. Rev. **183**, 880 (1969).
[7] H. Genz *et al.*, Z. Phys. A **341**, 9 (1991).
[8] A. García and B. A. Brown, Phys. Rev. C **52**, 3416 (1995).
[9] I. S. Towner and J. C. Hardy, Phys. Rev. C **72**, 055501 (2005).
[10] F. Osterfeld, Rev. Mod. Phys. **64**, 491 (1992).
[11] M. S. Fayache, L. Zamick, and B. Castel, Phys. Rep. **290**, 201 (1997).
[12] J. Rapaport and E. Sugarbaker, Annu. Rev. Nucl. Part. Sci. **44**, 109 (1994).
[13] T. N. Taddeucci *et al.*, Nucl. Phys. **A469**, 125 (1987).
[14] S. Aroua *et al.*, Nucl. Phys. **A720**, 71 (2003).
[15] D. Frekers, Nucl. Phys. **A731**, 76 (2004).
[16] Y. Fujita *et al.*, Phys. Rev. Lett. **95**, 212501 (2005).
[17] G. C. Ball and J. Cerny, Phys. Rev. **155**, 1170 (1967).
[18] A. M. van den Berg, Nucl. Instrum. Methods Phys. Res., Sect. B **99**, 637 (1995).
[19] S. Rakers *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **481**, 253 (2002).
[20] S. Kox *et al.*, Nucl. Phys. **A556**, 621 (1993).
[21] T. Wakasa *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **482**, 79 (2002), and references therein.
[22] A. Negret *et al.*, Phys. Rev. C **71**, 047303 (2005), and references therein.
[23] Y. Fujita *et al.*, Eur. Phys. J. A **13**, 411 (2002), and references therein.
[24] S. Rakers *et al.*, Phys. Rev. C **65**, 044323 (2002), and references therein.
[25] H. Okamura, Phys. Rev. C **60**, 064602 (1999).
[26] J. R. Comfort, a DWBA computer code DW81 (1981) and updated version (1986).
[27] A. Negret, Ph.D. thesis, Universiteit Gent, 2005, http://users.ugent.be/~ddfrenne.
[28] G. Kühner, Diploma thesis, TH Darmstadt, 1977 (unpublished).
[29] S. Lie, Nucl. Phys. **A181**, 517 (1972).
[30] H. T. Fortune *et al.*, Phys. Rev. Lett. **40**, 1236 (1978).
[31] A. A. Wolters, A. G. M. van Hees, and P. W. M. Glaudemans, Phys. Rev. C **42**, 2062 (1990).
[32] D. J. Millener, A. C. Hayes, and D. Strottman, Phys. Rev. C **45**, 473 (1992).
[33] N. Itagaki *et al.*, Phys. Rev. Lett. **92**, 142501 (2004).
[34] M. Milin *et al.*, Nucl. Phys. **A730**, 285 (2004).
[35] N. Soić *et al.*, Nucl. Phys. **A738**, 347 (2004).
[36] W. von Oertzen *et al.*, Eur. Phys. J. A **21**, 193 (2004).
[37] S. Cohen and D. Kurath, Nucl. Phys. **73**, 1 (1965).
[38] S. C. Pieper and R. B. Wiringa, Annu. Rev. Nucl. Part. Sci. **51**, 53 (2001).
[39] R. Roth *et al.*, Nucl. Phys. **A745**, 3 (2004).