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Hyperfine Interactions of the First Excited 2^+ State of ^{18}O in 7^+ and 6^+ Ions

G. Goldring,* D. A. Hutcheon,† W. L. Randolph, and D. F. H. Start
Nuclear Physics Laboratory, University of Oxford, Oxford, England

and

M. B. Goldberg and M. Popp‡
The Weizmann Institute of Science, Rehovot, Israel
(Received 11 October 1971)

Perturbed angular correlations were measured between 1.98-MeV γ rays de-exciting the 3.3-psec 2^+ state of ^{18}O and the $^{18}O^*$ particles following the reaction $^{12}C(^{18}O, ^{18}O^*)^{12}C$ at 33 MeV. A magnetic spectrometer was used to resolve the $^{18}O^*$ ions into the component 8^+, 7^+, and 6^+ charge states, and the correlations were determined separately for each. The measurements yield information on hyperfine interactions in the 7^+ and 6^+ charge states. Limits are obtained on the ionic ground-state occupancies and on the value of the nuclear g factor.

The particle-γ angular correlation of the 1.98-MeV transition from the first excited state of ^{18}O following the reaction $^{12}C(^{18}O, ^{18}O^*)^{12}C$ has been described recently.[1] These data are consistent with (i) pure $I_z=0$ population of the 2^+ state with the symmetry axis z close to the momentum-transfer direction, and (ii) strong hyperfine interaction (HFI) in the 7^+ ionization state. These measurements have now been repeated, with the difference that the predominant charge states 6^+, 7^+, and 8^+ of the scattered ^{18}O have been separated in a magnetic spectrometer and the correlations measured for each. For the 8^+ ions the correlation confirmed an essentially pure $I_z=0$ population. The 7^+ correlation exhibited a strong perturbation, and the 6^+ was almost unperturbed.

The experimental arrangement [Fig. 1(a)] was very similar to that of Ref. 1. A 100-μg/cm^2 carbon target was bombarded by 500 nA of 33-MeV ^{18}O 5^+ ions. The 8^+, 7^+, and 6^+ charge states of the ^{18}O ions in the 1.98-MeV state were resolved with a double-focusing, 188° magnetic spectrometer described by Start *et al.*[2] We placed the spectrometer at 21° to the beam, following Ref. 1. Both the magnetic rigidity and the energy of the particles were recorded by a position-sensitive counter at the spectrometer image. The only resolution problem encountered was overlap of the 6^+ ions with ^{12}C 5^+ ions emitted in the *same* reaction [but at a different c.m. angle, see Fig. 1(b)]. These groups were adequately separated by differential slowing down in a 1-mg/cm^2 nickel foil in front of the counter. The spectrometer entrance slit was 1° wide (in the reaction plane), 10° high, and curved to minimize kinematic broadening. Charge-exchange effects in the residual vacuum at any point around the whole of the magnet are estimated as being less than 0.3%.[3] The arrangement of the 3-in.×3-in. NaI scintillators is shown in Fig. 1(a). Coincidence spectra were recorded using the multiparameter system described in Ref. 2. Singles counting rates did not exceed 3×10^4/sec. The

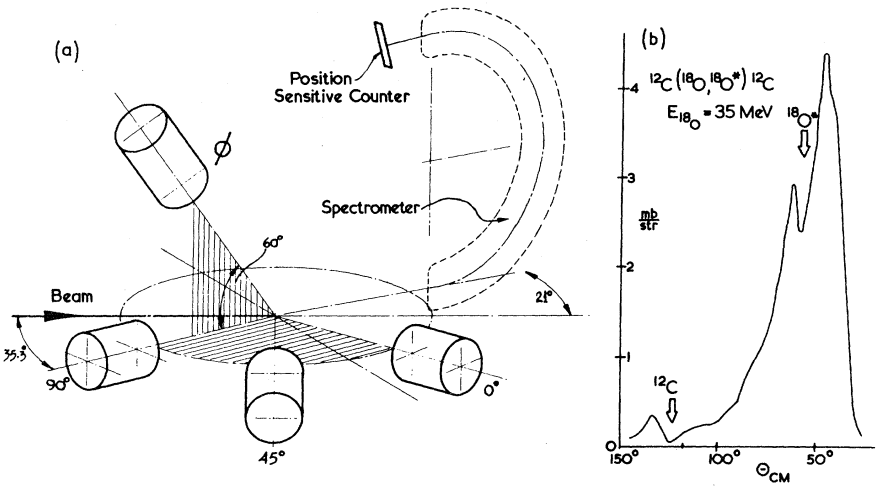

FIG. 1. (a) Schematic view of spectrometer and counter assembly. The three scintillators in the reaction plane are at lab angles of 52.7°, 97.7°, and 144.7° to the beam, or 0°, 45°, and 90° (in the $^{18}O^*$ rest frame) with respect to the symmetry axis (Ref. 1) at 56° lab. The "φ" detector is also at 90° but inclined 60° to the reaction plane. (b) Measured differential cross section (see Ref. 1) of inelastically scattered ^{18}O. Arrows refer to the spectrometer acceptance angles for $^{18}O^*$ and the kinematically coincident ^{12}C.

measured angular correlations for the three charge states are shown in Fig. 2 and in Table I.

Approximate cylindrical symmetry (around an axis very close to the momentum-transfer direction[1]) is demonstrated by the consistency of counting rates in the 90° and "φ" detectors. Consequently, the data have been analyzed according to the familiar expression

$$W(\theta_\gamma) = \sum_k A_k \hat{G}_k(Z) P_k(\cos\theta_\gamma), \quad k = 0, 2, 4, \quad Z = 6, 7, 8, \tag{1}$$

where the coefficients A_k are those for a pure $I_z = 0$, $2 \to 0$ transition (with the z axis along the symmetry line), namely, $A_2/A_0 = \frac{5}{7}$, $A_4/A_0 = -\frac{12}{7}$. The $\hat{G}_k(Z)$, which account for attenuations due to HFI, finite geometry, and nuclear reaction effects, can be written as

$$\hat{G}_k(Z) = G_k(Z) G_k(\text{geom}) G_k(\text{nucl}). \tag{2}$$

Within the statistics on the 8^+ data, where no HFI is involved [$G_k(8) = 1$], the attenuation observed is consistent with finite-geometry effects

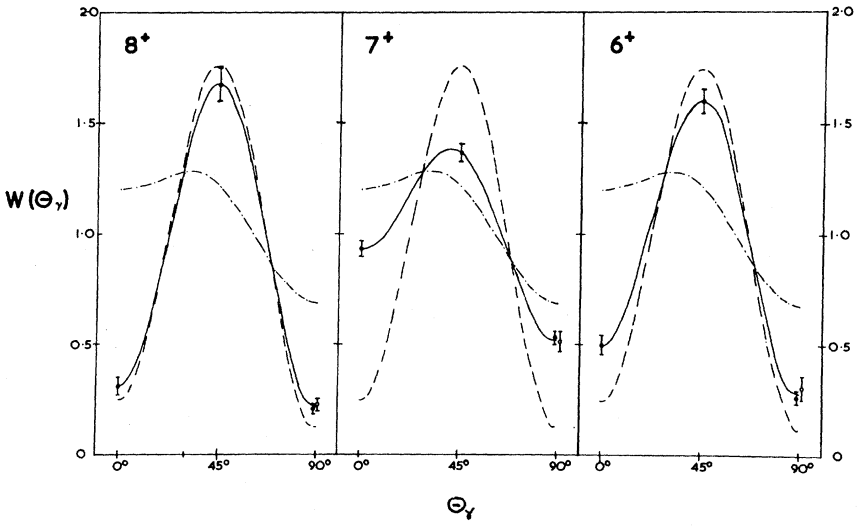

FIG. 2. Angular distributions of γ rays in coincidence with ^{18}O ions in the 8^+, 7^+, and 6^+ charge states. Counting rates have been corrected for movement of the γ-emitting source. Also shown are calculated curves for a pure $I_z = 0$, $2 \to 0$ correlation and for maximum (hard-core) perturbation.

TABLE I. Summary of counting rates.

θ (deg)	$N_Z(\theta)$ $Z=8$	$Z=7$	$Z=6$
0	54 ±7	589 ±21	343 ±28
45	289 ±13	862 ±25	1095 ±41
90	35 ±7	332 ±18	184 ±24
"φ"	43 ±9	322 ±30	215 ±36

of the scintillators, beam, and spectrometer slit. Evidently, the excited ^{18}O nuclei are almost completely aligned along the presumed symmetry axis.

At such short nuclear lifetimes only the contact field associated with a single $1s$ electron is large enough to generate a measurable perturbation.[1] Thus, the time-integral attenuation coefficients for static, randomly oriented HFI in the 7^+ charge state can be expressed as[4]

$$G_k(7) = 1 - \alpha(7)\frac{k(k+1)}{(2I+1)^2}\frac{(\omega\tau)^2}{1+(\omega\tau)^2}, \quad (3)$$

where the HFI frequency is given by

$$\omega = (2I+1)\mu_N g_I H(0)/\hbar. \quad (4)$$

The magnetic field at oxygen nuclei is calculated to be $H(0) = 85.5$ MG.[5] The quantity $\alpha(7)$ represents the ionic ground-state occupancy (or its average over the nuclear lifetime).

Similarly, in the two-electron system (charge state 6^+), any attenuation is due to configurations with an unpaired $1s$ electron. In this case, however, the effective hyperfine field will be reduced (in certain cases to zero) by the fine-structure coupling with the other electron. Thus, without independent information on the distribution of electronic excitations, only limits can be set on the parameters $\alpha(7)$, $\alpha(6)$, and $\omega\tau$—here $\alpha(6)$ represents the fraction of 6^+ ions in $1s$ X ($\neq 1s$) configurations. This leads to $\alpha(7) > 0.65$, $\alpha(6) > 0.14$, and $\omega\tau > 1.86$. With $\tau = 3.25 \pm 0.20$[6] (as measured by Doppler-shift attenuation method and recoil distance) one gets $|g| > 0.20$.

An indication for considerably higher ground-state occupation in the 7^+ ions is furnished by recent measurements on the relative electron pickup cross section to the $2s$ state for 6^+ carbon ions of comparable velocity.[7] A value of $(2.2 \pm 1.0)\%$ was found, implying predominant ground-state population. This result is in good agreement with Born-approximation calculations,[8] according to which some 80% of these ions are formed in the ground state, and another $[\tau/(\tau + \tau_{2p})] \times 7\%$ reach it from the $2p$ state in time to cause a perturbation ($\tau_{2p} = 0.4$ psec[9]). This would imply $\alpha(7) > 0.86$ and consequently $0.20 < |g| < 0.36$. Moreover the 6^+ data would then indicate $0.14 < \alpha(6) < 0.37$, again consistent with the prediction[8] of favored ground-state occupation and thus with the findings of Faessler, Povh, and Schwalm[10] for the first excited state of ^{20}Ne. Furthermore, the semiempirical approach of Dmitriev,[11] which is based on experimental charge-state probabilities, predicts a value $\alpha(7) = 0.85$. Within the framework of this theory the predominance of the ground-state occupancy can be understood in the following way. The ions are presumed to be stripped down to a charge state whose ground has a characteristic velocity v_I which matches the translational velocity of the ions. The ions can also be formed in excited states within a matching width corresponding roughly to a factor of 2 in velocity. For hydrogenlike ions produced with a velocity matching the $1s$ shell, the $n = 2$ shell is barely within the matching width and all higher levels are excluded.

The above considerations also explain the radically different pattern of HFI encountered in heavy nuclei, namely perturbations, characterized by long and complex cascades of optical transitions.[12] In these cases the ions have ground states with principal quantum numbers implying, in general, a large level density and consequently a large number of levels within the matching width.

The upper limit quoted above for the g factor ($|g| < 0.36$) is considerably smaller than the jj-coupling shell-model prediction, as the dominant components of the ^{18}O (2^+) wave function, $(d_{5/2})^2$ and $d_{5/2}s_{1/2}$, imply values of g ranging from -0.76 to -0.51.[13] However, even a small admixture of $d_{5/2}d_{3/2}$ would appreciably lower the calculated g factor.[14] A recent calculation with Kuo-Brown wave functions yielding $g = -0.246$[15] is well within the experimental limits.

The authors wish to express their sincere gratitude to Dr. M. A. Grace for his encouragement throughout this work and for many illuminating discussions. Three of us (G.G., M.G., and M.P.) are indebted to the Nuclear Physics Laboratory for its hospitality.

*On leave from The Weizmann Institute of Science, Rehovot, Israel.

†Currently at the Cyclotron Laboratory, University of Manitoba, Winnipeg, Manitoba, Canada.
‡On leave from Institut für Strahlen- und Kernphysik der Universität Bonn, Bonn, Germany.
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Giant Dipole Resonances in ^{12}C Observed with the Polarized Proton Capture Reaction*

H. F. Glavish, S. S. Hanna, R. Avida,† R. N. Boyd, C. C. Chang, and E. Diener
Department of Physics, Stanford University, Stanford, California 94305
(Received 22 February 1972)

The giant $E1$ resonances of ^{12}C have been studied with the polarized-proton capture reactions $^{11}B(p,\gamma_0)^{12}C$ and $^{11}B(p,\gamma_1)^{12}C$. The effects of proton polarization on the angular distributions were large and of opposite sign for γ_0 and γ_1. Coupled with the unpolarized measurements the polarized results produce additional significant limitations on the allowed configurations of the giant $E1$ resonances in ^{12}C.

One of the remarkable properties of the El giant dipole resonance (GDR) is the approximate constancy over the resonance of the angular distributions which involve the γ channel.[1] This phenomenon is often in marked disagreement with predictions of the simple particle-hole model and has not been entirely explained by refinements of this model.

In this Letter we report the first polarized-proton capture (p,γ) measurements and their application to a study of the configurations of the GDR. With transverse proton polarization the angular distribution of the capture radiation provides limitations on these configurations in addition to those obtained from the unpolarized measurements. Thus, the polarized measurements represent an important expansion of the experimental information which bears on the nature of the GDR and the question of the constancy of its angular distributions.

Because of its simplicity from both an experimental and theoretical point of view and the relative completeness of existing information on it,[2] the reaction $^{11}B(p,\gamma)^{12}C$ was the first one selected for study. Also attractive was the opportunity of obtaining good measurements on both the γ_0 (ground-state) and γ_1 (first-excited-state) transitions.

The polarized proton beam was provided by a polarized ion source of the atomic-beam, sextupole-magnet type,[3] and was then accelerated by the Stanford FN tandem Van de Graaff. Beam currents on target in the range 2–5 nA were available for the experiment. The ^{11}B target used for most of the work was approximately 1 mg/cm^2 thick and consisted of five separate self-supporting foils stacked closely together. The γ rays were detected in the Stanford 24 cm × 24 cm NaI spectrometer.[4] The reaction was monitored by counting particle yields at 35° and at 135° as well as with a current integrator. Although the particle yields are also dependent on the polarization, the reproducibility of the yields for a given polarization helped to establish the reliability of the measurements.

The polarized angular distribution can be written in the form

$$W_{\vec{P}}(\theta) = \frac{\sigma_0}{4\pi}\left[1+\sum_{k=1} a_k P_k(\cos\theta) + \vec{P}\cdot\vec{n}\sum_{k=1} b_k \sin k\theta\right], \quad (1)$$

where $\vec{P}$ is the polarization of the incident proton