Simultaneous Microscopic Description of $^{16}O(\gamma, n)$ and $^{16}O(\gamma, p)$ Including Δ Degrees of Freedom

Thomas B. Bright and Stephen R. Cotanch
North Carolina State University, Raleigh, North Carolina 27695
(Received 6 January 1993)

The photonuclear reactions $^{16}O(\gamma,n)^{15}O$ and $^{16}O(\gamma,p)^{15}N$ are simultaneously described within a coupled channels framework based on a continuum shell model formulation that includes all nonlocalities arising from antisymmetrization. This large-scale conventional many-body calculation provides a good description of the medium energy data. The inclusion of $\Delta(1232)$ degrees of freedom further, but slightly, improves the description of the available data. Complete quantitative agreement, however, is still lacking.

PACS numbers: 25.20.Lj, 24.10.Eq

The apparent inability to describe and understand fully photonuclear reactions below 400 MeV using conventional, nonrelativistic dynamics has attracted growing theoretical and experimental interest. This theoretical shortcoming has motivated many calculations that have separately investigated different mechanisms thought to be important, such as nucleon-nucleon correlations [1,2], relativistic equations of motion [3–5], meson exchange currents [6–9], and excitation of $\Delta(1232)$ resonances [10,11]. Despite such efforts, the available (γ, p) data [12–14] below 400 MeV are described at best only semiquantitatively, while the computed (γ, n) cross sections [15] are not even qualitatively described. The purpose of this Letter is to report a large-scale, supercomputer-based *ab initio* calculation that includes both nucleon correlations and $\Delta(1232)$ isobar excitations. Our objective is to provide a realistic microscopic framework within which to consistently assess the importance of the aforementioned effects. We find that $\Delta(1232)$ isobar effects are small except at very large momentum transfer, and that a comprehensive conventional many-body structure calculation is sufficient to obtain the correct magnitude and qualitative features for both (γ, p) and (γ, n) reactions over a wide range of energies and angles.

The calculation is a generalization of the microscopic continuum shell model treatment originally developed by Buck and Hill [16]. The many-body Hamiltonian for ^{16}O is diagonalized rigorously in a model space spanned by products of continuum single-particle states and the mass $A = 15$ bound states. We use a realistic two-body, finite-range nucleon-nucleon interaction with spin, isospin, and tensor components, and we rigorously include all nonlocalities arising from antisymmetrization. The central N-N interaction between nucleons i and j is

$$V_c\left[a_0 + a_\sigma(\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j) + a_\tau(\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j) + a_{\sigma\tau}(\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j)(\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j)\right] \times \left[Y_0(\mu_c r) - \frac{\Lambda}{\mu_c} Y_0(\Lambda r)\right],$$

while the tensor interaction has the form

$$V_t(\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j) S_{12}\left[Y_2(\mu_t r) - \left(\frac{\Lambda}{\mu_t}\right)^3 Y_2(\Lambda r)\right],$$

where

$$Y_0(x) = \frac{e^{-x}}{x},$$
$$Y_2(x) = \left(1 + \frac{3}{x} + \frac{3}{x^2}\right) Y_0(x),$$

and

$$S_{12} = 3(\boldsymbol{\sigma}_i \cdot \hat{\mathbf{r}})(\boldsymbol{\sigma}_j \cdot \hat{\mathbf{r}}) - (\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j).$$

The range parameters μ_c, μ_t and the effective strengths V_c, V_t for the respective interactions were previously determined phenomenologically by describing the giant dipole resonance for $^{16}O(\gamma,p)^{15}N$. We include Δ isobars by expanding the model space to incorporate explicitly Δ components, in addition to the usual nucleon components, in the scattering wave function. The form of the N-Δ and Δ-Δ interaction potentials is taken from the work of Niephaus, Gari, and Sommer [17], which explicitly involves both π and ρ meson exchange. The central Δ interaction Hamiltonian has a radial form that is proportional to

$$Y_0(\mu_c r) - \frac{\Lambda}{\mu_c} Y_0(\Lambda r)\left[1 + \frac{\Lambda^2 - \mu_c^2}{2\Lambda^2}\Lambda r\right],$$

while the tensor Δ interaction Hamiltonian is given by

$$Y_2(\mu_t r) - \left(\frac{\Lambda}{\mu_t}\right)^3 Y_2(\Lambda r) - \frac{\Lambda}{\mu_t}\frac{\Lambda^2 - \mu_t^2}{2\Lambda^2}\Lambda r Y_1(\Lambda r),$$

where

$$Y_1(x) = \left(1 + \frac{1}{x}\right) Y_0(x).$$

The quantity Λ, introduced to regularize the Yukawa singularity at $r = 0$, is the same for all interactions. The central interaction has only a spin-isospin term in the case of N-Δ transitions, whereas for the Δ-Δ case, the

0031-9007/93/71(16)/2563(4)$06.00

form is similar to the N-N interaction. We assume that the allowed Δ excitations are intermediate, and hence do not include Δ components in the $A = 15$ bound states or the final state of the $A = 16$ system. Further, these many-body bound states are calculated within the single-particle–single-hole limit of the shell model. The resulting large set of coupled integro-differential equations is solved numerically for the continuum scattering wave function. In order to perform the calculation, the use of high-performance facilities is necessary, taking advantage of their vectorization and run-time storage abilities. For more specific details, the reader is referred to Refs. [18,19].

The electromagnetic transition amplitude, $M = -\int d\mathbf{r}\Psi_f \mathbf{j}(\mathbf{r})\cdot\mathbf{A}(\mathbf{r})\Psi_i$, entails the nuclear current $\mathbf{j}(\mathbf{r})$ and the electromagnetic potential $\mathbf{A}(\mathbf{r})$, where Ψ_i is the initial nuclear state obtained from the coupled channels calculation, and Ψ_f is the final single-particle–single-hole shell model wave function describing the ^{16}O ground state. The usual multipole expansion is performed and, for the medium energies considered here, we found it necessary to include electric multipoles through $E17$ and magnetic multipoles through $M15$ to insure convergence of the series. The nucleon currents used in the present study are the one-body convective and magnetization currents. Because we do not allow Δ resonances in the final nuclear state, the Δ current involves only radiative transitions to the nucleon. Work is in progress to include the effects of two-body exchange currents.

Figure 1 summarizes our calculation for the reaction $^{16}\mathrm{O}(\gamma,p)^{15}\mathrm{N}$ below $E_\gamma = 400$ MeV. The dotted curve represents a calculation that includes only conventional nucleonic degrees of freedom. The agreement at lower energies is reasonable and expected since these energies probe the long-range N-N interaction that is well understood. As the energy is increased, the shorter-ranged physics becomes progressively more important, and the conventional model deviates from the available data. Similarly, for a fixed energy, the conventional model shows greater discrepancy as the scattering angle increases, corresponding to larger momentum transfers that again probe shorter-ranged physics. The dashed curve depicts a calculation that includes Δ isobar degrees of freedom. As expected Δ isobar effects increase with increasing energy or momentum transfer. The value of the $\Delta(1232)$ magnetic moment is taken to be $4.0\mu_N$, consistent with the experimentally determined value [20]. The strengths of the π and ρ exchange potentials are determined by the meson masses and the $\Delta N\pi$ and $\Delta N\rho$ coupling constants of Ref. [17]. The value of the $\frac{f^2_{\Delta N\rho}}{4\pi}$ coupling constant is not at all well known [21] and may be considerably smaller than 9.13, the value used in this study. The sensitivity to ρ exchange is indicated by the dash-dotted curve, where the ρ exchange potentional has been reduced by 50%, and by the solid curve where it has been set to zero. Consistent with the above momentum-range arguments, the longer-ranged π exchange contribution is more important at lower energies than ρ mediated effects which dominate at higher energies. The calculation with the ρ exchange potential set to zero best represents the data and is consistent with a smaller $\Delta N\rho$ coupling constant [21].

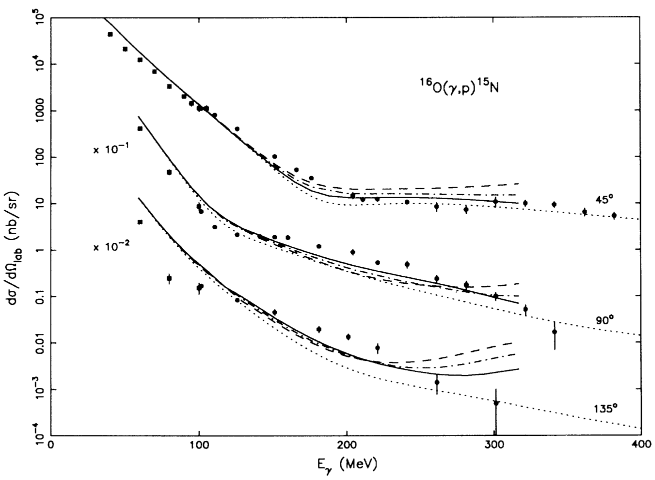

FIG. 1. Laboratory energy spectra for the reaction $^{16}\mathrm{O}(\gamma,p)^{15}\mathrm{N}$. Theory: Conventional calculation with only nucleonic degrees of freedom (dotted); calculation with full contribution from Δ degrees of freedom (dashed); calculation with ρ exchange potential reduced by 50% (dot-dashed) and 100% (full). Data: squares are from Ref. [13]. Circles are from Ref. [12]. The 90° and 135° spectra are scaled by 10^{-1} and 10^{-2}, respectively.

There is a limited amount of $^{16}\mathrm{O}(\gamma,n)^{15}\mathrm{O}$ data available in this energy range. Angular distributions for these data, as well as the available $^{16}\mathrm{O}(\gamma,p)^{15}\mathrm{N}$ data at the corresponding energies, are shown in Fig. 2 along with our calculations. As in Fig. 1, the dotted line represents the conventional calculation involving only nucleonic degrees of freedom. The solid line is the calculation including Δ degrees of freedom, using the coupling constants of Ref. [17], with the ρ exchange potential taken to be zero as in Fig. 1. The regularization parameter, Λ, was taken to be 1.2 GeV, which is within the usually quoted range [17]. In principle the regularization should be independent of Λ; however, for the large momentum transfers considered here, we have found appreciable numerical sensitivity. The dashed curve is for $\Lambda = 3.0$ GeV with only π exchange. Our calculation is stationary for this value of Λ, becoming insensitive to small changes in this parameter. The difference between the solid and dashed curves then roughly indicates the uncertainty in our calculation due to the regularization prescription. This difference not only indicates a clear need for a better regularization procedure, but also, and more importantly, an exciting opportunity to study short-range physics in a many-body environment by using an improved, more realistic interaction.

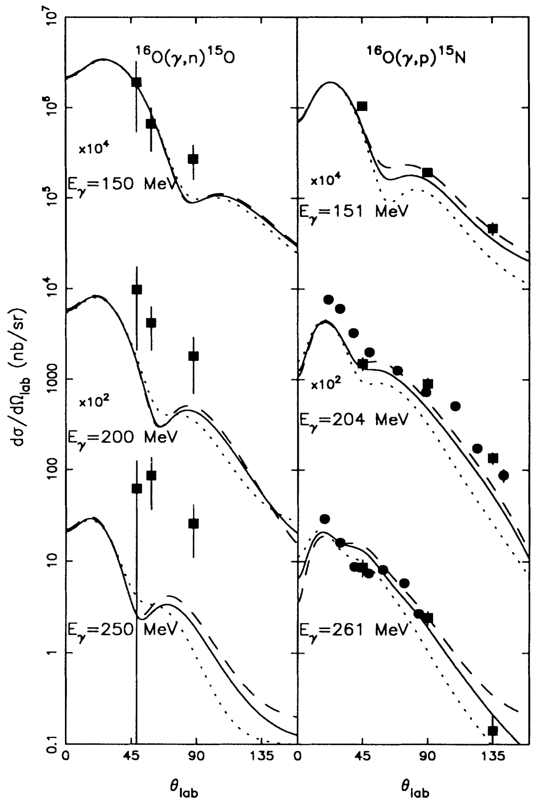

FIG. 2. $^{16}O(\gamma,n)^{15}O$ and $^{16}O(\gamma,p)^{15}N$ laboratory angular distributions for E_γ=150, 200, and 250 MeV. Theory: Conventional calculation (dotted); calculation with ρ exchange potential set to zero and Λ = 1.2 GeV (full) and 3.0 GeV (dashed). Data: (γ,n), Ref. [15]; (γ,p), circles are from Ref. [14] and squares are from Ref. [12]. The angular distributions for 150 and 200 MeV are scaled by 10^4 and 10^2, respectively.

In summary, a key new result of this study is that rigorous conventional calculations involving only nucleonic degrees of freedom describe the available data remarkably well. They are insufficient, however, to provide a complete quantitative description of $^{16}O(\gamma,n)$ and $^{16}O(\gamma,p)$ data at intermediate energies with the discrepancy increasing with larger momentum transfer. The inclusion of the $\Delta(1232)$ resonance, with its intrinsic short-ranged nature, somewhat improves the description of the available data, but, with the exception of the high energy Δ resonance region, the effects are small and complicated by the uncertainties in the short-ranged character of the interaction and our regularization procedure. This is in contrast to the results of Refs. [10,11], which both find significant contributions to the $^{16}O(\gamma,p)$ reaction, although Ref. [10] finds a much larger effect than Ref. [11]. However, their calculations, which are both direct knockout, omit what we find are very important nonlocal microscopic elements. In particular, without charge exchange it is definitely not possible for our model to reproduce the correct magnitude of the $^{16}O(\gamma,n)$ data.

Perhaps the most important element not included in this analysis is meson exchange currents. As is appropriately noted [10], at higher energies the photon probes the two-body component of the current, and exchange current effects should be increasingly more important as demonstrated [3] previously. Reference [3] calculates significant relativistic and exchange current effects, and finds that both effects are necessary to describe the $^{16}O(\gamma,p)$ data. However, that same model, even with exchange currents, cannot account [15] for the magnitude of the $^{16}O(\gamma,n)$ cross section. The work of Ref. [6] also implies that meson exchange currents play a major role in determining the $^{16}O(\gamma,p)$ reaction cross section. Similar to our finding, and perhaps surprising, this work also concludes that there is no significant Δ isobar contribution. While we agree with the approach of Ref. [6] for low energies, the extension to intermediate energies is inappropriate due to the limitations of Siegert's theorem in determining the exchange currents. Further, our calculations clearly indicate that magnetic multipoles, which are ignored in their calculation, are not negligible.

The diverse results in the above investigations clearly indicate that conclusions characterizing exchange current effects can be very model dependent. We submit that these differing findings are due to the nature and degree of approximations, and that an accurate assessment of exchange current effects requires a consistent, many-body framework.

A second major result of our work is the description of *both* $^{16}O(\gamma,n)$ and $^{16}O(\gamma,p)$ using the same microscopic model. It should be emphasized that our conventional model parameters were determined at lower energies by independently fitting the $^{16}O(\gamma,p)$ giant dipole resonance reaction, and therefore, with the exception of variations in the Λ potential parameters to document regularization sensitivity, all of our $^{16}O(\gamma,N)$ medium energy calculations are actually model predictions. While our calculations document the importance of the Δ resonance, it should be noted that there is strong sensitivity to the regularization parameter Λ, indicating not only the need for an improved model interaction, but also, and more importantly, the opportunity for studying interesting short-range physics including baryon repulsion. Efforts are presently underway to incorporate more sophisticated short-ranged N-N and N-Δ interactions and meson exchange currents which we also expect to be important.

This work was supported by the U.S. Department of Energy, Grant No. DE-FG05-88ER40461 and the North Carolina Supercomputing Center.

[1] B. Schoch, Phys. Rev. Lett. **41**, 80 (1978).
[2] H. Goringer and B. Schoch, Phys. Lett. **97B**, 41 (1980).
[3] J.P. McDermott, E. Rost, J.R. Shepard, and C.Y. Cheung, Phys. Rev. Lett. **61**, 814 (1988).

[4] G.M. Lotz and H.S. Sherif, Phys. Lett. B **210**, 45 (1988).
[5] S. Boffi, C. Giusti, and F.D. Pacati, Nucl. Phys. **A359**, 91 (1981).
[6] M. Gari and B. Hebach, Phys. Rep. **72**, 1 (1981).
[7] M. Cavinato, M. Marangoni, and A.M. Saruis, Nuovo Cimento Soc. Ital. Fis. **76A**, 197 (1983).
[8] J. Ryckebusch, in Proceedings of the Workshop on Nuclear Physics with Real Photons Below Pion Threshold, Gent, 25–26 May 1989 (unpublished).
[9] J. Ryckebusch, K. Heyde, L. Machenil, D. Ryckbosch, M. Vanderhaeghen, and M. Waroquier, Phys. Rev. C **46**, R829 (1992).
[10] J.T. Londergan and G.D. Nixon, Phys. Rev. C **19**, 998 (1979).
[11] C.Y. Cheung and B.D. Keister, Phys. Rev. C **33**, 776 (1986).
[12] M.J. Leitch, J.L. Matthews, W.W. Sapp, C.P. Sargent, S.A. Wood, D.J.S. Findlay, and R.O. Owens, Phys. Rev. C **31**, 1633 (1985). Data for E_γ=201.2 MeV were also used in Fig. 2.
[13] D.J.S. Findlay and R.O. Owens, Nucl. Phys. **A279**, 385 (1977).
[14] G.S. Adams, E.R. Kinney, J.L. Matthews, W.W. Sapp, T. Soos, R.O. Owens, R.S. Turley, and G. Pignault, Phys. Rev. C **38**, 2771 (1988). Data for E_γ= 196 and 257 MeV were used in Fig. 2.
[15] E.J. Beise, G. Dodson, M. Garcon, S. Hoibraten, C. Maher, L.D. Pham, R.P. Redwine, W. Sapp, K.E. Wilson, S.A. Wood, and M. Deady, Phys. Rev. Lett. **62**, 2593 (1989).
[16] B. Buck and A.D. Hill, Nucl. Phys. **A95**, 271 (1967).
[17] G.-H. Niephaus, M. Gari, and B. Sommer, Phys. Rev. C **20**, 1096 (1979).
[18] B. Hoistad, S. Isaksson, E. Nilsson, J. Thun, G.S. Adams, C. Landberg, T.B. Bright, and S.R. Cotanch, Phys. Lett. B **276**, 294 (1992).
[19] B. Hoistad, S. Isaksson, E. Nilsson, J. Thun, G.S. Adams, C. Landberg, T.B. Bright, and S.R. Cotanch, Nucl. Phys. **A553**, 543c (1993).
[20] E. Grecksch, M. Dillig, and W. Knupfer, Z. Phys. A **302**, 247 (1981).
[21] B.K. Jain, N.G. Kelkar, and J.T. Londergan, Phys. Rev. C **47**, 1701 (1993).