Pure-Resonance Model for Radiative Capture of Fast Nucleons

F. S. Dietrich
Lawrence Livermore Laboratory, Livermore, California 94550

and

A. K. Kerman
Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 12 March 1979)

A model for radiative capture is described that is based on the same assumptions as the direct-semidirect model, but in which the giant resonance is explicitly projected out of the continuum space. Calculations on ^{208}Pb(n,γ) show that the model is much less sensitive to form-factor ambiguities than the direct-semidirect model, and that reasonable fits to data are obtained.

Attempts to calculate the magnitudes and excitation functions for fast-nucleon radiative capture in medium and heavy nuclei have relied almost exclusively on the direct-semidirect (DSD) reaction model,[1-3] in which a slowly energy-dependent direct-capture amplitude interferes with a resonant term representing excitation of the giant-dipole resonance (GDR). With suitable adjustment of parameters, the model has been reasonably successful in reproducing experimental data. The model has also been extended with qualitative success to calculations of angular distributions and higher multipolarities.[4-6] However, a difficulty with the model is its sensitivity to assumptions about the nature of the form factor for coupling to the GDR. The real part of the form factor may be related to the isovector part of the optical potential, or to a microscopic model of the GDR and the isospin-dependent part of a two-body interaction; the origin of an imaginary part of the coupling is not well established, although it may in principle be present. Nevertheless, it has been found necessary to introduce an imaginary coupling to fit the observed shapes of excitation functions in the GDR region.[7] The strength of the imaginary coupling required to fit the data is usually larger than that found in typical optical potentials, and appears to increase with mass number, but otherwise its systematic behavior is poorly understood. As a result the DSD model has inadequate predictive capability, and the question naturally arises as to whether the particular form and strength of the imaginary coupling that has been used to fit the data is essential to the reaction mechanism, or simply covers up a defect in the model.

In this Letter, we present an alternative calculation of the same physical processes based on the Feshbach reaction formalism[8] which varies from the DSD model in that the GDR is explicitly projected out of the continuum space. We compare the results of this calculation with those of a DSD calculation using an identical set of input parameters for neutron capture on ^{208}Pb, and find that the new calculations are very insensitive to the imaginary part of the form factor. The assumption (common to both types of calculation) that the entire dipole strength of the target-plus-nucleon system resides in the GDR results in the absence of a nonresonant term in the new calculations, and we accordingly refer to this model as the pure-resonance model (PRM). The intuitive basis for the PRM calculations is most easily seen in the time-reversed (photonuclear) channel, in which an incident photon resonantly excites a single doorway (GDR), followed by ejection of a nucleon into the final channel. The techniques used to treat the continuum and its explicit separation from the GDR are most closely related to those developed for the analog-resonance problem.[9] The same intuitive picture has been used[10] to treat photoejection from ^{16}O, although in that work a description of the fragmentation of the GDR was emphasized, whereas an accurate treatment of the continuum (optical) potential was not attempted.

We have derived the DSD and PRM expressions from a common set of assumptions using projection-operator techniques to isolate the GDR of the combined system from the continuum channels, and to identify the component of the GDR with the same quantum numbers as the decay channel. It is the treatment of this component which is the essential difference between the two formulations. Nevertheless, the formal development shows that the two expressions are in principle identical, and therefore that any differences in their predictions must result from varying sensitivity to

the approximations (such as a particular parametrization of the optical potential) necessary to calculate with them.

For each incident channel, the reaction amplitudes in the two types of calculation are

$$c\langle w|\chi^{(+)}\rangle + \frac{\langle u_b|h'(r)|\chi^{(+)}\rangle}{E_\gamma - E_R + i\Gamma/2}$$

for DSD, and

$$\frac{c\langle w|\mathcal{H}^{\text{opt}}|\varphi^{(+)}\rangle + \langle u_b|h'(r)|\varphi^{(+)}\rangle}{E_\gamma - E_R + i\Gamma/2}$$

for PRM. The position E_R and width Γ refer to the GDR of the combined target-plus-nucleon system; $h'(r)$ is the coupling form factor; $\mathcal{H}^{\text{opt}}$ is the one-body optical potential; and u_b is the radial wave function of the captured nucleon in the final bound orbital. The spatially localized particle wave function w of the GDR component in the incident channel is obtained by multiplying u_b by the dipole operator r, then projecting out occupied-state components and normalizing. The continuum wave functions $\chi^{(+)}$ and $\varphi^{(+)}$ are solutions of $(E-\mathcal{H}^{\text{opt}})\chi^{(+)}=0$ and $F(E-\mathcal{H}^{\text{opt}})F\varphi^{(+)}=0$, where the projection operator F which removes the GDR from the continuum space is $1-|w\rangle\langle w|$. The quantity c is proportional to the amplitude of the particle-hole configuration $(w\otimes u_b)$ in the GDR and is obtainable from any microscopic model calculation of the GDR. The first term of the DSD expression may be shown to be equivalent to the usual direct-capture term, except for an RPA correction which has not previously been noted. That is,

$$c\langle w|\chi^{(+)}\rangle = \alpha q\langle u_b|r|\chi^{(+)}\rangle,$$

where q is the recoil effective charge (N/A and $-Z/A$ for protons and neutrons, respectively), and α is a random-phase-approximation (RPA) correction which in the schematic model[11] has a value of about 0.75. The first term in the PRM expression represents leakage into the continuum from the GDR component with the correct channel quantum numbers (single-particle escape amplitude), and the second represents decay from components for which a two-body interaction is necessary to yield the channel quantum numbers (rearrangement escape amplitude). Application of the projection procedure is not difficult, simply requiring solution of the optical equations a second time in each channel.[9]

In Fig. 1, DSD and PRM calculations are compared with data[12] for neutron capture on ^{208}Pb

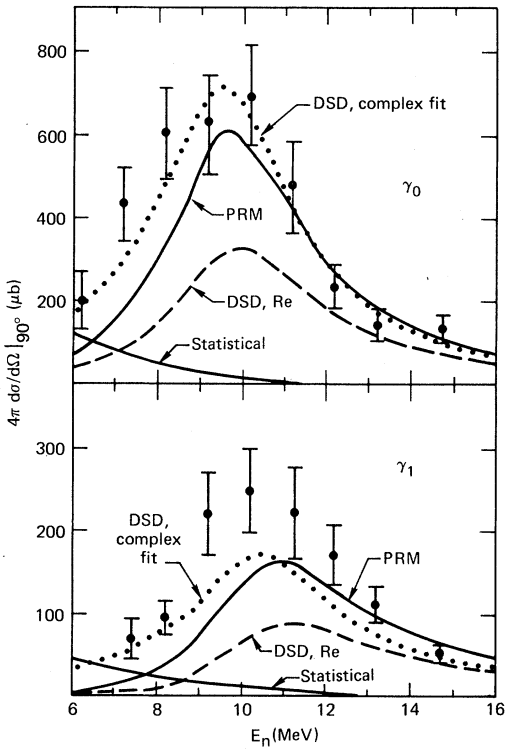

FIG. 1. Comparison of model calculations with ^{208}Pb(n,γ) data of Ref. 12. The PRM calculations are shown only with a real form factor, as the addition of an imaginary term changes the results by less than 15%.

leading to the ground and first excited states of ^{209}Pb. The optical parameters were taken from fits to neutron scattering[13] on ^{208}Pb. The GDR parameters[14] were $E_R = 13.43$ MeV and $\Gamma = 4.07$ MeV. Unit spectroscopic factors were assumed for both transitions. The coefficients c and the GDR transition densities were taken from the RPA schematic model assuming no exchange enhancement of the Thomas-Reiche-Kuhn sum rule. The form factor obtained by folding the transition density with a two-body force used in scattering calculations[15] was found to resemble the Steinwedel-Jensen hydrodynamic form factor[16] very closely, with parameters (in the notation of Ref. 7) $V_1 = 132$ MeV, $r_0 = 1.30$ fm and $a = 0.8$ fm. The calculations were performed with this equivalent hydrodynamic form factor, and the imaginary coupling was taken in the same form as in Ref. 7 with $W_1 = 132$ MeV, which was chosen to fit the shape of the excitation functions in the DSD model. The bound-state Woods-Saxon parameters were $r_0 = 1.27$ fm and $a = 0.67$ fm, and the RPA correction factor was calculated to be $\alpha = 0.76$.

Figure 1 also shows a statistical (Hauser-Feshbach) contribution to the capture reaction obtained with the same neutron optical model as above, and using γ transmission coefficients from observed photonuclear excitation functions.[14] The level densities were taken similar to the Gilbert-Cameron[17] form, but normalized to the observed number of low-lying levels in ^{208}Pb. Uncertainties in the level densities limit the accuracy of the normalization of the statistical calculation to perhaps a factor of 2.

With real coupling only, the DSD calculations are weaker in magnitude and more asymmetric than either the PRM calculations or the data. Addition of the imaginary coupling term has negligible effect on the PRM calculations, whereas the shape of the excitation functions can be varied rather arbitrarily in the DSD calculations by adjusting the relative strengths of the real and imaginary couplings. Although the PRM calculations fall below the data toward the lower energies, this portion of the excitation functions may plausibly be filled in by the statistical contribution.

In comparing the results of the two calculations, it is important to make clear that *both* expressions have been derived with the assumption that the *entire* $E1$ strength of the target-plus-nucleon system is concentrated in the GDR. The appearance of a nonresonant amplitude in the DSD model must therefore be illusory, and the formal expression for the semidirect amplitude (before approximations) in fact contains a term that subtracts the direct amplitude. This exact subtraction may be lost in actual DSD calculations, since the direct and semidirect amplitudes contain different phenomenological ingredients.

A closely related way of viewing the same problem is to consider the energy dependence of the $E1$ strength included in the direct term $\langle u_b | r | \chi^{(+)} \rangle$. This strength lies below the GDR at about the major-shell spacing above the final state, appearing either as a bound state or as a single-particle resonance in the channel wave function $\chi^{(+)}$. This single-particle strength is the feature that has been explicitly projected out of the continuum function $\varphi^{(+)}$, and so does not enter the PRM formalism. In the DSD model, the single-particle strengths associated with $\chi^{(+)}$ in the two terms must cancel. Failure of the cancellation because of inadequate approximations will yield an amplitude which is nonresonant in the vicinity of the GDR, and a consequent asymmetry in the excitation function. An additional spurious contribution to the nonresonant amplitude arises from nonorthogonality of the phenomenologically determined optical wave functions to the occupied orbitals, leading to transitions between the continuum wave function and the final bound state that should be forbidden by the Pauli principle. It is possible that the introduction of the imaginary form factor in the DSD model restores the cancellation in the amplitudes that have been lost by approximation.

We conclude that the PRM expression yields a reasonable description of the data for neutron capture on ^{208}Pb. Even though based on the same assumptions, the PRM calculations are much less sensitive to poorly understood details of the coupling form factor than the DSD. Accordingly, we feel that the PRM is more likely to be predictive than the DSD, both for electric dipole radiation and for extension to other multipolarities. Conversely, the insensitivity of the PRM to the imaginary coupling makes it impractical to extract information about this coupling from the model. However, the DSD model can be used to determine the nature of the coupling form factor only if the approximations in that model are sufficiently well understood so that the form factor is not improperly used to cancel the single-particle resonance structure in the DSD model which is eliminated *a priori* in the PRM. Further investigation of the consistency between the two models has led to a condition relating the strength of the coupling form factor to the elevation of the GDR above the major-shell spacing which is reminiscent of Brown's early DSD derivation.[1] Such a condition can be used to modify the PRM expression so that it is dependent on the radial shape of the form factor but not its strength; this will be reported elsewhere. The nonorthogonality of the continuum wave functions to occupied states is a problem that requires further attention in both models.

We wish to thank Dr. Donald Gardner for performing the statistical-model calculations. This work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore Laboratory under Contract No. W-7405-ENG-48.

[1]G. E. Brown, Nucl. Phys. 57, 339 (1974).

[2]C. F. Clement, A. M. Lane, and J. A. Rook, Nucl. Phys. 66, 273, 293 (1965).

[3]F. Cvelbar and S. L. Wheatstone, *Charged-Particle-Induced Radiative Capture* (International Atomic Energy Agency, Vienna, 1974), p. 271, and references therein.

[4]K. A. Snover, J. E. Bussoletti, K. Ebisawa, T. A. Trainor, and A. B. McDonald, Phys. Rev. Lett. 37, 273, 1651(E) (1976).
[5]F. S. Dietrich *et al.*, Phys. Rev. Lett. 38, 156 (1977).
[6]A. Likar, M. Potokar, and F. Cvelbar, Nucl. Phys. A280, 49 (1977).
[7]M. Potokar, Phys. Lett. 46B, 346 (1973).
[8]H. Feshbach, Ann. Phys. (N.Y.) 19, 287 (1962).
[9]N. Auerbach, J. Hüfner, A. K. Kerman, and C. M. Shakin, Rev. Mod. Phys. 44, 48 (1972).
[10]W. L. Wang and C. M. Shakin, Phys. Rev. C 5, 1898 (1972).
[11]G. E. Brown, *Unified Theory of Nuclear Models* (North-Holland, Amsterdam, 1967), 2nd ed.
[12]I. Bergqvist, D. M. Drake, and D. K. McDaniels, Nucl. Phys. A191, 641 (1972).
[13]C. Y. Fu and F. G. Perey, At. Data Nucl. Data Tables 16, 409 (1975).
[14]A. Veyssiere *et al.*, Nucl. Phys. A159, 561 (1970).
[15]V. A. Madsen, in *Nuclear Isospin*, edited by John D. Anderson (Academic, New York, 1969).
[16]G. R. Satchler, Nucl. Phys. A195, 1 (1972).
[17]A. Gilbert and A. G. W. Cameron, Can. J. Phys. 43, 1446 (1965).

Observation of Magnetic Dipole Strength in ^{16}O

K. A. Snover, P. G. Ikossi, and T. A. Trainor
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 27 April 1979)

We demonstrate that polarized-proton radiative capture may be used to unambiguously identify concentrations of magnetic dipole strength. Three $M1$ resonances are observed in the doubly magic ^{16}O nucleus between $E_x = 16$ and 20 MeV, with a relatively large total γ_0-transition strength $B(M1)\uparrow \geq 0.24\mu_0^2$.

In this Letter we report the discovery of magnetic dipole ($M1$) γ-ray transition strength built on the ground state of the (doubly magic) ^{16}O nucleus. This discovery is interesting in part because of the expectation that $M1$ strength should be weak, since the $M1$ operator has no radial dependence (in the long-wavelength approximation) and hence cannot excite the closed-shell component of the ground-state wave function. Thus the magnitude of ground-state $M1$ strength in doubly magic $N=Z$ nuclei such as ^{16}O provides a direct quantitative measure of core-breaking correlations in the ground-state wave function. Also, it would be very interesting to know if the $M1$ strength built on the ground-state of doubly magic nuclei is concentrated in one or a few of the lowest 1^+, $T=1$ levels, as is the case in other light $A=4n$ nuclei.

We studied the polarized-proton capture reaction $^{15}\mathrm{N}(p_{\mathrm{pol}}, \gamma_0)^{16}\mathrm{O}$ in a region of semi-isolated resonances located between 16 and 20 MeV excitation energy and found that we can unambiguously identify concentrations of $M1$ strength.[1] This differs from previous studies[1,2] of polarized-proton capture at higher energies in ^{16}O and other light nuclei where structure is broad, $E1$ and $E2$ radiation is present everywhere, and it is very hard to say how much, if any, $M1$ radiation is present.

Our data were obtained with a large NaI spectrometer and ~50 nA of ~75% polarized protons from the University of Washington tandem accelerator, using a gas cell with a 0.9-mg/cm^2 Ni entrance window and enriched ^{15}N gas at a pressure of 125–250 Torr for an overall proton-energy resolution of 40–60 keV.

We measured the cross section $\sigma(\theta)$ and analyzing power $A(\theta)$ at $\theta = 90°$ as a function of bombarding energy, in fine energy steps, to locate $M1$ and/or $E2$ resonances. Angular distributions were used to determine the multiple assignments of the resonances. The angular dependence is given in the usual fashion:

$$\sigma(\theta) = [\sigma^{\uparrow}(\theta) + \sigma^{\downarrow}(\theta)]/2 = A_0\left(1 + \sum_{i=1}^{4} Q_i a_i P_i(\cos\theta)\right), \quad (1)$$

$$\sigma(\theta)A(\theta) = [\sigma^{\uparrow}(\theta) - \sigma^{\downarrow}(\theta)]/2P = A_0 \sum_{i=1}^{4} Q_i b_i P_i^1(\cos\theta),$$

where $\uparrow$ and $\downarrow$ refer to the direction of the beam polarization (with magnitude P) relative to $\vec{k}_{\mathrm{in}} \times \vec{k}_{\mathrm{out}}$ and the Q_i are angular attenuation coefficients. Multipoles of order higher than 2 as well as magnetic quadrupole may be neglected here. Excitation curve measurements at $\theta = 90°$ are especially useful since at this angle the analyzing power arises only from interfering radiations of

