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Direct-Reaction Calculation of Intermediate-Energy Proton Radiative Capture on ^{11}B

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Photon spectra of the reaction $^{11}B(p,\gamma)^{12}C$ at $E_p = 40$, 60, and 80 MeV are calculated assuming a direct-capture mechanism. Observed capture spectra below 25-MeV excitation energy are reproduced well. Only about half of the observed cross section at the 19.2-MeV peak is found to come from the 4^- stretched configurations. Contributions of "charge-exchange currents" are shown to be important.

Kovash *et al.*[1] have recently measured photon yields for the (p,γ) reaction on several light nuclear targets. The spectra obtained were for incident proton energies E_p from 40 to 100 MeV. In Fig. 1, we show the observed excitation function for $^{11}B(p,\gamma)^{12}C$ at a scattering angle of 60°. At the lower proton energies, peaks are clearly evident in the low-excitation-energy end of the spectrum. These are easily identifiable as corresponding to the ground- and first excited-state transitions. However, an unexpected feature also shows up at the higher-excitation-energy end of the spectrum where we see a distinct peak clearly emergent on top of the rising continuum at an excitation energy of about 19.2 MeV in ^{12}C. For 80-MeV protons, both the low-lying and high-lying peaks are harder to identify as the resolution width of the photon detector, which is roughly proportional to E_γ, is now comparable with nuclear level spacings. Since this is the first observation of such a high-lying state in radiative capture measurement, it is of some interest to see if it can be accounted for with presently available models of the radiative capture process.

It was speculated[1,2] that the stretched 4^- states[3] in ^{12}C could be responsible for the observed 19.2-MeV peak, but no calculations were done to verify this point. Here we apply a model,[4] which gives a good quantitative description of the inverse photonuclear process at intermediate energies, to calculate the reaction $^{11}B(p,\gamma)^{12}C$. We are interested to see if this model can reproduce the observed features of the photon spectrum, such as the transition strength to the ground and first excited state, the rising trend of the photon spectrum with increasing nuclear excitation energy, and the change in the photon spectrum as the incident proton energy is varied. In particular, we want to investigate whether it is possible to have any localization of strength in the region of high excitation energy. The effect of the mesonic exchange currents will also be examined.

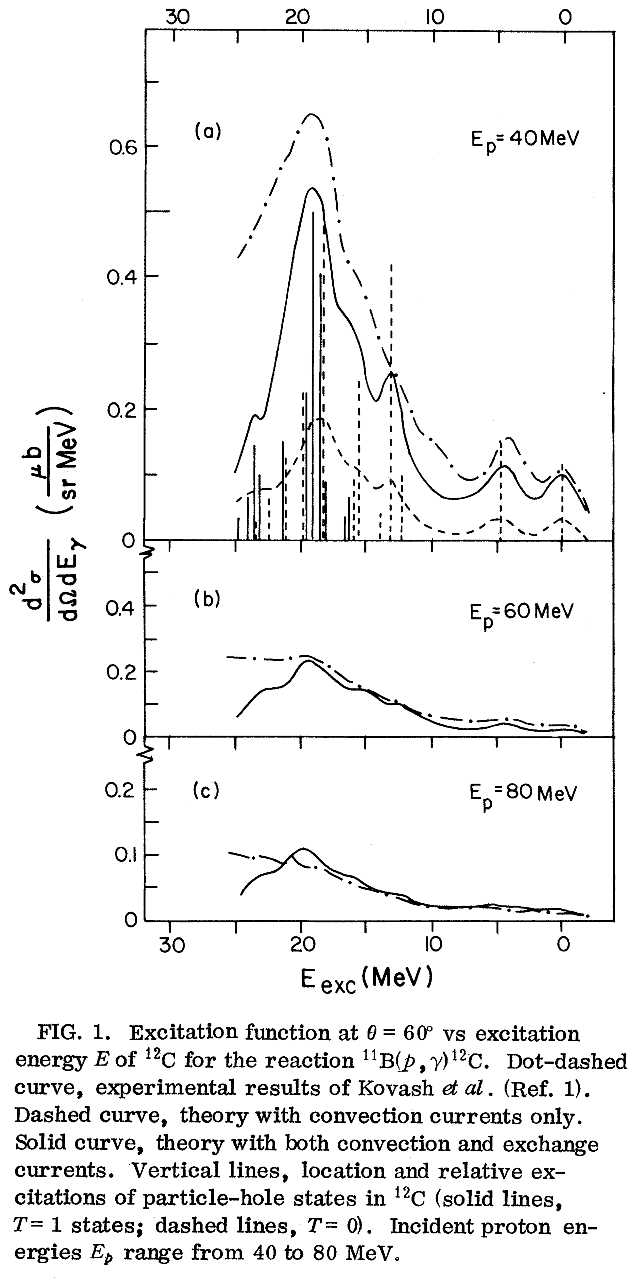

FIG. 1. Excitation function at $\theta = 60°$ vs excitation energy E of ^{12}C for the reaction $^{11}B(p,\gamma)^{12}C$. Dot-dashed curve, experimental results of Kovash *et al.* (Ref. 1). Dashed curve, theory with convection currents only. Solid curve, theory with both convection and exchange currents. Vertical lines, location and relative excitations of particle-hole states in ^{12}C (solid lines, $T = 1$ states; dashed lines, $T = 0$). Incident proton energies E_p range from 40 to 80 MeV.

We assume the ground state of the target nucleus ^{11}B to be a proton hole in the $0p_{3/2}$ subshell. The incident proton may be captured into an unfilled particle orbital or the $0p_{3/2}$ hole, with the final nucleus ^{12}C being formed in a particle-hole excited state or the ground state, respectively. The transition amplitude for emitting a photon of energy-momentum $(E_\gamma, \vec{k}_\gamma)$ and polarization $\vec{\epsilon}_\lambda$ is given by

$$T_{fi} = -(2\pi\hbar^2/E_\gamma)^{1/2} \int d^3r \langle\psi_f|\vec{J}(\vec{r})|\psi_i\rangle \times \vec{\epsilon}_\lambda{}^* \exp(-i\vec{k}_\gamma\cdot\vec{r}), \quad (1)$$

where ψ_i and ψ_f are, respectively, nuclear wave functions for the incoming and outgoing channels. Gauge invariance is ensured by requiring the nuclear current density $\vec{J}$ to satisfy the equation of continuity. We consider contributions from the convection current and exchange currents, using an approach similar to that of Hebach, Wortberg, and Gari.[4] Since we use correlated particle-hole wave functions, we do not use the approximation of closure to giant multipole resonances.[4,5]

The initial wave function ψ_i describes a proton incident on ^{11}B. The ground state of ^{12}C is assumed to have a doubly closed $0p_{3/2}$ subshell, while ψ_f of the excited states are taken from the random-phase-approximation (RPA) calculation of Gillet and Vinh Mau.[6] The $T = 0$ and $T = 1$ components of the $J^\pi = 4^-$ state, formed from the stretched $(0d_{5/2}0p_{3/2}{}^{-1})$ configuration, are put at 18.3 and 19.6 MeV, respectively. Both the incident proton wave and the single-particle orbitals are calculated using a single-particle potential consisting of a Woods-Saxon form with a spin-orbit term, plus a residual interaction with a Rosenfeld force and strength $U_0 = -50$ MeV.[7] Orthogonality of the single-particle wave functions is thus maintained.[8] The single-particle potential used by Hebach *et al.* is not adopted since it does not fit well with the single-particle spectrum given in Ref. 6.

In their RPA calculation, Gillet and Vinh Mau used harmonic-oscillator wave functions. The particle-hole amplitudes are, however, not expected to change much when wave functions generated by a Woods-Saxon potential are used instead, provided we also confine the $0d$-$1s$ and $0f$-$1p$ orbitals in a large enough spherical box. This will minimize the effect of nonorthogonality between the incident wave and the particle orbitals, yet still allow us to use the particle-hole amplitudes as given by the RPA theory.

We evaluate the transition amplitudes given in Eq. (1) for all of the particle-hole states listed in Ref. 6, except the spurious 1^- $(T = 0)$ state at 7.53 MeV, to obtain the differential cross section. To compare with the excitation function measured by Kovash *et al.*, we average the cross sections for individual particle-hole states over an energy interval determined by the detector resolution and the γ-decay widths of the excited states.[9]

The results are compared with the experimental data in Fig. 1. The peaks corresponding to the ground state and the first excited state at 4.4 MeV are reasonably well reproduced, as can also be seen from the differential cross section given

TABLE I. Differential cross sections to the ground and first excited state of ^{12}C.

	$d\sigma(\theta = 60°)/d\Omega$ (μb/sr)			
	^{11}B(p,γ_0)		^{11}B(p,γ_1)	
E_p (MeV)	Theory	Experiment [a,b]	Theory	Experiment [b]
40	0.321	0.500 ± 0.075	0.412	0.595 ± 0.090
60	0.104	0.180 ± 0.025	0.169	0.300 ± 0.045
80	0.035	0.055 ± 0.011	0.090	0.110 ± 0.022

[a] See Ref. 1. [b] See Ref. 2.

in Table I. The rise in the cross section with increasing nuclear excitation energy is given correctly by the theory, and the peak near 19 MeV is indeed quite prominent. This peak is largely due to the $T = 0$ and $T = 1$ $J^\pi = 4^-$ stretched states in ^{12}C, but there are also sizable contributions from nearby 2^- and 3^- states. A breakdown of partial contributions from states in the 18–20-MeV region is given in Table II. At all three proton incident energies, it is to be noted that the 4^- states make up only about one half of the total peak cross section. The $J^\pi = 2^-$, 3^-, 4^- states in this region are basically particle-hole states built upon the $0d_{3/2}0p_{3/2}{}^{-1}$ and $0d_{5/2}0p_{3/2}{}^{-1}$ configurations, which have an unperturbed energy of about 19 MeV. There is, however, not enough particle-hole collectivity to move these states away from their unperturbed values. We see, therefore, a concentration of particle-hole strength lying in this region. Since states with spin J are populated in (p, γ) reaction with the statistical weight of $2J + 1$, the higher-spin states contribute more importantly, thereby forming a peak. The RPA description of excited states should be reasonable up to about the giant-dipole-resonance region; above that region, the calculation does not have enough strength distributed there and we see a decrease in the calculated cross sections.

For $E_p = 40$ MeV, we have also displayed in Fig. 1 the contribution of the convection current only to the ^{11}B(p, γ) cross sections. It is seen to be a factor of about 2 to 3 smaller than the combined contributions of convection-plus-exchange currents, a fact which is already evident in the work of Hebach, Wortberg, and Gari.[4] It can be understood essentially as indicating the importance of a two-body mechanism is absorbing the excess momentum of the incident proton not carried off by the emitted photon.

In Fig. 2, we show angular distributions of the $E_p = 40$ MeV differential cross sections to the ground and various particle-hole states. All of these cross sections reach a peak for angles between 40° and 60° and fall smoothly with increas-

TABLE II. ^{11}B(p,γ) differential cross sections to $J^\pi = 2^-$, 3^-, 4^- states between 18 and 20 MeV.

	$d\sigma(\theta = 60°)/d\Omega$ (nb/sr)		
E_p (MeV)	$J = 2$	$J = 3$	$J = 4$
40	155.6	302.4	419.6
60	116.2	225.1	313.3
80	78.6	178.0	223.9

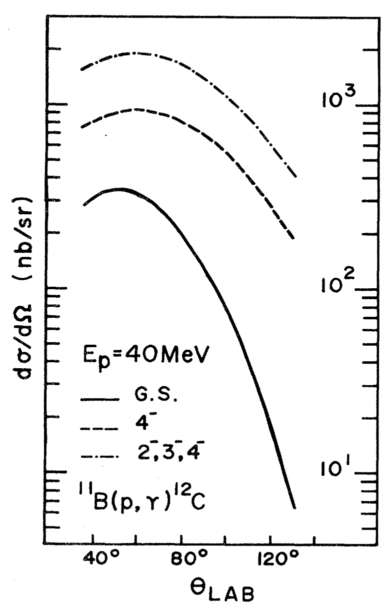

FIG. 2. Calculated angular distributions of differential cross sections for ^{11}B(p,γ) reaction at E_p = 40 MeV. Solid curve, cross section to the ground state of ^{12}C. Dashed curve, sum of cross sections to the stretched 4^-(T = 0, 1) states at 18.3 and 19.6 MeV. Dot-dashed curve, sum of cross sections to all states with excitation energy 18–20 MeV.

ing scattering angle. The ground-state curve, however, falls more rapidly than the excited-state curves. Consequently, if the photon spectrum were taken at a larger scattering angle, the 19-MeV peak should be even more prominent. From Fig. 2, we see again that the two 4^- states provide about half of the total (p,γ) strength in this excitation-energy region.

The direct-radiative-capture picture which we have presented gives a good fit to the observed $^{11}B(p,\gamma)$ spectrum, for excitation energies up to 25 MeV. This suggests that the primary reaction mechanism is dominated by formation of particle-hole states, as was conjectured by Arnold.[10] It also shows that a model which successfully reproduces the ground-state photonuclear transitions with photon energies 40–140 MeV is also able to account for the radiative-capture transitions if the exchange-current contributions in both processes are properly taken into account.

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Composition of He Metastable Beams Formed by Charge Exchange in He^+-Alkali-Metal Collisions at Medium Energy

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The composition of He metastable beams formed by charge exchange on alkali-metal vapors is determined by a time-of-flight analysis. The relative abundance of the two components He(2^3S) and He(2^1S) is measured in the 100-1500-eV energy range. It is shown that a pure He(2^3S) beam is obtained with sodium as the exchange target, whereas rubidium is found to be the most efficient target to yield a He(2^1S) beam. Comparison is made with theoretical predictions.

Collisions involving excited atoms, especially metastable atoms, have received much attention in the past few years. It is well known[1-3] that intense metastable beams of hydrogen and rare gases can be produced by charge-exchange collisions of the corresponding ions with alkali-metal atom targets. Since the ionization potentials of the alkali-metal atoms are close to those of the rare-gas atoms in their first excited states, these charge-exchange reactions are nearly resonant and yield large cross sections. In the case of helium, the two metastable states He(2^1S) and He(2^3S) can be produced *a priori*. However, only the sum of the singlet and the triplet total charge-exchange cross section has been measured.[2,4] Although the ground-state and metastable fractions of the beam are known from the measurements of Neynaber and Magnuson[5] and McCullough, Goffe, and Gilbody,[3] the relative population of the He(2^1S) and He(2^3S) states has never been determined to our knowledge. The standard reference to date for the He metastable production is the theoretical prediction of Olson and Smith.[6] The only experimental determination of a beam composition concerns the formation of a neon metastable beam using a laser-induced fluorescence (LIF) technique.[7] In this paper we report the first *direct* measurement of the relative He(2^3S) to He(2^1S) population of a metastable helium beam obtained by charge exchange with Na, K, Rb, and Cs at-