Atomic-Excitation Effects on Nuclear Reactions

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(Received 5 June 1980)

Atomic-excitation effects arising from sudden nuclear recoil are shown to be a significant factor in broadening the 14.23-MeV resonance in $^{12}C(p,p)^{12}C$ measured with a high-energy-resolution polarized beam. The total width of the resonance is found to be 1010 ± 30 eV.

PACS numbers: 25.90.+k, 24.30.-v, 24.70.+s, 34.90.+q

The effects of excitation of an atom on the reaction of its nucleus with a projectile are of interest because of the insight into the mechanisms of atomic and nuclear collisions these effects can provide. Here we demonstrate atomic-excitation effects on nuclear reactions in which the nuclear interaction time is shorter than atomic periods, so that the collision can be approximated as sudden with respect to atomic motions. The atomic effects are revealed by their contribution to broadening of the very narrow isolated resonance (width $\Gamma \sim 1$ keV) in $^{12}C(p,p)^{12}C$ at a proton energy near 14.23 MeV. Our attribution of the broadening to atomic effects is supported by measuring simultaneously at four proton scattering angles the excitation functions of the analyzing power, A_y, and differential cross section, σ, with a high-energy-resolution polarized beam. In the analysis we carefully consider other line-broadening effects. Further, our data and analysis resolve a discrepancy between two different methods[1,2] of determining the width of this resonance.

For a proton of energy about 14 MeV scattered from a carbon nucleus at angles of more than a few degrees, the proton and the recoiling nucleus move through the atom in a time less than a carbon K-electron period. The time delay implied by $\Gamma \sim 1$ keV ($<10^{-18}$ sec) is similarly small. Therefore, the excitation of the atom arises predominantly from the sudden recoil of its charge center (the C nucleus) from under the electron cloud. The probability of exciting the electrons to a state (f) with energy E_f from an initial state (i) is

$$P(E_f) = |\langle f|R|i\rangle|^2, \tag{1}$$

where the recoil operator R is

$$R = \exp(-i\vec{k}_R \cdot \textstyle\sum_j \vec{r}_j), \tag{2}$$

with $\vec{k}_R$ the nuclear recoil vector and $\vec{r}_j$ the coordinate of the jth electron. To the extent that the atom is an isolated system, an electronic excitation energy E_f implies a decrease in the energy available for the nuclear reaction. Thus, any observable O at nominal projectile energy E_p is measured as $\tilde{O}$, the convolution of O with P, where

$$\tilde{O}(E_p) = \int O(E_p - E_f)P(E_f)\,dE_f. \tag{3}$$

If P has a distribution of comparable width to that of O, then $\tilde{O}$ will be noticeably broadened relative to O.

The atomic system analyzed here has so many final states which can be excited that it is impractical to use Eq. (1) directly. Instead, we use sum rules for the moments of the energy distribution and infer a distribution $P(E_f)$ compatible with these moments. The mth moment about the mean excitation energy $\bar{E}_f$ is defined by[3]

$$\Delta E_m' = S_{E_f}(E_f - \bar{E}_f)^m P(E_f), \tag{4}$$

where a summation is carried over the discrete set together with an integration over the continuum set of $P(E_f)$, and this can be readily manipulated into

$$\Delta E_m' = \langle i|R^\dagger(H - \bar{E}_f)^m R|i\rangle, \tag{5}$$

where H is the Hamiltonian of the atomic system. By using hydrogenic wave functions, we find a dispersion given by

$$\Delta E_2' = \frac{8}{3}\left(\frac{v_R}{\alpha c}\right)^2 R_\infty^2 \sum_i Z_{\text{eff}}^2(i)\frac{2l_i+1}{n_i^2}, \tag{6}$$

where v_R is the nuclear recoil speed and $Z_{\text{eff}}(i)$ is the effective charge in orbit i.[4] The skewness is given by

$$\Delta E_3' = \frac{16}{3}\left(\frac{v_R}{\alpha c}\right)^3 R_\infty^3 \sum_i Z_{\text{eff}}^3(i)\frac{\delta_{l_i,0}}{n_i^3}. \tag{7}$$

For large E_f, a Born-approximation calculation shows that $P(E_f) \propto E^{-9/2}$; therefore the fourth and higher moments diverge. In Eqs. (5) and (6), exchange terms are neglected because we calculate that in the present analysis they contribute <1%

to the dispersion. From Eq. (1) the probability that the carbon atom remains in the ground state can be calculated directly if hydrogenic wave functions are used. It is found to be <4% for all proton scattering angles beyond 20°. Given the moments from Eqs. (6) and (7) and the behavior of $P(E_f)$ for large E_f, one can construct a distribution $P(E_f)$ for a given atom and recoil speed. An example is shown in Fig. 1(b) for the carbon recoil corresponding to scattering of the proton through a laboratory angle of 139°. This distribution is not unique and ignores the discreteness of the bound states, but we find it to be insensitive to the analytic representation chosen, given the moment constraints. Over much of its range $P(E_f)$ can be closely approximated by a Lorentzian having the same full width at half maximum

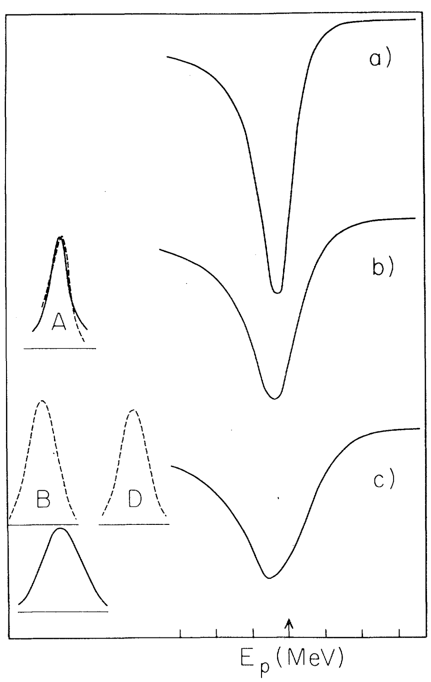

FIG. 1. Atomic-excitation and energy-resolution effects on a nuclear cross-section excitation function. Shown in (a) is the purely nuclear excitation function. The left of (b) is the atomic-excitation probability (dashed curve) and its Lorentzian approximation (solid curve). The convolution of A with (a) produces (b). To the left of (c) are the beam-energy profile used (dashed curve B), the Doppler-broadening profile (dashed curve D) and their convolution (solid curve); its convolution with (b) produces the excitation function (c), compared with data in Fig. 2. The tick marks show 1-keV energy steps, with the probability distributions on the same energy scale. The arrow indicates E_R.

Δ_A [Fig. 1(b)], and so we used this approximation in the subsequent analysis; the observed width of the resonance is thereby increased from Γ to $\Gamma + \Delta_A$. Also $\Delta_A = 600 \pm 20$ eV for all of the scattering angles chosen, and the peak moves insignificantly over this range. Note that although atomic-excitation effects are present and vary smoothly for all proton bombarding energies, the nuclear resonance is used here to make them evident.

The $^{12}C(p,p)^{12}C$ isospin-forbidden resonance at a proton energy near 14.23 MeV is very suitable for our study, since the ^{12}C-nucleus recoil speed is large, while the resonance is narrow and isolated. If only a single cross-section excitation function were analyzed, as was previously,[2] there would be sufficient ambiguity in the analysis that the atomic effects could not be clearly identified as contributing to the observed resonance anomaly. However, at Triangle Universities Nuclear Laboratory (TUNL) a number of recent improvements have allowed polarized beams to be used with the TUNL high-energy-resolution system.[5] The combination produced 50 nA of polarized proton beam with an average polarization of 88%, and an energy resolution $\Delta_E = 850 \pm 40$ eV, as deduced in the analysis described below. The evaporated, self-supporting target of natural carbon produced an average beam energy loss of 310 eV, and a beam energy profile, including energy straggling, shown in Fig. 1(c). Differential-cross-section excitation functions were measured simultaneously at proton scattering laboratory angles of 60°, 120°, 139°, and 160° (c.m. angles 64.1°, 124.1°, 142.1°, and 161.6°) using a conventional arrangement of left-right detector pairs. The data shown in Fig. 2 have absolute errors in σ of about 5% and in A_y of about 3%. These errors and the statistical errors shown in Fig. 2 were included in the analysis.

In the resonance analysis we used a Breit-Wigner resonance with total width Γ, proton elastic-scattering partial width Γ_p, resonance energy E_R, and helicity amplitudes to describe the elastic scattering.[6] The constraints imposed by simultaneous fits to σ and A_y uniquely defined the helicity amplitudes at each angle when the same resonance and resolution parameters were required at all angles. At the high resolution used here, target lattice vibrations produce a significant Doppler broadening, shown in Fig. 1(c). The spectrum of lattice vibrations for the graphite microcrystallite target was deduced, as in Ref. 2, from the phonon spectrum determined for

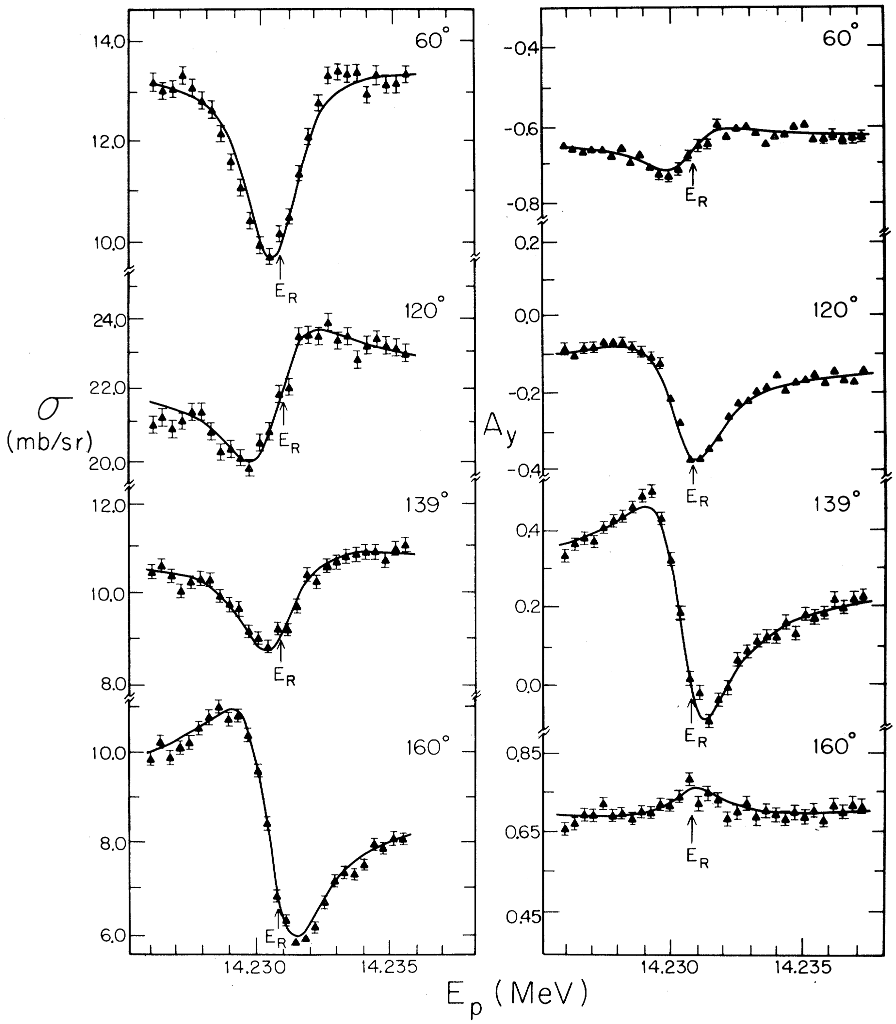

FIG. 2. Excitation functions of $^{12}C(p,p)^{12}C$ cross section (left) and analyzing power (right) in steps of 365 eV at four laboratory scattering angles. The error bars shown are statistical. The curves use the level parameters which simultaneously give the best fit to the eight excitation functions.

similarly prepared graphite. The large Doppler broadening of full width of half maximum $\Delta_D = 940 \pm 40$ eV arises from the large zero-point vibration in the intraplanar graphite lattice, and renders the analysis less sensitive to beam resolution, since the widths of these two distributions combine in quadrature. The atomic-excitation, beam-resolution plus straggling, and Doppler-broadening distributions were convoluted into the natural-resonance patterns, as indicated in Fig. 1, before comparison with the data. At each angle about 4000 combinations of parameters were used in grid searches to produce the best fits shown in Fig. 2 with use of the level parameters in Table I. The resonance energy $E_R = 14.230\,75$ MeV has been established elsewhere by an absolute determination.[7] The standard deviation among our values of E_R at the four angles is $\Delta E_R = 50$ eV (one-seventh of the energy step), confirming the consistency of our resonance analysis as a function of angle.

In Table I, we show level parameters for this state in ^{13}N as determined from a measurement of the decay branches of the state,[1] which is assumed to be not affected by atomic-excitation effects. Also shown are level parameters from a previous cross-section excitation-function analysis[2] which did not include atomic-excitation effects. If atomic-excitation effects are ignored in the analysis of our data, we find $\Gamma = 1610 \pm 20$

TABLE I. Level parameters for the 15.08-MeV state in ^{13}N as determined by decay and resonance methods. The total width Γ and proton elastic-scattering partial width Γ_p are given in the laboratory frame in electron volts. Uncertainties assigned in the present analysis are standard deviations among the widths determined at the four angles.

	Decay method	Resonance method	
	Ref. 1	Ref. 2	Present
Γ	930 ± 130	1200 ± 100	1010 ± 30
Γ_p	220 ± 25	230 ± 10	285 ± 15

eV, in strong disagreement with the value from the decay method. The comparison in Table I shows the importance of atomic-excitation effects on this resonance, and resolves the previous discrepancy between the decay and the resonance methods of determining Γ. The partial width Γ_p does not agree as well as do Refs. 1 and 2, a result for which we do not have an explanation, even though our results are based on the analysis of much more varied data than in Ref. 2.

Atomic-excitation effects similar to those investigated here are expected for other light nuclei,[8] and should be manifested by narrow resonances. Measurement of the corresponding spectrum of atomic excitation indicated in Fig. 1(b) is a challenge to atomic physicists and would provide data for further study of the interplay between atomic and nuclear physics.

We acknowledge help from S. A. Tonsfeldt and G. B. Lipton in the experiment and analysis. This research was supported in part by University of North Carolina Research Council grants and by the U. S. Department of Energy.

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Photodisintegration of Quasifree Nucleon-Nucleon System in the Beryllium Nucleus

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(Received 5 May 1980)

Momentum spectra of protons in the reaction of γ + Be→p + anything in the incident energy range from 180 to 420 MeV were measured. The spectrum obtained shows two peaks which are interpreted to be due to the protons in reactions γ + "N" →p + π and γ + "d" →p + n, where "N" and "d" are the quasifree nucleons and neutron-proton systems, respectively, in the beryllium nucleus.

PACS numbers: 25.20.+y, 21.60.Gx, 27.20.+n

A measurement was performed of the momentum spectrum of the photoproduced protons from the beryllium nucleus in order to investigate the nucleon-nucleon correlations or nuclear clustering effects inside the nucleus. A photon tagging system at the 1.3-GeV electron synchrotron at