Measurement of Nuclear Time-Delay Effects in δ-Electron Emission

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We demonstrate the feasibility of using δ electrons to study the influence of time-delay effects associated with isolated nuclear resonances on atomic excitation. With present techniques, variations in atomic ionization probabilities on the order of 20% can be detected. We present results for the case of δ-electron emission across the 12-keV-wide $p+{}^{12}C$ elastic-scattering resonance at 4.808 MeV. Such studies can extend measurements of nuclear-atomic time-delay effects to a range of time and energy previously inaccessible to experimental investigation.

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Experiments utilizing the effect of nuclear time delay on atomic excitation have been viewed as providing an alternative means of extracting information about nuclear scattering and reaction processes.[1] Theoretical and experimental activity in this field has demonstrated the existence of a phase change in the time development of atomic amplitudes in ionization[2] and capture[3] processes due to nuclear reactions. A similar effect has also been demonstrated in studies of nucleus-nucleus bremsstrahlung[4] in the vicinity of nuclear scattering resonances. The basic ingredient common to all these studies is the simple notion that a nuclear resonance or deep inelastic reaction[5] causes an interruption in the time evolution of the atomic or bremsstrahlung amplitudes by an amount t. This translates, within the context of semiclassical time-dependent perturbation theory,[6] into a shift in phase of the outgoing relative to the ingoing trajectory excitation amplitudes by an amount $\exp(i\omega t)$, where $\hbar\omega$ is, in general, the inelasticity of the ionization or bremsstrahlung process. This phase change causes variations in the atomic production probabilities for scattering events in which nuclear interactions occur. Full quantum-mechanical calculations of this effect have been performed,[7] and the physical picture associated with this semiclassical approach remains essentially the same.

For the case of ionization, $\hbar\omega$ is given approximately by the binding energy of the ionized electron in its initial state since excitation occurs with largest probability to low-lying continuum states. Quantitative evaluation of the interference effect, however, demands an integration over the entire ionized or δ-electron spectrum for the collision process being studied. This integration causes an averaging out of the inelasticity parameter and, as a result, a reduction in the experimentally observable interference effect. Measurement of the δ-electron spectrum itself therefore, in principle, allows for a simpler and more direct comparison between experiment and theory.

In studies of nuclear time-delay effects on atomic excitation carried out to date, the orbital time of the atomic electron in its initial state, $1/\omega$, and the nuclear time delay, t, were of comparable magnitude. However, if sufficiently energetic δ electrons are selected, the atomic inelasticity is no longer given by the binding energies of the electrons in their initial states, but rather by the sum of binding plus kinetic energy of the continuum electron in its final state. In such cases, the time scale associated with the orbital period of the initial-state atomic electron can be much longer than the time scale associated with nuclear time delay, although the inelasticity of the atomic collision process remains comparable to the resonance width. Such a study, therefore, affords a unique opportunity to explore the extent to which the atomic-nuclear interference effect reflects the time scale for atomic excitation versus the energy scale associated with this excitation.

We illustrate these remarks with the results of measurements of the nuclear time-delay effect associated with the 12-keV-wide, 4.808-MeV $d_{5/2}\,p+{}^{12}C$ resonance[8] on δ-electron emission in which the ionization probability for 6.5-keV electrons was studied. These measurements constitute the first studies of δ-electron emission in the vicinity of an isolated nuclear resonance. The experiment was performed at the Rutgers University's model FN tandem Van de Graaff accelerator with proton beams from both universal (UNIS) and Duoplasmatron-type negative ion sources. The accelerator object and image slits were used to reduce the beam intensity on target to approximately 15 pA, thereby simultaneously assuring that the energy spread of the beam was much less than 10 keV.

The apparatus consisted of a 25.4-cm inside diameter cylindrical brass chamber 1.68 m long, wound with six layers of water-cooled 0.635-cm-diam copper tubing to

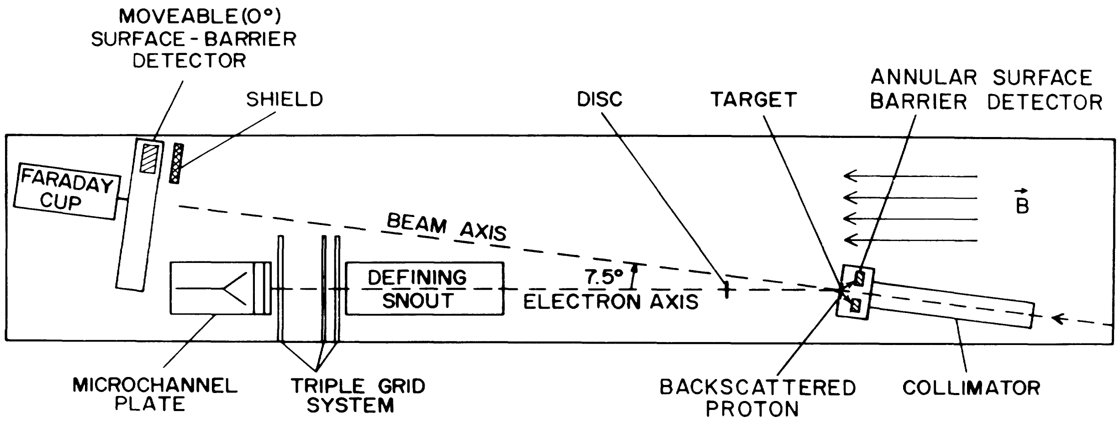

FIG. 1. Schematic illustration of solenoid–electrostatic-grid system used in this experiment. The movable surface-barrier detector at zero degrees was used, after our first strongly attenuating the beam, for monitoring and calibration purposes (Ref. 9).

produce a uniform solenoidal magnetic field of 1.9 G/A (see Fig. 1). The experiment was done with a field setting of 190 G. The beam entered the apparatus at an angle of 7.5° with respect to the solenoid axis and was collimated before being passed through an annular silicon surface barrier detector located 5.1 mm from the target foil subtending angles between 118° and 155°. The targets were 0.7-$\mu g/cm^2$ self-supporting carbon foils mounted on aluminum frames with 3.8-mm holes. Electrons were guided by the magnetic field from the target region past a small disk baffle and a cylindrical snout baffle through a triple electrostatic grid system to a microchannel plate (MCP). A shielded Faraday cup located downstream of the MCP served as a beam dump.

The surface-barrier detector located directly in front of the Faraday cup in Fig. 1 could be controlled from outside the vacuum system and, after collimation of the beam with slits located roughly 1 m upstream of the target (not shown in Fig. 1), moved directly into the beam. In this way, coincidences between the proton-beam particles and the MCP could be recorded. This technique was extremely valuable for our periodically checking the stability of the electronics, setting up timing, etc. For measurements of the ionization probability, this detector was removed from the beam, the beam current was increased, and coincidences between the MCP and the annular surface barrier detector were recorded with standard techniques. Coincidence and singles proton spectra were registered for off-line analysis and the singles MCP data were taken with scalers. Elastic-scattering background from ^{16}O due to water and hydrocarbon contaminants in the target could be resolved by the annular surface-barrier detector from elastic scattering due to ^{12}C and was eliminated by cuts in the off-line analysis. Background studies showed that more than 99% of the singles electrons originated from the target. At a beam current of approximately 15 pA, the singles proton rate was $\simeq 1$ Hz, the singles electron rate $\simeq 1\times10^4$, and the coincidence rate $\simeq 1$ event every 1 to 2 h for a true-to-chance ratio of 2 to 1. These rates resulted in a typical data taking time of 24 to 48 h per data point. Further experimental details and a description of the principle of operation of the spectrometer can be found in Ref. 9.

The acceptance of the spectrometer is determined by a combination of constraints on the electron momentum component perpendicular to the magnetic field due to the disk and snout baffles, and the component parallel to the field as given by the effect of the triple grid voltage. In addition, software cuts on the electron time of flight can be made using as start signals either the zero-degree surface barrier detector (for calibrations and checks), or, for the ionization probability data, the backward-angle detector. In general, the acceptance of the spectrometer depends strongly on the angular distribution of the δ electrons.[9] In particular, only electrons emitted from the target into the forward hemisphere can be detected. For forward-peaked binary-encounter–approximation angular distributions,[10] the acceptance is maximum at 6.5 keV and has a band pass (full width at half maximum) of 3.5 keV with an average detection efficiency within this band pass of 30%. For an isotropic angular distribution, the acceptance centroid is 6.4 keV with a band pass of 5.2 keV and an average detection efficiency of 7%.[9]

Since the production cross section for δ electrons in these collisions is large (3000 b/keV at 7 keV),[11] and the probability of production of a δ electron in collisions involving a backscattered proton is small (see Fig. 2 below), multiple collisions in which the proton produces a δ electron in one collision and then undergoes backscattering from the nucleus of a different atom in a second collision are not negligible. These backgrounds were checked by measurement of the δ-electron production probability in coincidence with backscattered protons as a function of target thickness. On the basis of

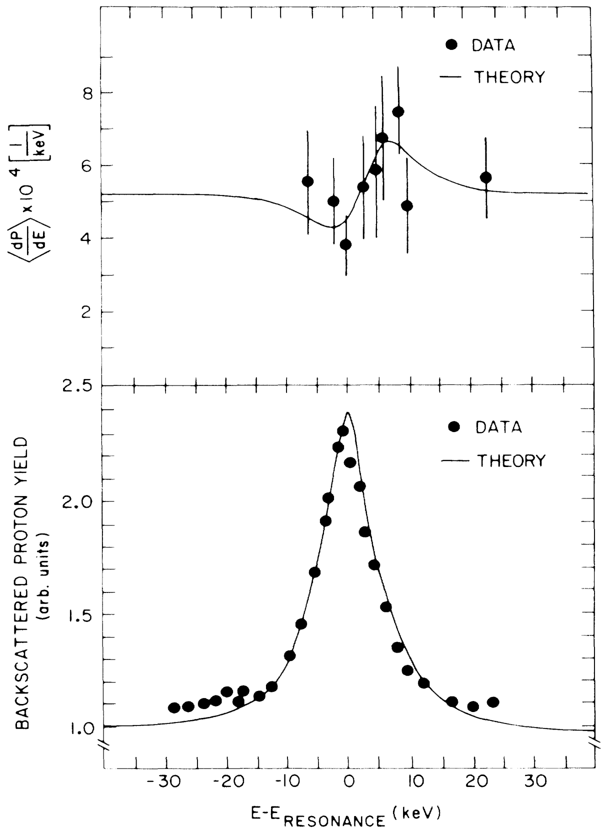

FIG. 2. Upper panel: Ionization probability for 6.5-keV δ electrons measured in this experiment vs beam energy. Lower panel: Resonance in backscattered proton yield in 4.808-MeV elastic $p+{}^{12}C$ scattering measured in this experiment. Points, data; smooth curves, theory. See text for details.

these studies, we estimate the double-collision contribution to the coincidence yield for 0.7-$\mu g/cm^2$ targets to be less than 25%. No correction to the data was made for these effects.

Figure 2 shows results for the δ-electron production probability determined in this experiment versus proton energy across the 4.808-MeV resonance (upper portion of figure). The lower part of Fig. 2 shows the variation in the proton scattering cross section as the resonance is traversed. In our determining the absolute magnitude of the ionization probability, the spectrometer acceptance corresponding to isotropic δ-electron emission has been assumed. The error bars are relative errors only and reflect a convolution of statistical and systematic errors. There is an additional overall error in absolute magnitude of 30% due to uncertainties in absolute electron detection efficiency and target thickness.

The smooth solid curves in the lower and upper parts of Fig. 2 are theoretical calculations of the nuclear scattering yields and ionization probabilities, respectively. The resonant portion of the nuclear scattering cross section was taken to be of Breit-Wigner form with an elastic-proton partial width of 10 keV. Background phase shifts due to Coulomb and direct nuclear scattering were included in the calculations. Values for these background phase shifts were checked by our confirming that measured off-resonance cross sections[8] are successfully reproduced. Inspection of the bottom part of Fig. 2 shows that the measured backscattered proton yields are well reproduced by theory throughout the resonance region. Since the experiment did not attempt to measure absolute values for the proton-scattering cross sections, theory has been normalized to the data in this figure.

The atomic portion of the calculation includes contributions from K-shell δ electrons only over the experimentally detected electron-energy interval.[12] In principle, L-shell contributions could also be computed with a code containing more precise calculation of the L-shell wave functions and excitation matrix elements. The electron angular distributions were not calculated, but with half of the differential K-shell ionization probability arising from monopole excitations, we estimate this angular dependence to be nearly isotropic. In comparison of theory and experiment (upper portion of Fig. 2), an isotropic electron angular distribution has been assumed, and theory has been arbitrarily multiplied by a factor of 2. Calculations of the relative K- and L-shell contributions at δ-electron energies up to 2 keV were made, and extrapolations of these results to the electron energies of interest to this experiment indicate that comparable contributions to the δ-electron yields from the two shells can be expected. Therefore, the use of an overall normalization factor of 2 in Fig. 2 is physically reasonable. Theory predicts first a dip, then a rise in the ionization probability as the beam energy is increased through the resonance region. Examination of Fig. 2 shows overall agreement with the data.

In conclusion, we have measured the dependence of the ionization probability for 6.5-keV δ electrons across the 4.808-MeV $p+{}^{12}C$ resonance. The data exhibit a fluctuation whose relative size and shape are well reproduced by theory. These results show that measurements of nuclear resonant effects in ionization are possible even if the atomic binding energy does not match the nuclear width. So far, this restriction has only been partially circumvented by measurement of electron capture instead of ionization.[1,3,12] However, even this method has a kinematical restriction though, instead of $\Gamma \sim E_b$, as for ionization, one has $\Gamma \sim E_b + v^2/2$, where Γ is the resonance width, E_b is the binding energy, and v the collision velocity (atomic units). Thus, the δ-electron method permits studies of interference effects which have, up to this time, not been accessible to experimental investigation.

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