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Nuclear "Time-Delay" and X-Ray–Proton Coincidences near a Nuclear Scattering Resonance

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The probability for production of K-shell x rays by protons elastically scattered from ^{58}Ni is observed to change as one varies the proton energy over the $s_{1/2}$ nuclear resonance at $E_p = 3.151$ MeV. The results are interpreted theoretically in terms of interfering products of atomic ionization and energy-dependent nuclear scattering amplitudes.

We present experimental evidence for a change in the probability for production of K-shell x rays by protons elastically scattered to a definite angle θ as one varies the incident proton energy over a narrow nuclear resonance. This is the first experiment in which the nuclear "time delay" associated with a resonance has been observed to change the rate of an atomic excitation. In a time-dependent description, a time delay τ causes the amplitude for excitation of an electron "before" to be advanced in time relative to the amplitude for excitation "after" the nuclear collision by the factor $\exp(-i\omega\tau)$, where $\hbar\omega$ is the energy transfer to the electron.[1,2] In the time-independent description actually used in interpreting our experiment, we find that the exponential factor is replaced by the ratio of nuclear-reaction amplitudes $f(E-\hbar\omega)/f(E)$; time delay is manifested by the energy variation of these amplitudes. We demonstrate that this type of experiment, unlike previous scattering experiments,[3] is sensitive to the imaginary part of the dominant (monopole) atomic ionization amplitudes. The present experimental results suggest that this imaginary part may not be well understood.

Our theoretical treatment was motivated by the need for expressions appropriate to experiments which involve a "mixture" of nuclear lifetimes (as is the case for a resonance-plus-Coulomb scattering) and incident beams whose energy spread is small compared to the width of the nuclear resonance. Semiclassical time-dependent perturbation-theory treatments[1,2] of K-shell ionization are inappropriate in these circumstances. Therefore, we have reformulated the theory of K-shell ionization in terms of time-independent perturbation theory, taking explicit account of conservation of energy and angular momentum in all portions of the electron-nuclear wave function as well as correct matching of nuclear wave functions at a radius small compared to atomic but large compared to nuclear dimensions; a WKB approximation is used in obtaining the atomic amplitudes. The resulting cross section for producing a nuclear particle at angle θ (c.m.) in coincidence with a K-shell X ray takes the intuitively plausible form[4]

$$\frac{d\sigma_{\text{coinc}}}{d\Omega}=2\omega_K\sum_{l,m}\int_0^\infty d\epsilon|A(\epsilon,l,m)f(\theta,E-\hbar\omega)+B(\epsilon,l,m)f(\theta,E)|^2. \tag{1}$$

Here ω_K is the fraction of K-shell vacancies which produce K-shell x rays; f is the nuclear reaction amplitude (in our case, a single complex amplitude representing an s-wave resonance plus a Coulomb background); A is the semiclassical amplitude for the projectile "on the way in" to excite an electron into the continuum with final kinetic energy ϵ, orbital angular momentum l, and angular momentum projection m, while B is the corresponding amplitude for exciting the electron "on the way out." (The imaginary parts of the $l=0$ amplitudes include contributions due to the altered charge of the united atom while the projectile is inside the nucleus.) The energy transfer to the electron is $\hbar\omega=\epsilon+I$ where I is the ionization energy; E is the center-of-mass incident projectile energy. Excitation of bound states is neglected. The probability for x-ray production in this reaction is just the ratio of Eq. (1) to the nulcear cross section $|f(\theta,E)|^2$; a measure of this probability is the coincidence-to-singles ratio for the nuclear particle.

The crucial feature of Eq. (1) is that the energies characterizing the nuclear amplitudes differ by the atomic excitation energy $\hbar\omega$, and thus the cross section will contain products of interfering nuclear amplitudes with differing projectile energies. In this time-independent formulation the effects of time delay are contained in the energy dependence of Eq. (1).[5]

In a situation where the nuclear amplitudes are well understood, one is afforded the opportunity of studying the atomic amplitudes. Only monopole ($l=0$) and dipole ($l=1$) atomic excitations are typically important. At $\theta=90°$ the only interference terms arise from the monopole amplitudes, since it is readily shown[1-3] that the semiclassical dipole amplitudes make no interference contribution at this angle. When the nuclear reaction is elastic scattering of a charged particle, a further important simplification results for monopole amplitudes[2,3] in first-order perturbation theories; namely, $A^*(\epsilon,0,0)=B(\epsilon,0,0)$. This has the immediate consequence that when there is no nuclear time delay, i.e., when $f(\theta,E)=f(\theta,E-\hbar\omega)$ (which was the case in previous coincidence-scattering experiments[3]), the coincidence-to-singles ratio involves only $[\mathrm{Re}A(\epsilon,0,0)]^2$. Thus the imaginary part of the monopole amplitude becomes accessible to observation only when there is a time delay.

This variation in the x-ray production probability is analogous to the change in the probability for bremsstrahlung production due to nuclear time delay. The original discussion[6] of a bremsstrahlung effect was also couched in terms of semiclassical time-dependent perturbation theory. A later time-independent formulation[7] yields a result similar in form to that of Eq. (1) (unlike the atomic case, however, the bremsstrahlung amplitudes are essentially real in situations of practical interest). Experimental confirmation of the predictions of Ref. 6 has recently been reported.[8]

Another related phenomenon is the observed splitting of the α-α resonance at 184 keV due to the transitory formation of a united ^{8}Be atom.[9] A quantitative discussion[10] of this has been given which assumes sudden formation of the united atom. Because of this assumption and the restriction to a resonance width very much less than the atomic splittings, the expression for the probability of producing a K-shell vacancy implicit in Ref. 10 differs considerably from Eq. (1) and does not manifest an interference effect.

Our experiment consists of coincident observations of K-shell x rays and protons elastically scattered from ^{58}Ni in the region of the narrow ($\Gamma=5.6$ keV) $s_{1/2}$ nuclear scattering resonance $E_p=3.151$ MeV.[11] We chose this resonance because the nuclear amplitudes are known, the cross section is large, and the width is much larger than the experimental proton energy spread (< 1 keV in our measurements). Here also the electron energy transfer $\hbar\omega$, which is $\gtrsim I=8.3$ keV, is comparable to Γ. This maximizes the interference effect.

Protons scattered from a 9-μg/cm^2 ^{58}Ni target on a 20-μg/cm^2 C backing with $\theta_{\text{target}}=45°$ were detected in a solid-state detector behind a rectangular 0.45×1.7-cm^2 aperture subtending $\Delta\theta=\pm 18°$ centered at $\theta\simeq 95°$. This choice of proton angle and solid angle resulted in a large yield and a deep symmetric resonance minimum and eliminated significant contributions from weak neighboring p-wave resonances. Also, as mentioned above, only monopole interference is important at $\theta\simeq 90°$.

The energy resolution of the proton detector was 60 keV; this permitted us to distinguish the protons which were elastically scattered by ^{58}Ni from those scattered by the backing. X rays were detected in the scattering plane by a 4.8-cm-diam $\times$0.08-cm NaI(Tl) scintillator ($\Delta E/E \simeq 40\%$ at 7 keV) 0.8 cm from the target, centered at $\theta = -90°$, and viewed by an RCA 8575 phototube. The x-ray spectrum was dominated by a single line near $E \simeq 7.5$ keV due to the K x rays from ^{58}Ni. A separate spectrum taken with a Si(Li) detector ($\Delta E \simeq 300$ eV) showed no other lines near this energy. Using standard fast-timing techniques, singles protons, singles x rays, and coincidences between protons and x rays were event recorded for three parameters: proton energy, x-ray energy, and time-to-amplitude–converter amplitude. The time resolution was $\simeq 12$ nsec full width at half maximum and a typical real-to-random ratio was ~1:10 (for a window 60 nsec wide encompassing the strongly asymmetric peak) obtained at a beam current of $\simeq 0.8$ nA.

A typical singles-proton excitation curve is shown in Fig. 1(a). Coincidence measurements were made at five energies; the ratios of coincidence-to-singles events, normalized to unity off resonance, are shown in Fig. 1(b). The middle points (at $E_p = E_R$, $E_R + 4$ keV, and $E_R + 8$ keV,

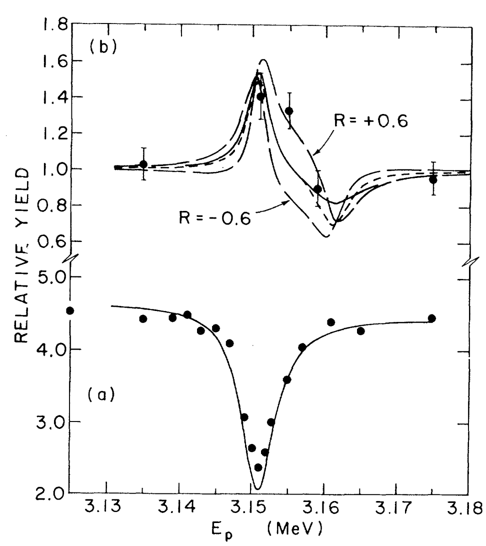

FIG. 1. (a) Observed and calculated singles excitation functions for protons elastically scattered for ^{58}Ni. (b) Ratio of proton yield in coincidence with K x rays to the singles-proton yield, normalized to unity off resonance. Long-dashed curves, zero-order calculations with R ($\equiv \mathrm{Im}B/\mathrm{Re}B$) $= +0.6$ and -0.6; short-dashed curve, $R=0$; solid curve, a detailed calculation (see text).

where E_R is the nuclear resonance energy) are in the region where interference effects are expected to be greatest. The measured ratios show a clear variation with energy.

Each ratio is the sum of three separate runs, ~6 h/run, which were all in good statistical agreement. These data contain corrections for dead time, randoms subtraction, and small changes in the x-ray gain. We have neglected small corrections ($\lesssim 3\%$ in both cases) for the effects of small beam motion in the close geometry, and for events in which the proton scattering and the x-ray production take place in separate atoms.

Our interpretation of these coincidence measurements proceeds at two levels:

(a) To illustrate the role of the atomic amplitudes, we display in Fig. 1(b) some "zero-order" calculations of the coincidence-to-singles rate in which we neglect dipole contributions and we assume that we need consider only the monopole amplitude corresponding to a single value of the electron energy transfer, namely $\hbar\omega = 10$ keV (detailed calculations indicate that this is the most probable value). All of our calculations include proper angular averages over the detector acceptances. Using the monopole relation $A = B^*$ (see above), it is easily shown that the coincidence-to-singles ratio then depends only on the ratio $R \equiv \mathrm{Im}B/\mathrm{Re}B$. Here, rather than adopt a value of R calculated with a specific model for the ionization, we treat R as a parameter. One sees from Fig. 1(b) that the excitation function for the coincidence-to-singles ratio is indeed sensitive to the value of R. The curve for $R = +0.6$ is in reasonable agreement with the present experimental results.

(b) Next we turn to more detailed theoretical calculations in which we perform the integration over the electron kinetic energy and use standard semiclassical expressions for the monopole amplitudes.[3,12,13] Nonrelativistic hydrogenic wave functions are assumed in the derivation of these expressions. Proper evaluation of the relatively unimportant dipole amplitudes has not been made; we have, however, estimated them from the calculated results of Andersen *et al.*[3] for 2.0-MeV protons on Cu. The resulting solid curve in Fig. 1(b) is similar to the $R=0$ "zero-order" result at energies $\lesssim E_R + 8$ keV. Like the latter, it is consistent with experiment at $E = E_R$ but not at $E = E_R + 4$ keV. The failure to fit the intermediate datum point cannot be attributed to our estimate of the dipole contributions: Changing the dipole rate by ± 100% alters the three middle points of Fig. 1(b) by $\lesssim \pm 4\%$. Therefore, the standard treatment of the atomic monopole amplitude does not appear adequate when compared to our experimental results.

In summary, we have presented theoretical expressions for x-ray production in nuclear reactions involving time delay, and we have shown the unique effect of this nuclear time delay in making the imaginary parts of the atomic monopole amplitudes accessible to experiment. We have experimentally observed the effect of a nuclear time delay on the probability for x-ray production by protons scattered at energies near a narrow nuclear resonance. Our detailed calculations agree with experiment except at $E = E_R + 4$ keV, suggesting that the imaginary parts of the atomic monopole amplitude may not be given adequately by standard semiclassical theory.

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$$f(E-\hbar\omega) \cong f(E) - \hbar\omega\, df(E)/dE$$

the x-ray production probability consists of the term which one would have if f were independent of E plus the "correction" term

$$4\omega_K \sum_{l,m} \int d\epsilon\, \omega\, \mathrm{Im}\{[A(\epsilon)B^*(\epsilon) + |A(\epsilon)|^2]\Delta t_E\},$$

where $\Delta t_E = -i\hbar d(\ln f)/dE$ is the (complex) nuclear time delay for energy E; see N. Austern, *Direct Nuclear Reaction Theories* (Wiley Interscience, New York, 1970). This definition of Δt_E is consistent with τ of our first paragraph when the factors there are expanded to first order in ω.

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Magnetic Field Generation by the Rayleigh-Taylor Instability

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A theoretical and simulation study shows that a plasma subject to a Rayleigh-Taylor instability exhibits spontaneous magnetic fields. Such magnetic fields in a laser-fusion configuration may significantly reduce the hot-electron thermal transport. Modification in the transport also suggests that the ablation velocity is altered.

It has been recognized that spontaneous magnetic fields generated in laser-produced plasmas strongly modify the transport processes,[1] in particular, the heat conduction due to both hot and cold electrons. This modified transport may significantly change the compression processes of the pellet core. Many mechanisms of magnetic field generation have been intensively investigated[2-5] in recent years. Some of them are directly related to the plasma production and heating due to intense laser irradiation: (i) Nonuniform irradiation produces a nonzero $\nabla n \times \nabla T$, which gives rise to magnetic fields; (ii) upon absorption of the radiation, the momentum and energy of the electromagnetic wave are transferred to electrons and the incurred eddy currents generate magnetic fields. The latter effect is particularly prominent at the critical-density region