ed ions in the Pm sequence. The dipole transition matrix elements were computed directly from the Hartree-Fock 5s and 5p wave functions with use of a frozen core: No corrections for relativity or core polarization (an inert-gas core tends to be rigid to dipole distortions) were made in the line-strength calculations. The leading relativistic corrections to the energy levels were made as discussed above and these effects have been included in the predicted wavelengths and mean lives.

These systems should be amenable to study by beam-foil excitation methods. In the grazing incidence spectral region techniques have been developed[9] which permit a beam segment as short as 80 μm to be spatially resolved, which should permit lifetime measurements down to the 10-psec range with the beam velocities required to produce these states.[10] Beams of sufficient energy to produce these ionizations have already been produced[11] for studies in the $\lambda = 30-80$ Å region.

In conclusion we suggest that the spectra of the ions in the upper half of the promethium sequence will be approximately alkalilike, will be of interest in plasma diagnostics, and will be fruitful objects of further research, both experimental and theoretical.

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Experimental Evidence for the Influence of Inner-Shell Ionization on Resonant Nuclear Scattering

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Coincident measurements on ^{12}C of *KLL* Auger electrons and backscattered protons at 125° show that the *K*-shell ionization probability varies over the 461-keV *s*-wave resonance. The data are explained through a change in the phase shifts for simultaneous ionization and scattering, due to the dipole ionization amplitude.

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In heavy-particle collisions with zero impact parameter and at sufficient energy, atomic excitation and ionization processes may occur simultaneously with nuclear reactions. In such cases the two kinds of processes influence each other by different mechanisms. A simple example is the broadening and shift of a nuclear scattering resonance as observed in the formation of the ^{8}Be compound nucleus in α scattering on He,[1] which are caused by energy loss in atomic processes. Usually, however, the influence of atomic excitation or ionization processes is small so that this influence on the nuclear reaction is hardly detectable. In order to study the mechanisms of interaction it is then necessary to perform coincidence measurements by which the simultaneous atomic and nuclear events are selected for observation. Such a measurement has been performed for the case of the 3.151-MeV resonance in proton scattering on ^{58}Ni.[2] The difference between the simultaneous events and the single-nuclear events was explained by "time delay" connected with the nuclear resonance that leads to a phase shift between the two coherent amplitudes for K-shell ionization before and after the nuclear collision. Although the main features of the observed resonance structure for the combined nuclear and atomic events could be explained in this way, there remained a significant discrepancy which was quoted as not understood and which therefore suggested that some other mechanism may be involved.

To search for such a mechanism we have performed similar measurements on the 461-keV resonance in proton scattering on ^{12}C. This system was chosen because the effect of "time delay" is negligible.[3,4] The energy loss due to K-shell ionization is much smaller than the width of the resonance (38 keV). In this Letter we report our results which indeed prove the existence of another mechanism. We propose that it can be identified as the effect of the dipole and higher-multipole amplitudes for K-shell ionization.

At low energies—particle velocities of Z_2 a.u. (Z_2 being the target atomic number)—the monopole and dipole amplitudes ($\Delta l = 0$ or 1) are the main contributions to the K-shell ionization probability.[4] For total ionization cross sections the possible change in angular momentum of the projectile will not be important. The angular momenta involved in the projectile scattering can be as large as $200\hbar$.[5] For low-energy nuclear scattering, where only s-wave scattering is important, it has been argued before that the dipole and higher-multipole ionization amplitudes may have an influence on the interaction.[6] It has also been calculated that these effects will not easily be seen in purely elastic scattering.[7,8] We will demonstrate that it may be possible to observe the influence of dipole and higher-multipole amplitudes by comparing nuclear s-wave resonance shapes corresponding to scattering with and without simultaneous K-shell ionization.

The measurements on K-shell ionization in coincidence with elastic proton scattering on ^{12}C near the 461-keV s-wave resonance[9] were performed with a 1-MeV Van de Graaff generator, which had an energy resolution of 500 eV. The target, a 2-μg/cm^2 self-supporting natural-carbon foil (>99% ^{12}C), had a stopping power of 2 keV. Both values, the stopping power and the resolution, are sufficiently small compared with the width of the resonance so that the shape of the resonance is not distorted.

Scattered protons were detected by a surface-barrier detector centered at a scattering angle of 125°, covering a solid angle of 0.25 sr. The energy resolution of the detector was about 50 keV. K-shell ionization was identified by the KLL Auger electrons. In this way an optimal detection efficiency for ionization was obtained, because K-shell holes of carbon decay for more than 99% by Auger electrons. To ensure the best possible ratio of Auger electrons to secondary electrons, detection was done at backward angles with respect to the incoming protons. The proton beam, with a diameter of 0.3 mm, was directed through a 10-cm-long tube (diameter 3 mm), through the center of a specially designed electron spectrometer.

The spectrometer consisted of a combination of a retarding grid and a cylindrical-mirror analyzer with a Channeltron as the detector. A circular aperture, with its center directed at 170° with respect to the beam, covered 175°–145° in θ and 30% of the φ range. The resulting solid angle was about 0.2 sr. The spectrometer showed an energy resolution of 7 eV, independent of the electron energy, and a transmission of about 40%. Since in our experiment a foil is used instead of a gaseous target, the KLL Auger peak is slightly shifted and smeared out with a tail to the lower-energy side. Electrons from deeper layers than the surface will have lost energy. In the coincidence experiment a fixed setting of the spectrometer at 250 eV was chosen.

Coincidences between protons and electrons were recorded with a time-to-amplitude converter and a pulse-height analyzer. A time resolution of 12 nsec full width at half maximum was obtained. Typical count rates of 50–100 protons/sec and ~3000 electrons/sec with beams of ~150 pA resulted in a real-to-random coincidences ratio of 1 : 1 in a 30-nsec time window.

A yield curve of backscattered protons as a function of the energy of the incoming protons is shown in Fig. 1(a). Since the probability for K-shell ionization along any trajectory is small compared to 1, this curve represents nuclear scattering without simultaneous ionization. The energy dependence of the noncoincident electron rate was found to be constant within 3%. This can be understood for two reasons: (i) The K-shell ionization cross section for "noncentral" collisions is almost constant in our proton-energy region; (ii) the contribution to ionization from "central" collisions is small because the main contribution to K-shell ionization comes from large impact parameters. The constancy with proton energy of the noncoincident electron rate was used to correct for the decreasing gain of the Channeltron during the experiment.

The backscattered protons measured in coincidence with Auger electrons show a similar energy dependence as the protons without simultaneous ionization. To bring out the difference, the ratio of coincident to single proton scattering events is plotted in Fig. 1(b). Each measurement, with a total running time of about 24 h, consists of several runs and represents 100–500 coincidences depending on the primary energy.

To interpret our results we want to make an *Ansatz* which incorporates the influence on the nuclear scattering with simultaneous ionization of both the resonance width and other possible mechanisms. To achieve this aim, we will formulate expressions for both the yields of backscattered protons with and without simultaneous K-shell ionization in terms of proton-scattering amplitudes. The ratio of the two expressions will represent the ionization probability at a specific scattering angle. This expression differs only from the usual way of expressing an impact-parameter–dependent ionization probability through the fact that the resonant–projectile-energy dependence has been explicitly taken into account.

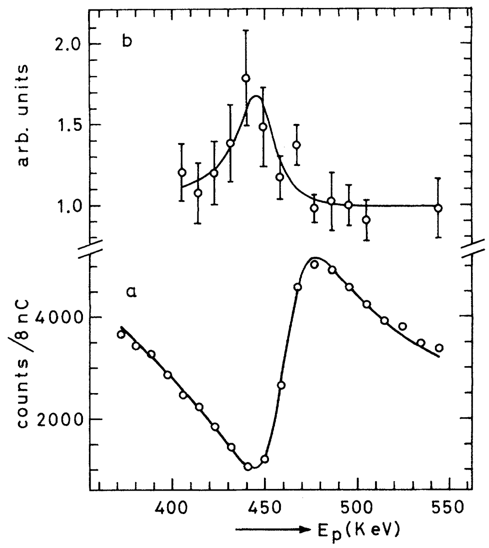

FIG. 1. (a) Elastically scattered protons from ^{12}C measured at $\theta_{scat} = 125°$. The data are fitted with the expression given by Eq. (2). (b) The ratio of the yields of backscattered protons with and without a coincident electron normalized to unity (off the resonance at 550 keV). The data are fitted with the expression given by Eq. (4).

We will first analyze the energy dependence of the yield of single backscattered protons. The two scattering amplitudes involved, the Coulomb amplitude and the resonant amplitude, will add coherently[10]:

$$I_s = N_1 | -\gamma [2k \sin^2(\theta/2)]^{-1} \exp\{-i\gamma \ln[\sin^2(\theta/2)] + 2i\sigma_0\} + k^{-1} \sin\delta \exp(i\delta + 2i\sigma_0)|^2 \quad (1)$$

with $\gamma = Z_1 Z_2 e^2/\hbar v$, $\sigma_0 = \arg\Gamma(1+i\gamma)$, $\delta = \tan^{-1}[\Gamma/2(E_r - E)]$ (where $E_r = 461$ keV, $\Gamma = 38$ keV), N_1 the normalization constant, and k the wave number.

We modify Eq. (1) to include direct nuclear scattering. Since this scattering is mostly s wave and slowly varying with energy, we separate from the addition of the coherent amplitudes the $1/E$ dependence of the Coulomb scattering amplitude. The direct nuclear scattering is included in the free parameters C and φ:

$$I_s = N_1 k^{-1} | C \exp i\varphi + \sin\delta \exp i\delta |^2 = N_2 E^{-2} | 1 + C^{-1} \sin\delta \exp[i(\delta - \varphi)]|^2. \quad (2)$$

A fit of the data with Eq. (2) gives the following values for the two parameters: $C = -0.75 \pm 0.01$ and $\varphi = 0.45 \pm 0.01$ rad. For pure Coulomb scattering $C_C = -\gamma(2\sin^2\theta/2)^{-1} = -0.89$ and $\varphi_C = -\gamma \ln(\sin^2\theta/2) = +0.33$. The difference between the fitted and the calculated values confirms that direct nuclear scattering is present in this energy region. Phase-shift analysis shows that the phase shift does not completely change by π over the resonance.[9]

Including the effect of energy loss due to K-shell ionization, we deduce from Eq. (2) the following formula to analyze the coincident data, which correspond to scattering with simultaneous ionization:

$$I_c = N_3 E^{-2} | 2 + D^{-1}[\exp - i\theta][\sin\delta(E')\exp i\delta(E') + \sin\delta(E)\exp i\delta(E)]|^2, \quad (3)$$

where $E' = E - E_k$, with E being the proton energy and E_k being the K-shell binding energy. D and θ account for the size and the phase of the Coulomb amplitude with respect to the resonant-scattering amplitude. They are used as free parameters to incorporate the possibility of a different interference between Coulomb scattering and resonant nuclear scattering, when ionization is present. The resonant scattering amplitude is split into two parts corresponding to ionization before and after compound-nucleus formation.

An expression for the ratio of scattered protons with and without simultaneous ionization is obtained by combining Eqs. (2) and (3):

$$\frac{N_1|2+D^{-1}[\exp-i\theta][\sin\delta(E')\exp i\delta(E')+\sin\delta(E)\exp i\delta(E)]|^2}{|1+C^{-1}\sin\delta(E)\exp i[\delta(E)-\varphi]|^2}. \quad (4)$$

The fit of the measured ratio with formula (4) is shown in Fig. 1(b); only D and φ are varied while C and θ are determined from the fit of the singles yield with formula (2). The following values are found: $D=-0.62\pm0.05$ and $\theta=0.20\pm0.06$ rad. The inequality of the parameters D and C and of the parameters θ and φ, respectively, shows that the Coulomb scattering and the nuclear resonant scattering interfere in a different way for the case with and without simultaneous K-shell ionization.

We conclude, therefore, that the phase change observed is due to the influence of dipole and higher-multipole ionization amplitudes, causing angular momentum exchange, on the combined process of inner-shell ionization and the scattering of the ionizing particle from the nucleus. This influence manifests itself through the change of the impact-parameter–dependent ionization probability in the neighborhood of a nuclear scattering resonance; or, formulated in a different way, in the change of the shape of a nuclear s-wave resonance when measured with or without simultaneous K-shell ionization. In the study of time-delay effects in compound-nucleus formation, this effect should be taken into account.

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Theory of Spin Relaxation and Recombination in Spin-Polarized Atomic Hydrogen

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A calculation is presented of the relaxation rate T_1^{-1} between the lowest two hyperfine states of a dilute gas of H atoms in high magnetic field at low temperatures. Dipole-dipole interactions dominate T_1^{-1}, leading to long relaxation times at low temperatures ($T_1^{-1}\approx10^{-2}n_{\rm H}T^{1/2}$ sec^{-1} at $H\approx100$ kG). The recombination rate due to wall collisions is much greater than T_1^{-1} and can lead to a depletion of the lowest hyperfine state from thermal equilibrium and an effective recombination rate equal to T_1^{-1}.

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Recently, two groups have stabilized samples of spin-polarized atomic hydrogen (H$\downarrow$). Silvera and Walraven[1] have obtained densities up to 5×10^{16} cm^{-3} at 0.27 K, and Cline *et al.*[2] report densities up to 10^{17} cm^{-3} at 0.30 K, both in high magnetic fields, with holding times of greater than an hour. These conditions are now close to those necessary for Bose-Einstein condensation. Siggia and Ruckenstein's recent Letter[3] on the properties of Bose-condensed H$\downarrow$ predicts the formation of a two-component superfluid, with each component consisting of atoms in one of the

