upon one must (apart from the discretization) expect errors of 15–20% in the excitation spectrum; or one uses large-amplitude collective theories like ATDHF, wherein one describes just one energy moment out of a broad spectrum[20] with no known relationship to the experimental peak energy. On the other hand, for heavier nuclei the monopole resonance is expected to be narrower, and there those large-amplitude theories should be very appropriate.

In this paper I was concerned with a formulation in coordinate space of the adiabatic time-dependent Hartree-Fock theory for collective masses and potentials in terms of Skyrme's interaction. It was shown that one can apply the theory to realistic cases avoiding altogether the discretization of the continuum of unbound single-particle orbits. By application to monopole vibrations in ^{16}O the approach presented could be used to demonstrate the weakness of RPA calculations suffering under the neglect of large-amplitude corrections and often under the discretization of the continuum using too small basis spaces. The monopole vibration could be shown to be a broad resonance.

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Determination of Strong-Interaction Widths and Shifts of Pionic X-Rays with a Crystal Spectrometer*

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Pionic $3d$-$2p$ atomic transitions in F, Na, and Mg have been studied using a bent crystal spectrometer. The pionic atoms were formed in the production target placed in the external proton beam of the Space Radiation Effects Laboratory synchrocyclotron. The observed energies and widths of the transitions are $E = 41\,679(3)$ eV and $\Gamma = 21(8)$ eV, $E = 62\,434(18)$ eV and $\Gamma = 22(80)$ eV, $E = 74\,389(9)$ eV and $\Gamma = 67(35)$ eV, in F, Na, and Mg, respectively. The results are compared with calculations based on a pion-nucleus optical potential.

Stimulated by the innovative work of Marushenko *et al.*,[1] we have set up a 2-m curved crystal spectrometer in the external proton beam of the Space Radiation Effects Laboratory synchrocyclotron with the aim of studying the strong-interaction shifts and widths of pionic x rays from light pionic atoms. We have chosen the $3d$-$2p$ transition in F, Na, and Mg. These transitions have energies in the 41–75-keV region and widths in the neighborhood of 100 eV and are, therefore, well suited for diffraction spectroscopy.

The 0.1-μA external proton beam with energy of 600 MeV struck the production target which consisted of a multilayer sandwich of copper (an effective pion producer) and the target material. Eighteen copper plates of 3.2-mm thickness, 2.5 cm wide, and 10 cm high were interleaved with similar plates of the target material, consisting,

respectively, of LiF, NaOH, and Mg metal. The spacing between the copper plates was 8.5 mm. The whole array was 21-cm long. The energy loss of the protons in the target was about 80 MeV, and the proton beam spot size was 2 cm high and 1 cm wide.

The pionic x rays produced in the target at 90° to the beam were transmitted through a 4.6-m-long precision steel collimator. This collimator had an aperture height of 10 cm and tapered in width from 20.3 to 6.6 cm, converging to an imaginary point coinciding with the virtual focus of the curved crystal spectrometer situated behind the collimator. There are twenty vertical plates in the collimator which was built in three sections. These plates were aligned with the copper plates of the target so as to prevent the diffraction crystal from directly viewing the pion production target (Cu). The angular resolution (full width at half-maximum) of the collimator was 1.97′, corresponding to a wavelength width of 1.35 mÅ.

The curved 310 quartz crystal (thickness 2 mm, area 45 mm×55 mm) located 30 cm downstream from the end of the collimator is part of the crystal spectrometer described in detail by Henrikson and Boehm.[2] The diffracted radiation was focused onto a 0.2-mm-wide resolving slit. The high-purity Ge detector (of which one 8-cm-long element was used) has a resolution of 3 keV at 60 keV.

The collimator was surrounded with steel and concrete over its entire length, reducing the neutron background from the production target to a value of 10 neutrons/cm^2 sec near the Ge detector. The detector, shielded with lead and boron-paraffin, was gated with the proton beam pulses (gate period is 200 μs; repetition rate of the synchrocyclotron is 55 sec^{-1}). The observed background counting rate was beam-related; about half of it was due to neutrons and the other half due to electromagnetic radiation shining through the narrow acceptance angle of the collimator.

Scans over the pionic x rays and the calibration lines were conducted by rotating the crystal in steps of 0.05 or 0.1 mÅ while tracking the collimator as required by Bragg's law, the receiving slit being stationary. Crystal sine screw motion and collimator motion were activated remotely with use of stepping motors. A Ge(Li) monitor counter recorded the γ-ray spectrum transmitted directly through the collimator.

The overall efficiency of the spectrometer and collimator system was determined with a 3-Ci ^{241}Am source positioned at the site of the proton target. At 59.5 keV the efficiency is 1.7×10^{-9}. The same source, in conjunction with Eu and Sm radiators, was used for energy calibration and determination of the instrumental resolution. In addition, a ^{125}I source was used. Other calibration lines were the K x rays of Os and of Pb excited by placing the samples in the proton beam. The energies of the calibration γ lines are $E(^{125}\mathrm{I})$ = 35.4919(5) keV [3] and $E(^{241}\mathrm{Am})$ = 59.537(1) keV. The x-ray wavelengths were taken from Bearden[4] using the wavelength-energy conversion constant $E\lambda$ = 12 398.23(18) keV mÅ*.[5] The observed x-ray line profiles were treated as convolutions of Gaussian (instrumental) and Lorentzian (natural linewidth) profiles. The Lorentzian widths were taken from Scofield[6] and Bambynek *et al.*[6] For Pb for example, the Lorentzian width is 63 eV, and the Gaussian width is 0.285 mÅ (81.5 eV).

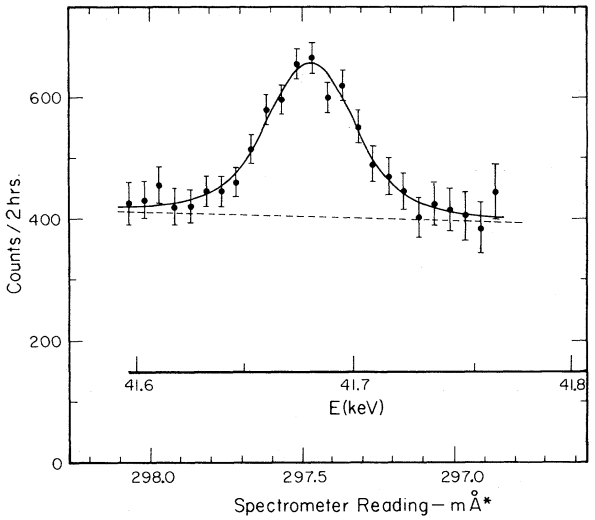

FIG. 1. Crystal diffraction spectrometer data for the $3d$-$2p$ pionic transition in F. The fitted curve is the convolution of a Gaussian (spectrometer response) and a Lorentzian (natural linewidth).

For F, the energy calibration was based on the x-ray energies of Eu and Sm. The observed diffraction peak for F is shown in Fig. 1. In the case of Na and Mg, the Os and Pb K x rays, respectively, were used as standards. The Mg data are shown in Fig. 2. In all cases an instrumental linewidth inferred from the observed width of the ^{125}I and ^{241}Am γ lines was unfolded from the measured spectrum.

Table I shows the results of the experiments. The total measuring time for each transition and the event and background rates are given, as well as the final result of the energy and width analy-

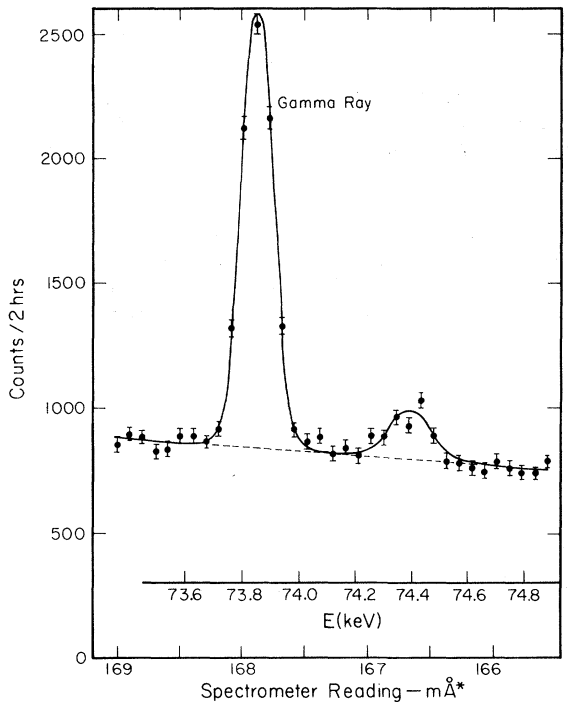

FIG. 2. Crystal diffraction spectrometer data for the $3d$-$2p$ pionic transition in Mg. The peak marked "gamma ray" is probably a transition in ^{22}Na. The fitted curve takes into account the isotope composition of Mg and the quadrupole splitting of ^{25}Mg.

sis.

Possible multiple ionization in the Os and Pb calibration targets as a result of the proton bombardment was estimated to produce a negligible increase in width, and a shift not exceeding 5 eV. A 5-eV uncertainty was, therefore, added to the errors of the centroids of Na and Mg. In the case of Na, a correction for the quadrupole hyperfine splitting (assuming $Q = 0.11$ b) was made. For Mg the effect of the isotopes ^{25}Mg and ^{26}Mg was taken into account.

The γ line observed near the Mg π x-ray line (Fig. 2) is probably due to the second excited state in ^{22}Na. Its energy is $E_\gamma = 73\,853(5)$ eV. It was observed in both the gated and the antigated spectrum, as well as in the gated and antigated monitor spectrum.

In addition to the observed energies and widths, Table I contains also the values of calculations using "standard" pion-nucleus optical model parameters.[7] The strong-interaction shifts and widths depend primarily upon the p-wave (nonlocal) part of the optical potential which is of the form

$$V_p = \frac{4\pi}{2m_\pi}\nabla\frac{\alpha_0(r)}{1+4\pi\xi\alpha_0(r)/3}\nabla,$$

with $\alpha_0 = c_0(\rho_n+\rho_p) + c_1(\rho_n-\rho_p) + iC(\rho_n+\rho_p)\rho_p$. In the vicinity of the standard values the observable quantities in the case of the $3d$-$2p$ transitions in Mg depend on the variables in the following way:

$$E(\text{eV}) = E_0 + 172\frac{\Delta c_0}{c_0} - 48\frac{\Delta r}{r} - 33\frac{\Delta\xi}{\xi},$$

$$\Gamma(\text{eV}) = \Gamma_0 + 55\frac{\Delta C}{C} + 41\frac{\Delta c_0}{c_0} - 24\frac{\Delta r}{r} - 50\frac{\Delta\xi}{\xi}.$$

Our observations are in good agreement with the calculated values, except in the case of F where our energy deviates from calculation by more than 2 standard deviations.

In conclusion, we have determined, using a curved crystal spectrometer, the strong-interaction shifts to about 10% and widths to 50% accuracy. It is apparent that the shifts depend sensitively on the nuclear potential parameters. In a future experiment, we plan to improve the precision of the centroid determination allowing a 1% accuracy for the strong-interaction shift.

TABLE I. Energies and widths of the $3d$-$2p$ pionic transitions in F, Na, and Mg. The energies are in eV.

	F	Na	Mg
Measuring time (h)	63	54	70
Peak rate (min^{-1})	2	0.8	1.7
Background rate (min^{-1})	3.5	3.3	6.7
Observed energy	41 679(3)	62 434(18)	74 389(9)
Observed Lorentzian width	21(8)	22(80)	67(35)
Calculated energy	41 672	62 438	74 392
Calculated width	14	51	86
Strong-interaction shift	25	77	122
$r_{\text{rms}}/A^{1/3}$ (fm)	1.069	1.036	1.043

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Evidence for Surface-Interaction Effects via a Nuclear Hyperfine-Interaction Experiment

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A rotation of the perturbed angular correlation of de-excitation γ rays from ^{18}O nuclei recoiling into vacuum at high velocity has been observed in a tilted-foil geometry. This rotation is due to the polarization of electronic configurations which interact strongly with the nuclear state via the hyperfine interaction. This experiment provides the first experimental evidence for polarization by surface interactions of deeply bound electrons in highly stripped oxygen ions.

Much theoretical and experimental effort has recently been focused on beam-foil measurements in which the normal to the foil surface does not lie along the beam axis.[1-4] Circularly polarized light, characteristic of electronic configurations polarized perpendicular to the plane defined by the beam axis and the normal to the foil surface, has been observed for various ionic configurations which decay be visible light. Circular-polarization measurements on shorter-wavelength radiation emitted by more deeply bound configurations are, however, exceedingly difficult.[5] There is thus no previous experimental information regarding the orientation of inner-shell electronic configurations by surface interactions in beam–tilted-foil experiments.

Here we report on a method that can provide this information by utilizing the strong magnetic hyperfine interaction (HFI) between inner electronic configurations and an excited nuclear level. The very strong HFI with unpaired $1s$ electrons can cause a significant attenuation of the angular correlation for de-excitation γ rays from the nuclear level; this interaction provides an experimental tool for measuring magnetic moments of short-lived states in light nuclei and for studying relative populations of electronic configurations on a picosecond time scale.[6-10] Moreover, if the electronic configurations participating in the HFI are polarized, a net *rotation* of the angular correlations results. Observation of this rotation is a clear signature of polarized electrons in the atomic ensemble and is the subject of the present experiment. The 2^+, 1.98-MeV ($\tau = 3.6$ ps, $g = -0.3$) level of ^{18}O is well suited for such a measurement since the value of $\omega\tau$ (where ω is the Larmor frequency due to the HFI and τ is the nuclear mean life) is close to unity. The condition $\omega\tau = 1$ is the condition for maximum sensitivity in this method.[11]

A 19.7-MeV ^4He beam from the Rutgers University–Bell Laboratory tandem accelerator impinged on a 100-μg/cm^2 $Si^{18}O$ self-supporting target. Backscattered ^4He particles were detected