rather large errors of the $B(E2)$ value is sufficient to bring the first interval listed in Table I for spin 7/2 to overlap with the $|\delta|$ interval. To achieve overlap with the range of δ values expected for spin 3/2, on the other hand, a highly improbable increase in the error of the $B(E2)$ value would be needed. Spin 3/2 is, therefore, excluded. Spin 5/2 cannot be excluded with certainty, but the probability of the correct spin value being 7/2 is several times that for spin 5/2.

The $M1+E2$ character of the transition and the assignment of 5/2+ to the ground state make the parity of the excited state even. In all probability, the 319-keV state in Pd^{105} is, therefore, a 7/2+ state. This means that the mean life of the ground-state transition is $\tau_\gamma = 7.3\times10^{-11}$ sec. Since this lifetime falls into the range accessible to delayed coincidence techniques, it might be pointed out that, in view of the good accuracy of the resonance fluorescence measurement, a direct lifetime measurement with comparable accuracy would unambiguously determine the spin of the 319-keV state.

SUMMARY

Resonance scattering from the 319-keV state in Pd^{105} has been studied with the following results:

(1) The most probable spin value is 7/2+; spins 1/2 and 3/2 are eliminated.

(2) The $E2/M1$ mixing amplitude ($I=7/2$) is $\delta=-0.11$.

(3) The gamma-transition probability ($I=7/2$) is $T_\gamma=(1.37\pm0.07)\times10^{10}$ sec^{-1}.

(4) The $M1$ transition probability is approximately seventy times smaller than the single-particle estimate,[9] the $E2$ transition probability is close to the single-particle estimate,[9] using $R_0=1.2\times10^{-13}\times A^{1/3}$.

[9] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), Chap. XII.

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Nuclear Resonance Excitation Using a Diffraction Monochromator*

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Nuclear resonance scattering from the first excited states in F^{19} and Mn^{55} has been studied with the bent-diffraction-crystal monochromator. The experiment was performed by observing the scattered radiation from nuclei exposed to nearly monoenergetic x rays selected by crystal diffraction from the bremsstrahlung spectrum of an x-ray tube. Gamma rays scattered at 135° from samples of lithium fluoride and manganese placed in the diffracted beam were observed as a function of the incident photon wavelength. With the lithium fluoride sample three measurements were made under different experimental conditions. In each case pronounced resonance peaks 10 to 15% above background were observed. A least-squares analysis of the data gives 109.894±0.005 keV for the energy position of the first excited level in F^{19}. From the observed yield the width of this level was deduced to be $(5.1\pm0.7)\times10^{-7}$ eV. Measurements with a Mn^{55} scattering sample gave 125.95±0.01 keV for the position of the first excited level and $(1.1\pm0.3)\times10^{-6}$ eV for the resonance width.

I. INTRODUCTION

VARIOUS techniques have been used to excite low-lying nuclear states from their respective ground states with electromagnetic fields. The techniques which have been most important in the energy region below a few MeV can be placed into four groups: (i) "Coulomb-excitation" reactions in which the nuclear excitation results from interaction of the nucleus with the electromagnetic fields of bombarding particles,[1] (ii) resonance excitation by means of gamma radiation emitted by a radioactive source,[2,3] (iii) techniques which use a nuclear reaction to provide a Doppler-shifted source of gamma radiation for nuclear excitation,[4,5] and (iv) techniques using a portion of the continuous bremsstrahlung radiation.

The possibility of observing nuclear resonance excitation using continuous radiation from a betatron was first discussed by Schiff.[6] A review of some experiments using betatron bremsstrahlung for nuclear excitation

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[1] K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Revs. Modern Phys. **28**, 432 (1956).

[2] F. R. Metzger, in *Progress in Nuclear Physics*, edited by O. R. Frisch (Pergamon Press, New York, 1959), Vol. 7.

[3] H. Frauenfelder, *The Mössbauer Effect* (W. A. Benjamin, Inc., New York, 1962).

[4] C. P. Swann and F. R. Metzger, Phys. Rev. **108**, 982 (1957).

[5] P. B. Smith and P. M. Endt, Phys. Rev. **110** 397, 1442 (1958).

[6] L. I. Schiff, Phys. Rev. **70**, 761 (1946).

at energies greater than 5 MeV is given by Devons.[7] Some more recent work on resonance scattering of bremsstrahlung in the region from 3 to 20 MeV from a linear accelerator is described by Seward.[8] Booth[9] has successfully used bremsstrahlung from an electron Van de Graaff for nuclear excitation in the energy region from 0.5 to 2.5 MeV.

In this work we are presenting the results of measurements of the resonance energy and width of the first excited levels of F^{19} and Mn^{55} using method (IV). The experiments were performed by observing the scattered radiation from nuclei exposed to nearly monoenergetic x rays selected from the bremsstrahlung spectrum of an x-ray tube by the bent-crystal monochromator described in a separate article.[10] It has long seemed desirable to use this technique; however, previous to the research reported here and in a preliminary communication[11] no successful measurement of nuclear resonance excitation using this method has been reported.

Using the method of nuclear excitation with a diffracted x-ray beam one is not restricted by special absorber conditions or by recoil problems occurring in resonance-excitation experiments with a radioactive source. The use of crystal diffraction to select a narrow band of x rays from the bremsstrahlung spectrum results in a considerable reduction in the background from nonresonance radiation present in experiments in which the entire bremsstrahlung spectrum is incident on the scattering sample. The information on nuclear properties which can be obtained is in many ways similar to the information obtained through Coulomb-excitation experiments. In addition to the excitation through the electric transitions one can study excitation of nuclei through magnetic multipole transitions. From the yields of the magnetic dipole excitation, for example, one can directly determine the magnetic transition probability $B(M1)$. As another example of the application of our method we mention the determination of the g factors of excited states by an angular correlation measurement in an external magnetic field at the target nucleus. Here, in contrast to the excitation by impinging particles or by beta decay the attenuating effects from atomic shell disturbances are absent.

The advantage of the diffracted x-ray beam technique is obvious. However, the energy resolution which can presently be obtained from x-ray diffraction is several orders of magnitude larger than the energy width of nuclear resonance absorption lines. As a result the nuclear excitation effect has to be observed in the presence of a large background from nonresonant atomic scattering. The main problems in the experimental technique are therefore: (i) that of obtaining sufficient x-ray intensity in the narrow region of the absorption line and (ii) that of reducing the nonresonant background effects to a minimum.

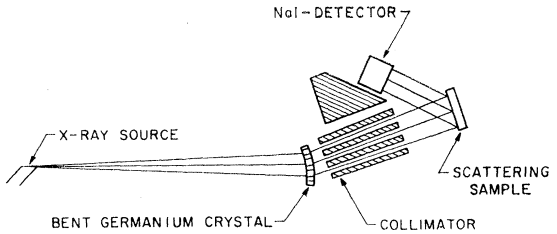

FIG. 1. Schematic arrangement for the nuclear resonance excitation experiment. The bent-germanium crystal is used to diffract a nearly monoenergetic beam of x rays from the bremsstrahlung spectrum of the x-ray source (anode of an x-ray tube). The diffracted beam passes through the collimator and is incident on the scattering sample. The radiation scattered through 135° is observed with a NaI detector.

II. DESCRIPTION OF THE EXPERIMENT

The monochromator described in reference 10 was used to supply a beam of monoenergetic x rays. Figure 1 shows the arrangement for the experiment. A bent-germanium (or quartz) crystal is used to diffract a nearly monoenergetic beam of x rays from the bremsstrahlung spectrum of the x-ray source (anode of an x-ray tube). The diffracted beam passes through the collimator and is incident on the scattering sample. Radiation scattered through an angle of about 135 deg is observed with a NaI scintillation detector. The scattering sample is mounted in a vacuum scattering chamber, and the radiation shielding is arranged so that the detector observes scattering from the sample only. Pulses from the detector are amplified by a standard amplifier and fed into two pulse-height analyzers. One of them is set to select pulses from the detector whose height corresponds to that of elastically scattered photons. The second pulse-height analyzer is set to select pulses whose height corresponds to that of inelastically Compton-scattered photons. Also, a 100-channel pulse-height analyzer is periodically used during the experiment to observe the entire pulse spectrum from the scintillation detector.

With this experimental equipment several different measurements of the scattered radiation from scattering samples of lithium fluoride and manganese were made. Essentially, the experimental observations give the ratio of the number of elastically scattered photons to the number of inelastically Compton-scattered photons as a function of the wavelength of the incident x-ray beam. Except for a negligible recoil correction, the nuclear resonance excitation-peak is observed at the wavelength corresponding to the energy of the nuclear level; therefore, the wavelength position of the

[7] S. Devons, in *Nuclear Spectroscopy*, edited by Fay Ajzenberg-Selove (Academic Press Inc., New York, 1960), Part A.
[8] F. D. Seward, Phys. Rev. **125**, 335 (1962).
[9] E. C. Booth, Nuclear Phys. **19**, 426 (1960).
[10] E. J. Seppi, H. E. Henrikson, F. Boehm, and J. W. M. DuMond, Nucl. Instr. and Methods **16**, 17 (1962).
[11] E. J. Seppi and F. Boehm, Bull. Am. Phys. Soc. **6**, 503 (1961); F. Boehm, J. W. M. DuMond, H. E. Henrikson, and E. J. Seppi, Proceedings of Gatlinburg Conference on Electromagnetic Lifetimes and Nuclear States, 1961 (Publication 974, National Academy of Sciences, Washington, D. C., 1962).

peak gives directly the energy position E_r of the level. The energy width Γ of the level is determined from the observed yield through the following formulas.

In an analysis of nuclear resonance excitation one must use cross-section formulas which account for the dynamics of the atomic motion.[2,12] For our purposes the cross section $\sigma(E)$ for nuclear resonance scattering of a photon of energy E is given by

$$\sigma(E)=(\sigma_0\Gamma\pi^{1/2}/2\Delta)\exp\{-[(E-E_r)/\Delta]^2\}, \quad (1)$$

$$\sigma_0\equiv\frac{2\pi\lambda\!\!\!^{-}_r{}^2}{(1+\alpha)^2}\frac{(2J_1+1)}{(2J_0+1)}, \quad (2)$$

where Γ is the resonance width, E_r is the resonance energy, J_1 and J_0 are the total angular momenta of the excited and the ground state, $\lambda\!\!\!^{-}_r$ is the resonance wavelength divided by 2π, α is the conversion coefficient, and Δ is the effective Doppler width. Equation (1) is obtained for crystalline materials through the use of the Debye approximation and the assumptions that the Debye-Waller factor is small compared to unity, the resonance width is small compared to the Doppler width, and the recoil energy is small compared to the resonance energy. The effective Doppler width used in Eq. (1) is obtained from the usual formula for a perfect gas through the use of an effective temperature as described by Metzger.[2]

The analysis of the experimental yield for the determination of the nuclear resonance width is complicated by: (i) attenuation in the thick scattering sample required by intensity considerations, (ii) multiple scattering in the sample, (iii) variation of detector efficiency for the detection of Compton and nuclear scattered radiation, and (iv) anisotropy of the Compton and nuclear scattering cross sections. Neglecting these complications it can be shown that for a thin scattering sample

$$\Gamma=(2\sigma_cE_r/\sigma_0\lambda\!\!\!^{-}_r\pi)\left[\int R_n(\lambda)d\lambda/R_c(\lambda_r)\right], \quad (3)$$

where σ_c is the Compton scattering cross section, $R_n(\lambda)$ is the intensity of nuclear scattering observed when the monochromator setting corresponds to the wavelength λ, and $R_c(\lambda_r)$ is the intensity of Compton scattering observed at the resonance wavelength. In deriving Eq. (3) use is made of Eq. (1) and the fact that the experimental energy resolution is several orders of magnitude larger than the Doppler width of the resonance.

A formula similar to Eq. (3) can be derived for a scattering sample of arbitrary thickness. The formula obtained can be written

$$A(\Gamma)=(CE_r/\lambda\!\!\!^{-}_r)\left[\int R_n(\lambda)d\lambda/R_c(\lambda_r)\right], \quad (4)$$

where $A(\Gamma)$ is given by

$$A(\Gamma)=\int_{-\infty}^{+\infty}\frac{dE\,\sigma(E)[1-\exp\{-NL[\sigma_e(E_r)+\sigma(E)](1+1/|\cos\xi|)\}]}{\{\sigma_e(E_r)+\sigma(E)\}\{1+1/|\cos\xi|\}}\Bigg/\frac{\sigma_c(E_r)[1-\exp\{-NL[\sigma_e(E_r)+\sigma_e(E_r')/|\cos\xi|]\}]}{\sigma_e(E_r)+\sigma_e(E_r')/|\cos\xi|}. \quad (5)$$

In these equations $\sigma(E)$ is given by Eq. (1), $\sigma_e(E)$ is the total atomic cross section, ξ is the scattering angle, N is the density, L is the sample thickness, and E_r' is the energy of the Compton-scattered photons. The correction factor C is introduced into the equation to account for the relatively small effects of multiple scattering of photons in the sample, variation of detector efficiency with incident photon energy, and anisotropy in the Compton and nuclear scattering. The value of C was estimated to be 1.05 in the F^{19} experiment and 1.09 in the Mn^{55} experiment. The above expression for $A(\Gamma)$ becomes a function of Γ when Eq. (1) is substituted for $\sigma(E)$. Then Eq. (4) is an implicit equation from which the nuclear resonance width is determined from the observed experimental results.

[12] W. E. Lamb, Jr., Phys. Rev. **55**, 190 (1939); K. S. Singwi and A. Sjölander, *ibid.* **120**, 1093 (1960).

III. RESULTS OF THE EXPERIMENTS WITH A LITHIUM FLUORIDE SCATTERING SAMPLE

For the study of the first excited level in F^{19} a scattering sample was prepared using powdered lithium fluoride. The physical dimensions of the sample were 8.0 $\times$8.0$\times$1.9 cm. Two sheets of 0.0025-cm-thick Mylar bound the lithium fluoride powder and formed the window through which the electromagnetic radiation passed. Their contribution to the total scattering and absorption is completely negligible. The thickness of the lithium fluoride was 1.32 g/cm^2.

With this sample, three experiments were performed in which nuclear resonance excitation of the first excited level of F^{19} was observed.

(1) In the first experiment performed with the lithium fluoride scattering sample, a quartz crystal in first-order diffraction from the (310) planes was used

TABLE I. Typical counting rates observed in experiments with LiF and Mn scattering samples.

Scattering sample	Diffraction plane	Counting channel	On resonance (counts/min)	Off resonance (counts/min)
LiF	Quartz (310)	Elastic	8.88±0.17	7.74±0.18
	Quartz (310)	Inelastic	12 340	12 375
LiF	Ge (800)	Elastic	13.66±0.19	12.24±0.19
	Ge (800)	Inelastic	10 096	10 118
Mn	Ge (800)	Elastic	79.9 ±0.3	78.6 ±0.3
	Ge (800)	Inelastic	5337	5362

in the monochromator, and the nuclear excitation peak was observed on both sides of the monochromator zero position. In this experiment the two pulse-height analyzers mentioned in the previous section were set to observe, respectively, elastically and inelastically scattered radiation from the scattering sample.

Figure 2 shows a resonance peak resulting from resonance excitation of the first excited level in F^{19}. The ordinate of the figure is the observed ratio of the intensity in the elastic channel to that in the inelastic channel. The abscissa is the monochromator wavelength setting λ. The data shown in the figure were accumulated in the following manner. With automatic recording equipment the monochromator was caused to record counts from the pulse-height analyzers for two minutes sequentially at each of ten monochromator wavelength positions spaced at intervals of 0.08 xu over the resonance position. At the completion of this 20-min cycle the monochromator automatically returned to the starting position and repeated the cycle. A data run consisted of data accumulated on one side of the monochromator zero wavelength position for 63 cycles. The points shown on Fig. 2 represent the average of four data runs taken alternately on one side (positive side) then on the other side (negative side) of the monochromator zero-wavelength position. Periodically during each data run the W $K\alpha_1$ x-ray calibration line from the tungsten x-ray tube was measured to obtain a check on the monochromator zero position. The wavelength settings of the monochromator shown on Fig. 2 were determined relative to 208.571 xu for the W $K\alpha_1$ x-ray calibration line.

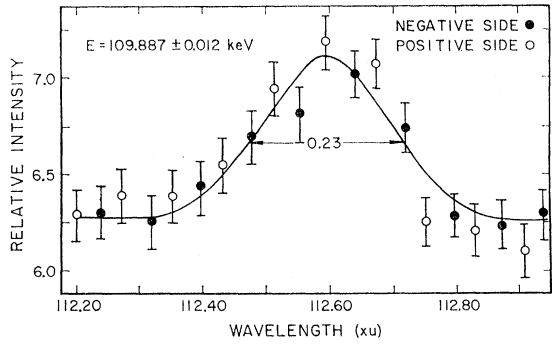

FIG. 2. Nuclear resonance excitation of the first excited state in F^{19} observed with a quartz (310) diffraction crystal. The figure shows the ratio of elastic to inelastic scattered radiation from a lithium fluoride sample as a function of the wavelength of the incident beam.

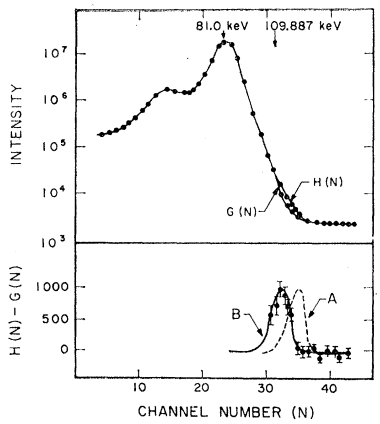

FIG. 3. Upper part: Pulse spectra observed from the NaI detector resulting from photons scattered by the lithium fluoride sample. Curve $H(N)$ is the spectrum observed with the monochromator set at the resonance position (112.592 xu). Curve $G(N)$ is the sum of pulse spectra obtained with the monochromator set at off resonance positions: 112.092 xu and 113.092 xu. Lower part: Nuclear excitation peak corresponding to 109.9-keV photons observed in the pulse spectrum $H(N)$. Curve B is the actual difference observed in the spectra. Curve A is a calibration curve obtained by using 122.05-keV gamma rays from a Co^{57} source.

Some typical counting rates observed in the experiment are given in Table I, lines 1 and 2.

The curve drawn through the data in Fig. 2 represents a least-squares fit of a Gaussian[13] with an arbitrary base line to the data. The resonance wavelength, and hence the resonance energy, is given by the position of the maximum of the Gaussian. The yield relative to the inelastic Compton scattered intensity was determined from the integrated area under the Gaussian and used in Eq. (4) to determine the resonance width. The results which were obtained are given in Table II, line 1.

TABLE II. Results of resonance excitation measurements on fluorine resonance.

Experiment number	Resonance position (keV)	Resonance width (eV)
1	109.887±0.012	(5.1±1.2)×10⁻⁷
2		(3.7±1.2)×10⁻⁷
3	109.897±0.005	(6.5±1.2)×10⁻⁷
Averages	109.894±0.005	(5.1±0.7)×10⁻⁷

[13] Several authors [J. W. M. DuMond, Rev. Sci. Instr. 18, 626 (1947); W. F. Edwards, Ph.D. thesis, California Institute of Technology, Pasadena, California, 1960 (unpublished)] have discussed factors which contribute to window profile for a curved crystal monochromator. The correct distribution function consists of a fold of functions describing the crystal reflectivity, the source spacial distribution, the source spectral profile, and imperfections in the focus of the bent crystal. The assumption of a Gaussian distribution made in the analysis of the data in this experiment has been justified to the accuracy of the results obtained.

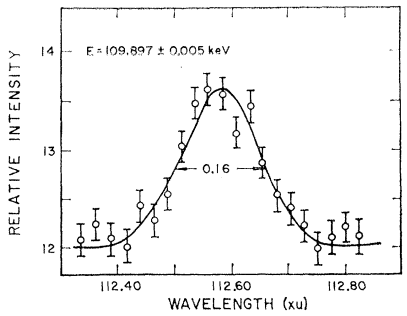

FIG. 4. Nuclear resonance excitation of the first excited state in F^{19} observed with the germanium (800) plane. The figure shows the ratio of the elastic to inelastic radiation from a lithium fluoride sample as a function of the wavelength of the incident beam.

(2) The second experiment with the lithium fluoride scattering sample was also performed with the quartz (310) plane. A pulse-height spectrum was obtained using a 100-channel analyzer at each of the following monochromator wavelength settings: 112.092 xu (off resonance), 112.592 xu (the resonant wavelength), and 113.092 xu (off resonance). In the data accumulation five minute observations were taken alternately on and off the resonance for a total of 40 h at each position. The pulse spectrum H vs channel number obtained from the sum of the data observed at the resonance position is shown in Fig. 3 by the curve labeled $H(N)$. Also illustrated in Fig. 3 is the background pulse-spectrum G vs channel number obtained from the sum of the spectra observed in the two off-resonance positions. The nuclear excitation peak is seen in the difference $H(N)$-$G(N)$ between these two spectra shown in the bottom part of Fig. 3. Curve A indicates the pulse-height distribution obtained for the 122.05-keV gamma ray from a Co^{57} source. The line shape and center position for the curve B through the experimental points was determined from that of the 122.05-keV calibration line.

The nuclear resonance width obtained from the ratio of intensity of the elastic resonance peak to the inelastic Compton-scattered intensity is tabulated in Table II.

(3) The procedure in a final measurement of nuclear excitation in F^{19} was identical to experiment (1) except that (i) a germanium-crystal (800)-plane diffraction was used in the monochromator and (ii) the data were observed on only one side of the monochromator zero. Figure 4 shows the results. As in experiment (1), the wavelength settings of the monochromator were determined relative to 208.571 xu for the W $K\alpha_1$ x-ray calibration line. Some typical counting rates observed in the experiment are given in Table I, lines 3 and 4. The results obtained for the resonance position and width are given in Table II.

Weighted averages of the results of the scattering experiments on lithium fluoride for the resonance energy and width are given in Table II. The resonance-energy value obtained is in good agreement with the result, $E_r = 109.87 \pm 0.04$ keV, obtained by Chupp, DuMond, Gordon, Jopson and Mark[14] in Coulomb excitation experiments with a bent-crystal spectrometer. The resonance width implies a mean life of $(1.3 \pm 0.1) \times 10^{-9}$ sec for the excited state. This result is in good agreement with the value $(1.0 \pm 0.25) \times 10^{-9}$ sec which was obtained by Thirion, Barnes, and Lauritsen[15] in a Coulomb-excitation experiment.

IV. RESULTS OF EXPERIMENTS WITH A MANGANESE SCATTERING SAMPLE

For the study of the first excited level in Mn^{55} a scattering sample was prepared using powdered manganese. The physical dimensions of this sample were $8.0 \times 8.0 \times 0.48$ cm. The thickness determined from the weight and area of the sample was 3.21 g/cm^2.

The procedure for the measurement of nuclear excitation in Mn^{55} was the same as for the third lithium fluoride experiment described above. As in the previous experiments on lithium fluoride the W $K\alpha_1$ line from the x-ray tube was used to determine the monochromator wavelength setting.

Although the width of manganese resonance studied is actually larger than that of fluorine, the size of the relative nuclear excitation effect observed in manganese is smaller. This results from an increase in the background in the elastic counting channel caused by atomic Rayleigh scattering in the sample. The contribution of atomic scattering to the observed ratio of the intensity of the elastic counting channel to that of the inelastic counting channel can be shown to vary approximately as $(1+BZ^2\lambda^3)$, where B is a constant and Z is the atomic number. For the case of manganese the term in $Z^2\lambda^3$ contributes significantly and thus reduces the size of the relative resonance effect. The term in $Z^2\lambda^3$ also introduces a nonresonant variation with λ in the observed ratio. After applying corrections for these effects we find the results shown in Fig. 5.

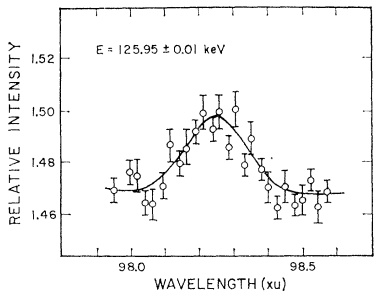

FIG. 5. Nuclear resonance excitation of the first excited state in Mn^{55} observed with the (800) plane. The figure shows the corrected ratio of the elastic to inelastic radiation from a manganese sample as a function of the wavelength of the incident beam.

[14] E. L. Chupp, J. W. M. DuMond, F. J. Gordon, R. C. Jopson, and Hans Mark, Phys. Rev. **112**, 532 (1958).
[15] J. Thirion, C. A. Barnes, and C. C. Lauritsen, Phys. Rev. 94, 1076 (1954).

The figure shows the corrected ratio of the elastic to inelastic intensities as a function of the monochromator setting. Some typical counting rates observed in the experiment are given in Table I, lines 5 and 6.

Analysis of the data gives 125.95 ± 0.01 keV for the energy of the resonance and $(1.1\pm0.3)\times10^{-6}$ eV for the width. From the value for the width one obtains a mean life of $(0.6\pm0.2)\times10^{-9}$ sec for the excited state. Chupp *et al.*[14] also measured the energy of this level. They found 125.87 ± 0.05 keV for the resonance energy. Using fast timing techniques Holland and Lynch[16] have measured the mean life of this level to be $(0.34\pm0.10)\times10^{-9}$ sec. The $B(E2)$ transition probability of this level in manganese has been measured by Temmer and Heydenburg.[17] From their result the $E2$ mean life is calculated to be 4.2×10^{-8} sec. Comparing this with our result one obtains 0.014 for the ratio between the intensities of $E2$ and $M1$ radiation. This is in agreement with angular correlation measurements by Bernstein and Lewis[18] which indicate that the value of this ratio is less than 0.02.

V. CONCLUSION

We have shown experimentally that it is possible to excite low lying states of nuclei with diffracted x rays from a bent crystal monochromator. Our method has been successful in the case of F^{19} and Mn^{55}, and our results on the level width are in good agreement with experiments using other techniques.

The observations made here indicate two general directions in which further work is required. (i) Experimental work should be directed towards increasing the intensity and resolution of the incident diffracted beam. This might be attained through the use of larger diffraction crystals in higher order reflections and through the use of a more intense x-ray source. (ii) A second problem which needs to be solved is that resulting from the background coming from electronic scattering in the sample. For nuclei with large atomic numbers, Rayleigh scattering from the atomic electrons places a severe restriction on the size of the nuclear scattering effect which can be observed. This problem might be solved taking advantage of the instantaneous character of atomic scattering as compared to the relatively long life time of the nuclear excited states. Through the use of a pulsed x-ray beam and a properly gated detector it should be possible to observe only the nuclear excitation events in the sample.

ACKNOWLEDGMENTS

We wish to express our appreciation to Professor J. W. M. DuMond for his constant interest in the progress of the research and for his valuable advice and encouragement. Thanks are due to H. E. Henrikson for his excellent engineering advice throughout this work. We furthermore wish to thank C. H. Holland and D. Agresti for their assistance in collection and analysis of the data.

[16] R. E. Holland and F. J. Lynch, Phys. Rev. **121**, 1464 (1961).
[17] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **104**, 967 (1956).
[18] E. M. Bernstein and H. W. Lewis, Phys. Rev. **100**, 1367 (1955).

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Polarization of 24-MeV Neutrons Elastically Scattered from C, Al, Fe, Sn, Pb, and Bi†

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Employing the 64% polarized neutron source from the $T(dn)He^4$ reaction at 30° for an incident deuteron energy of 7.7 MeV, the angular dependence of the polarization for elastic scattering of 24-MeV neutrons from C, Al, Fe, Sn, Pb, and Bi has been measured from 20° to 70° in 5° steps. The "left" and "right" measurements are obtained by precessing the neutron spin magnetic moment plus and minus 90° with a suitably designed solenoid. The measured polarizations are in reasonable agreement with the optical-model predictions of Bjorklund and Fernbach, provided that the sign of the spin-orbit potential agrees with that deduced from the shell model. The magnitude of the spin-orbit potential (25 times Thomas) is in agreement with that deduced from fitting the proton polarization data.

INTRODUCTION

THE nuclear optical model[1,2] has had considerable success in correlating many features of the nucleon-nucleus interaction, such as total cross sections, nonelastic cross sections, elastic angular distributions, and polarization data (mainly for protons). The experimental effort at Livermore has been directed, for some years, towards evaluating the parameters of the Bjorklund-Fernbach optical-model potential[3] by performing

† This work was performed under the auspices of the U. S. Atomic Energy Commission.

[1] For a complete bibliography see L. Rosen, J. E. Brolley, and L. Stewart, Phys. Rev. **121**, 1423 (1961).
[2] *Proceedings of the International Conference on the Nuclear Optical Model, Florida State University Studies, No. 32* (Rose Printing Company, Tallahassee, Florida, 1959).
[3] F. Bjorklund and S. Fernbach, Phys. Rev. **109**, 1295 (1958).