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TERMINAL REPORT

RESEARCH IN NUCLEAR PHYSICS

Contract AT(11-1)1468

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Submitted by

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I. INTRODUCTION

For the past six and one-half years the U.S. Atomic Energy Commission, under Contract AT(11-1)1468, has supported research in nuclear physics at the University of Arizona. During this period, from April 1, 1965, to September 30, 1971, the AEC has provided \$567,000.00 in operational funds and \$44,350.00 as a special equipment grant. This report summarizes the research accomplished under that contract.

The research has been done by Professors D. J. Donahue, J. D. McCullen, and L. C. McIntyre, Jr., and their graduate students. The major facilities used in the work were, originally, a 2 MV Van de Graaff purchased by the University of Arizona, and later, since February, 1968, a 5.5 MV Van de Graaff, purchased with funds from an NSF Science Development grant.

The major emphasis of the program has been on experiments in γ -ray spectroscopy. We were among the first to use a coincidence version of the Doppler-shift attenuation method to measure mean lives of excited nuclear states, and to use the coincidence version of the DSAM in which γ rays were detected with a germanium detector. This method is a powerful one because, in principle, it allows us to measure Doppler shifts for γ rays from any nuclear state which can be produced by a nuclear reaction, and to deduce from these Doppler shifts the average speed of the decaying nuclei. In some cases this average speed can be used to obtain the mean life of the decaying state. We have also developed and applied techniques to measure particle- γ -ray angular correlations from which multipole mixing

ratios of electromagnetic transitions can be obtained, and to measure decay schemes in complex nuclei.

An ion source has been designed and built which can be installed in the terminal of the 5.5-MeV Van de Graaff, and which will produce polarized ions. The design and construction of this source has been financed partly from a Science Development Program grant and from a Sloane Foundation Fellowship. The construction of the source has been completed and it has been installed in the terminal of the Van de Graaff several times. To this date minor problems have prevented it from operating successfully.

An experiment has been undertaken and completed in which measurements have been made of cross sections for (d,p) reactions in which the incoming deuteron and outgoing proton have energies below the coulomb barriers of the target and product nuclei. These cross sections have been used to obtain spectroscopic factors of excited states of the product nuclei. Target nuclei used in this experiment were Sn^{116} , Sn^{122} , and Sn^{124} .

As a summary of the work done under the AEC contract: (a) 20 articles were published in appropriate journals; (b) 14 abstracts were published in the Bulletin of the American Physical Society; and (c) 8 Ph.D. theses have been completed. In addition, two more Ph.D. theses will be completed in the near future.

Abstracts of articles published are presented in Section II of this report, titles of Ph.D. theses are given in Section III, and titles of abstracts are given in Section IV.

II. ABSTRACTS OF PUBLISHED ARTICLES

1. J. A. Lonergan and D. J. Donahue, Mean Lives of the 2.15- and 1.74-MeV Levels in ^{10}B , Phys. Rev. 139, B1149 (1965).

The mean lives of the 2.15- and 1.74-MeV levels of ^{10}B were measured by the Doppler-shift attenuation method. The reaction $^{11}\text{B}(^3\text{He},^4\text{He})^{10}\text{B}$ was used and the direction of the recoiling ^{10}B nuclei was selected by a coincidence technique. The mean lives were found to be $(1.41 \pm 0.17) \times 10^{-12}$ sec for the 2.15-MeV level and $(1.52 \pm 0.24) \times 10^{-12}$ sec for the 1.74-MeV level. The results are compared with estimates based on the independent-particle model. The mean lives of allowed $M1$ transitions are found to agree with these estimates. Evidence was found for the inhibition of an $M1$ transition for which $\Delta T = 0$ in a self-conjugate nucleus, and for enhancement of an $E2$ transition.

2. J. A. Lonergan and D. J. Donahue, Mean Lives of Excited States in ^{14}N , Nucl. Phys. 74, 318 (1965).

Abstract: The Doppler-shift technique was used to measure the mean life $\tau = (8.3 \pm 3) \times 10^{-14}$ s for the 2.31 MeV level in ^{14}N and to establish limits of $\tau \leq 2.5 \times 10^{-14}$ s and $\tau > 6 \times 10^{-13}$ s on the mean lives of the 3.95 and 5.10 MeV levels of ^{14}N , respectively. These measurements are compared with predictions made on the basis of the shell model.

3. J. A. Lonergan and D. J. Donahue, Angular Distributions of α -particles from the Reaction $^{11}\text{B}(^3\text{He}, \alpha)^{10}\text{B}$, Nucl. Phys. 88, 465 (1966).

Abstract: The angular distributions of α -particles from the reaction $^{11}\text{B}(^3\text{He}, \alpha)^{10}\text{B}$ leading to the four lowest states in ^{10}B were measured for ^3He energies of 1.0, 1.8 and 2.15 MeV. The distributions were compared with predictions made from the plane-wave, Butler pick-up theory which was extended to the case of $(^3\text{He}, \alpha)$ reactions. The comparison indicates the presence of the direct interaction mechanism for the excitation of the three lowest states in ^{10}B . The α -particles associated with the formation of the 2.15 MeV state in ^{10}B were symmetric about 90° in the centre-of-mass system. The excitation functions for the formation of the five lowest states in ^{10}B by the $^{11}\text{B}(^3\text{He}, \alpha)^{10}\text{B}$ reaction were measured for ^3He energies from 1.0 MeV to 2.15 MeV.

4. D. J. Donahue, M. J. Wozniak, R. L. Hershberger, J. E. Cummings, and J. A. Lonergan, Mean Lives of Some State in B^{10} , Phys. Rev. 165, 1071 (1968).

Doppler shifts of γ rays from some excited states of B^{10} nuclei produced in the reaction $\text{B}^{11}(\text{He}^3, \alpha)\text{B}^{10}$ have been measured with Ge(Li) and NaI(Tl) detectors. From these Doppler shifts the following information concerning mean lives of states in B^{10} has been deduced: $\tau(1.74 \text{ MeV}) \leq 4 \times 10^{-14}$ sec, $\tau(2.15 \text{ MeV}) = (2.1_{-0.6}^{+0.8}) \times 10^{-12}$ sec, and $\tau(3.59 \text{ MeV}) = (1.7 \pm 0.7) \times 10^{-13}$ sec.

5. C. A. Pearson, J. C. Wilcott, and L. C. McIntyre, Vector Analysing Power in (d,p) Reactions and the WBP Model, Nucl. Phys. A125, 111 (1969).

Abstract: Calculations for vector analysing power P_D with the Weakly Bound Projectile model are compared with measured values for (d, p) reactions on ^{12}C , ^{24}Mg , ^{40}Ca , and ^{52}Cr . All the available measurements for P_D are reproduced, as well as measurements for the proton polarization P_p in reactions with unpolarized deuterons, and the j_n dependence of differential cross sections.

6. M. J. Wozniak, Jr., R. L. Hershberger, and D. J. Donahue, Mean Lives of States in Si^{29} below 5 MeV, Phys. Rev. 181, 1580 (1969)

The Doppler-shift attenuation method was used to obtain the following information concerning the mean lives of the low-lying states in Si^{29} : $\tau(1.27\text{-MeV}) = (3.7_{-0.6}^{+0.6}) \times 10^{-13}$ sec, $\tau(2.03\text{-MeV}) = (3.7_{-0.6}^{+0.7}) \times 10^{-13}$ sec, $\tau(2.43\text{-MeV}) \leq 4.6 \times 10^{-14}$ sec, $\tau(3.07\text{-MeV}) \leq 7.4 \times 10^{-14}$ sec, $\tau(3.62\text{-MeV}) = (4.8_{-1.5}^{+3.0}) \times 10^{-12}$ sec, $\tau(4.08\text{-MeV}) = (7 \pm 2) \times 10^{-14}$ sec, $\tau(4.84\text{-MeV}) \leq 1.3 \times 10^{-14}$ sec. The results of a series of measurements to test the calculation of the unattenuated Doppler shift are reported. Some information concerning the branching ratios of the states at 4.84, 4.89, and 4.93 MeV in Si^{29} is also presented. A value of $\frac{1}{2}^+$ is suggested for the spin and parity of the 4.08-MeV state. Some of the results are compared to a simple pure-rotational-model interpretation of Si^{29} .

7. L. C. McIntyre, Jr., P. L. Carson, and D. L. Barker, Mean Lives of States in Mg^{27} , Phys. Rev. 184, 1105 (1969).

Mean lives of several low-lying states in Mg^{27} were measured using the Doppler-shift-attenuation method. These levels, with measured mean lives, are 0.984 MeV [$\tau = (1.4 \pm 0.5) \times 10^{-12}$ sec], 1.69 MeV [$\tau = (1.3 \pm 0.5) \times 10^{-12}$ sec], and 1.94 MeV [$\tau = (1.4_{-0.4}^{+0.6}) \times 10^{-12}$ sec]. In addition, limits on the mean lives of the states at 3.48 and 3.56 MeV were obtained. The $\text{Mg}^{28}(d, p)\text{Mg}^{27}$ reaction with 2-MeV incident deuterons was used to populate levels in Mg^{27} . The attempt to interpret the low-lying levels of Mg^{27} in terms of the strong-coupling rotational model is met with conflicting evidence concerning the membership of the ground-state rotational band.

8. J. D. McCullen, W. S. Smith, and W. J. Tipton, Two-Frequency Hyperfine Transitions in Atomic Deuterium, Phys. Rev. Letters 23, 457 (1969).

A modified fast-passage transition scheme, using two frequencies, is described and discussed.

9. R. L. Hershberger, M. J. Wozniak, Jr., and D. J. Donahue, Mean Lives, Branching Ratios, and Excitation Energies of Levels in ^{20}F below 4 MeV, Phys. Rev. 186, 1167 (1969).

The $^{19}\text{F}(d, p)^{20}\text{F}$ reaction has been used to study the mean lives, branching ratios, and excitation energies of several of the levels of ^{20}F . The Doppler-shift attenuation method was used to obtain the following information concerning the mean lives of the low-lying levels in ^{20}F : $\tau(0.66\text{ MeV}) = (3.6 \pm 0.7) \times 10^{-13}$ sec, $\tau(0.82\text{ MeV}) \geq 4.4 \times 10^{-12}$ sec, $\tau(0.98\text{ MeV}) = (1.3_{-0.4}^{+0.6}) \times 10^{-12}$ sec, $\tau(1.06\text{ MeV}) \leq 9.2 \times 10^{-14}$ sec, and $\tau(1.31\text{ MeV}) = (1.1_{-0.3}^{+0.4}) \times 10^{-12}$ sec. In addition, upper limits were found for levels at 2.04, 2.19, 2.96, 3.49, and 3.53 MeV. A previously unreported branching ratio of the 2.96-MeV level was found to be $(2.96 \rightarrow 0.0\text{ MeV}) 0.24 \pm 0.03$, $(2.96 \rightarrow 0.66\text{ MeV}) 0.14 \pm 0.02$, and $(2.96 \rightarrow 0.82\text{ MeV}) 0.62 \pm 0.06$. A value of 3^+ is suggested for the spin and parity of the 0.66-MeV level.

10. J. D. McCullen and R. G. Seyler, Reaction Mechanism Independent Particle-Gamma Correlation Functions Using Polarized Particles, Nucl. Phys. A139, 203 (1969).

Abstract: The use of polarized particles in particle-gamma correlation experiments permits the extraction of the spectroscopic information in a manner independent of the reaction mechanism. Two methods for doing this are proposed. The results extend reaction-independent techniques to virtually any common projectile-outgoing particle reaction.

11. J. E. Cummings and D. J. Donahue, Mean Lives of Some States in ^{33}S , Nucl. Phys. A142, 609 (1970).

Abstract: The mean lives of the 0.84, 1.97, 2.31, 2.94 and 3.22 MeV levels were studied using the Doppler-shift attenuation method (DSAM). The $^{32}\text{S}(d, p)^{33}\text{S}$ reaction was used with deuteron energies ranging from 1.86 to 2.50 MeV to populate the excited levels of ^{33}S . The directions of the recoiling nuclei were determined by detecting γ -rays in coincidence with protons. Mean lives of $\tau_m = 0.9^{+0.5}_{-0.4}$, 0.15 ± 0.03 , 0.14 ± 0.04 , > 1.4 and $0.04^{+0.02}_{-0.01}$ ps were found for the levels at $E_x = 0.84, 1.97, 2.31, 2.94$ and 3.22 MeV, respectively. Where applicable, the results are compared to predictions of the strong-coupling rotational model.

12. M. J. Wozniak, Jr. and D. J. Donahue, Mean Lives of Some States in Si^{31} below 3.54 MeV, Phys. Rev. C 1, 601 (1970).

A Ge(Li) detector and the reaction $\text{Si}^{30}(d, p)\text{Si}^{31}$ with $E_d = 2-4$ MeV are used in the coincidence version of the Doppler-shift attenuation method to obtain the following information concerning the mean lives of some low-lying states in Si^{31} : $\tau(0.75 \text{ MeV}) = (7.2^{+1.8}_{-1.5}) \times 10^{-13}$ sec, $\tau(1.69 \text{ MeV}) = (7.4 \pm 2.3) \times 10^{-13}$ sec, $\tau(2.32 \text{ MeV}) < 3 \times 10^{-13}$ sec, $\tau(3.14 \text{ MeV}) = (5.0^{+2.2}_{-2.5}) \times 10^{-13}$ sec, $\tau(3.53 \text{ MeV}) < 3.7 \times 10^{-14}$ sec. From these results, the reduced matrix elements for electromagnetic transitions among some of these states are obtained. A comparison is made between these reduced matrix elements and those predicted by the extreme single-particle model, the Nilsson rotational model, and the shell model with configuration mixing in the $2s_{1/2}$ and $1d_{3/2}$ shells. Our results indicate a value of $|\eta| = 2.8^{+0.4}_{-0.3}$ for the Nilsson deformation parameter for Si^{31} . A value of 752 ± 1 keV was obtained for the excitation energy of the 0.75-MeV state.

13. C. A. Pearson, D. Rickel, and D. Zissermann, Effects of the D-State of the Deuteron in the WBP Model for (d,p) Reactions, Nucl. Phys. A148, 273 (1970).

Abstract: The effect of the D-state of the deuteron on polarization, vector analysing power, and differential cross sections for (d, p) reactions is discussed within the framework of the weakly bound projectile model. It is shown that D-state corrections are comparable to the uncertainties due to ambiguities in optical potentials. For a quantitative comparison of the theory with experiment it is necessary to calculate the D-state contribution.

14. J. E. Cummings and D. J. Donahue, $^{30}\text{Si}(\alpha, n\gamma)^{33}\text{S}$ Angular-Correlation Measurements, Phys. Rev. C 2, 942 (1970).

The particle- γ -ray angular-correlation method of Litherland and Ferguson was used to gain information on the multipole mixing ratios for the $1.97 \rightarrow 0.0$ -MeV, $2.31 \rightarrow 0.84$ -MeV, and $2.31 \rightarrow 0.0$ -MeV transitions in ^{33}S . Ions of $^4\text{He}^{++}$ with $E = 7.52$ MeV populated the excited states through the reaction $^{30}\text{Si}(\alpha, n)^{33}\text{S}^*$. Neutrons were detected in the direction of the beam axis. Pulse-shape discrimination for determining neutron- γ -ray coincidence was studied. γ rays were detected by 3-in. $\times$ 3-in. NaI(Tl) crystals at angles of 45, 55, 65, and 90° with respect to the beam axis. Results are examined with regard to predictions of the strong-coupling rotational model.

15. J. E. Cummings and D. J. Donahue, Mean Life Measurements in ^{29}P , Phys. Rev. C 2, 1570 (1970).

The Doppler-shift attenuation method was used to obtain the mean lives of the first two excited states in ^{29}P : $\tau(1.38 \text{ MeV}) = (2.1 \pm 0.6) \times 10^{-13}$ sec and $\tau(1.95 \text{ MeV}) = (3.2^{+1.5}_{-1.1}) \times 10^{-13}$ sec. The excited states were populated by the reaction $^{28}\text{Si}(d, n)^{29}\text{P}$ using deuteron energies ranging from 2.93 to 3.50 MeV. Pulse-shape discrimination was employed for the neutron- γ -ray coincidence measurements. The results are compared with those in ^{29}Si and with the predictions of the strong-coupling rotational model.

16. K. S. Burton and L. C. McIntyre, Jr., Mean Lives and Angular Correlations in ^{35}S with the $^{34}\text{S}(d, p\gamma)^{35}\text{S}$ Reaction, Nucl. Phys. A154 551 (1970).

Abstract: The $^{34}\text{S}(d, p\gamma)^{35}\text{S}$ reaction at incident energies between 2 and 3.25 MeV has been used to investigate the properties of the first three excited states in ^{35}S . The Doppler-shift attenuation method of measuring mean lives gives the following results for the levels at 1.57, 1.99 and 2.35 MeV: $\tau \geq 1.8$ ps, $\tau \geq 4.5$ ps and $\tau = 0.8 \pm 0.2$ ps, respectively. Angular correlation measurements were also performed using a collinear geometry. The 2.35 MeV level is found to have $J^\pi = \frac{3}{2}^-$.

17. L. E. Porter, L. C. McIntyre, and W. Haeberli, Stopping Power of Havar for 2.5 to 7.0 MeV Deuterons, Nucl. Instr. and Meth. 89, 237 (1970).

Energy losses of 2.5 to 7.0 MeV deuterons in thin Havar foils have been measured. The results are fitted by means of the Bichsel energy loss computer code with fixed shell correction parameters common to the major constituent elements and a variable

mean excitation energy. The best fit value of the mean excitation energy is 15% lower than the value calculated from an assumed additivity of stopping effects.

18. K. S. Burton and L. C. McIntyre, Jr., Mean Lives and Angular Correlations in ^{57}Co with the $^{54}\text{Fe}(\alpha, p\gamma)^{57}\text{Co}$ Reaction, Phys. Rev. C 3, 621 (1971).

The reaction $^{54}\text{Fe}(\alpha, p\gamma)^{57}\text{Co}$ with incident α -particle energies of 9 and 10 MeV has been used to investigate the properties of ^{57}Co levels below 3 MeV in excitation. Using the Doppler-shift-attenuation method, mean lives were obtained for 11 excited levels. These results are as follows: $\tau(1.22 \text{ MeV}) = 0.084 \pm 0.018$, $\tau(1.68 \text{ MeV}) = 0.26^{+0.12}_{-0.09}$, $\tau(1.76 \text{ MeV}) = 0.36 \pm 0.07$, $\tau(1.89 \text{ MeV}) = 0.12 \pm 0.03$, $\tau(1.92 \text{ MeV}) = 0.03 \pm 0.02$, $\tau(2.31 \text{ MeV}) = 0.32 \pm 0.09$, $\tau(2.48 \text{ MeV}) = 0.036^{+0.014}_{-0.011}$, $\tau(2.60 \text{ MeV}) = 0.11 \pm 0.03$, $\tau(2.73 \text{ MeV}) = 0.11 \pm 0.03$, $\tau(2.80 \text{ MeV}) = 0.04 \pm 0.02$, and $\tau(2.87 \text{ MeV}) = 0.05 \pm 0.02$, all in psec. In addition multipole mixing ratios were obtained for several transitions. Arguments are given for a spin assignment of $J = \frac{7}{2}$ to the 2.31-MeV level.

19. Harold J. Kennedy and John D. McCullen, Search for Branching in the β Decay of ^{42}Sc , Phys. Rev. Letters 27, 198 (1971).

Experimental limits have been set on the intensity of a branching in the β^+ decay of the the ^{42}Sc ground state to the 1838-keV 0^+ state in ^{42}Ca , providing an upper limit on the departure from isospin purity in the $A=42$ system. The limits are branching ratio $< 4.6 \times 10^{-4}$ with 95% confidence; branching ratio $< 1.2 \times 10^{-4}$ with 50% confidence.

20. D. J. Donahue and R. L. Hershberger, Doppler Shifts with Gas Backings: Mean Lives in ^{17}O , ^{25}Mg , and ^{55}Fe , Scheduled for Phys. Rev. November 1971.

Abstract: Measurements of Doppler shifts of γ rays from nuclei recoiling in gas are described. Mean lives of the 0.87-MeV state in ^{17}O , of the 0.58- and 0.97-MeV states in ^{25}Mg , and of the 0.41-, 0.93-, 1.32- and 1.41-MeV states in ^{55}Fe produced by (d,p) reactions were obtained from these Doppler shifts. The effect on these mean lives of a variation in the deuteron current has been investigated. Finally, the known mean lives of the 0.87-MeV state in ^{17}O and the 0.58-MeV state in ^{25}Mg were used, together with the measured Doppler shifts, to obtain information concerning the slowing down of ^{17}O and ^{25}Mg ions in krypton gas.

III. PH.D. THESES

1. James A. Lonergan, A Study of Some Properties of Excited States in Light Nuclei Using ^3He -Induced Reactions, 1966.
2. Matthew J. Wozniak, Jr., Properties of Si^{29} and Si^{31} Nuclei from Doppler-Shift Attenuation Measurements, 1969.
3. John E. Cummings, Properties of ^{29}P , ^{33}S , and ^{33}Cl Nuclei from Doppler-Shift Attenuation and Angular Correlation Measurements, 1970.
4. Winfield S. Smith, The Development of a Polarized Ion Source, 1970.
5. Robert L. Hershberger, Properties of Electromagnetic Transitions in Fluorine-20 and Iron-55, 1970.
6. Kenneth S. Burton, Properties of ^{35}S and ^{57}Co Nuclei from Angular Correlation and Doppler-Shift Attenuation Measurements, 1970.
7. Allan S. Goodman, Electromagnetic Transitions in V^{51} and Mn^{53} , 1971.
8. Paul L. Carson, Measurement and Analysis of Coulomb (d,p) Stripping to States in ^{117}Sn , ^{123}Sn , and ^{125}Sn , 1971.
9. Dwight G. Rickel, The Low Lying Energy Level Structure of the Vanadium Isotopes ^{47}V , ^{49}V , and ^{50}V , 1971*
10. Harold J. Kennedy, A Search for Branching in the Beta Decay of Sc-42 , 1971*

*Not quite complete on termination date of contract.

IV. ABSTRACTS

1. J. A. Lonergan and D. J. Donahue, Mean Life of the 1.74-MeV State in ^{10}B , Am. Phys. Soc. 10, 525 (1965).
2. J. A. Lonergan and D. J. Donahue, Mean Lives of Excited States in N^{14} , Bull. Am. Phys. Soc. 10, 1195 (1965).
3. J. A. Lonergan and D. J. Donahue, Study of Some Transition Probabilities in B^{10} , Bull. Am. Phys. Soc. 11, 27 (1966).
4. D. J. Donahue, R. L. Hershberger, and J. E. Cummings, Doppler Shifts of Gamma Rays from F^{20} , Bull. Am. Phys. Soc. 12, 535 (1967).
5. L. C. McIntyre, Jr., P. L. Carson, and D. L. Barker, Mean Lives in Mg^{25} and Mg^{27} , Bull. Am. Phys. Soc. 14, 628 (1969).
6. J. D. McCullen, Review of Experimental Findings, Bull. Am. Phys. Soc. 14, 1199 (1969).
7. J. D. McCullen and R. G. Seyler, Reaction Mechanism Independent Particle Gamma Correlation Functions Using Polarized Particles, Bull. Am. Phys. Soc. 14, 1223 (1969).
8. J. E. Cummings and D. J. Donahue, Neutron-Gamma Ray Angular Correlation Measurements in ^{33}S , Bull. Am. Phys. Soc. 15, 37 (1970).
9. K. S. Burton and L. C. McIntyre, Mean Lives and Angular Correlations in S^{35} with the $\text{S}^{34}(\text{d},\text{p})\text{S}^{35}$ Reaction, Bull. Am. Phys. Soc. 15, 600 (1970).
10. K. S. Burton and L. C. McIntyre, Mean Lives and Angular Correlations in Co^{57} with the $\text{Fe}^{54}(\alpha,\text{p})\text{Co}^{57}$ Reaction, Bull. Am. Phys. Soc. 15, 601 (1970).
11. A. S. Goodman and D. J. Donahue, Mean Lives of Some States in V^{51} , Bull. Am. Phys. Soc. 15, 601 (1970).
12. R. L. Hershberger and D. J. Donahue, Lifetime Measurements of Low-Lying States in ^{55}Fe , Bull. Am. Phys. Soc. 15, 602 (1970).

13. H. J. Kennedy and J. D. McCullen, Isospin Purity in the Beta Decay of ^{42}Sc , Bull. Am. Phys. Soc. 15, 1666 (1970).
14. L. C. McIntyre, Jr. and D. J. Donahue, Investigations of Spin Assignments in ^{41}Ca , ^{53}Cr , and ^{55}Fe (November, 1971, meeting).