Transition Probabilities for Low-Lying States in Sc^{46}†

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Lifetimes of the low-lying levels of Sc^{46} have been studied using the $Sc^{45}(d,p\gamma)Sc^{46}$ reaction. The half-life of the 52-keV level was measured to be $t_{1/2}=8.8\pm0.4$ μsec, which implies a $B(E2)=3.1\times10^{-51}\,e^2\,\mathrm{cm}^4$ for an $E2$ transition to the ground state. A comparison of this result with shell-model calculations implies effective charges for the unpaired nucleons of $(e_p+e_n)=5.43e$. Half-life limits from <200 to <400 psec have been placed on seven other low-lying transitions. No unusually large $M1$ hindrances were observed.

I. INTRODUCTION

CONSIDERABLE experimental information exists on the level structure of the odd-odd nucleus Sc^{46}. Angular distributions[1] of the $Sc^{45}(d,p)Sc^{46}$ reaction show that a number of the low-lying states are populated by $l=3$ neutrons. Yntema and Satchler[2] have suggested several hole states in Sc^{46} from their data for the proton pickup reaction $Ti^{47}(d,He^3)Sc^{46}$. An additional study of levels in Sc^{46} has been performed by Bjerregaard *et al.*[3] with (d,p) and (d,α) reactions. Several $Sc^{45}(n,\gamma)Sc^{46}$ experiments[4–6] have revealed detailed information about γ transitions and excited states in Sc^{46}. Van Assche *et al.*[6] have recently proposed spin and parity assignments for levels in Sc^{46} up to about 1 MeV using their (n,γ) data obtained with a bent crystal spectrometer and other available information on Sc^{46}. The ground-state spin assignment of 4 has been measured directly by atomic-beam techniques.[7]

Theoretical studies on $f_{7/2}$ particle states in Sc^{46} have been made by McCullen *et al.*[8] They predict a 6^+ ground state and, respectively, 4^+, 3^+, 5^+, and 2^+ levels below 400 keV from the $(\pi f_{7/2})^1(\nu f_{7/2})^5$ configuration (π refers to protons and ν to neutrons). Except for an inversion in the ordering of the lowest two states, these predictions are consistent with assignments of Van Assche[6] for the levels exhibiting $l=3$ stripping distributions. Bansal and French[9] have calculated the center of gravity of the $(\pi d_{3/2})^{-1}(\pi f_{7/2})^2(\nu f_{7/2})^5$ configuration and find that it lies at 800-keV excitation energy in Sc^{46}. The levels at 143, 290, and 585 keV in Sc^{46} do not show stripping patterns. In addition, the 143- and 585-keV levels exhibit $l=2$ proton pickup contributions in the $Ti^{47}(d,He^3)Sc^{46}$ data of Yntema and Satchler.[3] This information suggests the $d_{3/2}$ hole configuration for these levels.

The purpose of the present experiment is to look for additional nuclear structure properties in Sc^{46} by making a survey of lifetimes for the low-lying states. The lifetimes coupled with information on branching ratios and multipolarities lead to the γ-ray transition probabilities and the individual electromagnetic matrix elements. From these matrix elements, one can hope to unfold properties of the nuclear wave functions involved in the γ-ray transitions. There is one lifetime known in Sc^{46} which serves as an example of this approach: The isomeric state at 143 keV is known to have a lifetime of 20 sec.[10] The corresponding transition strength is consistent with a 1^- assignment and an $E3$ transition between a $d_{3/2}$ hole state and the ground state, which is thought to consist of only $f_{7/2}$ particles relative to the Ca^{40} core. The γ-ray transition is hindered by a factor of 15 from that expected for a transition between particle states.

Two additional features make a study of Sc^{46} interesting. One is the observation by Ristinen and Sunyar[11] of $M1$ hindrances of 1×10^6 and $\geq6.6\times10^9$ for low-lying γ-ray transitions in Sc^{44}. The configuration of $(\pi f_{7/2})^1(\nu f_{7/2})^3$ for Sc^{44} has similarities with Sc^{46} if one views the neutron configuration of Sc^{46} as three $f_{7/2}$ neutron holes. These large $M1$ hindrances in Sc^{44} are not theoretically understood. It is possible that the nuclear properties responsible for these large hindrances in Sc^{44} might manifest themselves in the low-lying levels

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[2] J. L. Yntema and G. R. Satchler, Phys. Rev. **134**, B976 (1964).
[3] J. H. Bjerregaard, P. F. Dahl, O. Hansen, and G. Sidenius, Nucl. Phys. **51**, 641 (1964).
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[8] J. D. McCullen, B. F. Bayman, and L. Zamick, Phys. Rev. **134**, B515 (1964).
[9] R. K. Bansal and J. B. French, Phys. Letters **11**, 145 (1964).
[10] M. Goldhaber and C. O. Muelhause, Phys. Rev. **74**, 1877 (1948).
[11] R. A. Ristinen and A. W. Sunyar, Phys. Rev. **153**, 1209 (1967).

of Sc^{46}. The other feature of interest in Sc^{46} is the possible experimental justification for the predicted seniority selection rules within a nuclear j^n configuration of neutrons and protons.[12] Hindrances resulting from these selection rules could lead to evidence regarding the extent of seniority mixing in the $f_{7/2}$ shell.

The approach in this experiment is to use the Sc^{45} $(d,p\gamma)Sc^{46}$ reaction, where the timing information for the various excited states is obtained from the protons and the de-excitation γ rays. By using solid-state counters for detecting the protons one can obtain good energy resolution along with the timing information, so that individual excited states can be experimentally isolated in the lifetime survey.

II. EXPERIMENT

In order to determine which levels are significantly populated in the $Sc^{45}(d,p\gamma)Sc^{46}$ reaction, a preliminary investigation was made with a Ge(Li) γ-ray detector where with good energy resolution, γ rays of similar energies can be separated, and because a γ-ray detector includes transitions from both direct and cascade populations. The γ-ray singles spectrum produced by

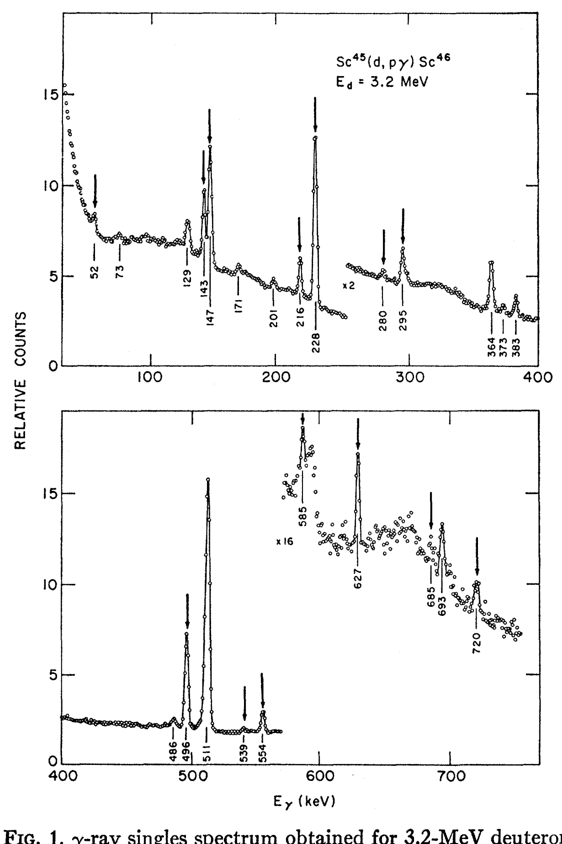

FIG. 1. γ-ray singles spectrum obtained for 3.2-MeV deuterons bombarding a thin Sc target. The γ rays associated with the $Sc^{45}(d,p\gamma)Sc^{46}$ reaction are identified by arrows. For energies less than 100 keV there is significant γ-ray absorption.

[12] C. Noack, Phys. Rev. 132, 1213 (1963).

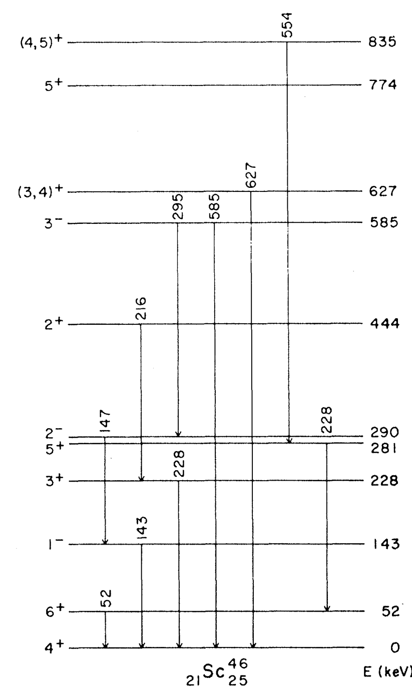

FIG. 2. γ-ray transitions in Sc^{46} that are of sufficient strength for timing studies. The level scheme and spin-parity parameters are those of Ref. 6.

bombarding a 1.5 mg/cm² Sc-metal target with 3.2-MeV deuterons was measured with a 20 cm³ Ge(Li) detector placed at 90° to the beam. The detector energy resolution was approximately 3 keV. Figure 1 shows the resulting γ-ray spectrum. For energies of less than 100 keV, there was significant γ-ray absorption. The Sc^{46} γ rays that are identified by comparison with the $Sc^{45}(n,\gamma)$ decay scheme of Van Assche *et al.*[6] are indicated in Fig. 1. The other observed γ rays do not appear to be related to the low-lying levels in Sc^{46}. γ rays that are believed to be of sufficient strength for timing studies are shown in Fig. 2. The criterion for determining sufficient strength is discussed below. The level scheme and level parameters shown in this figure are those of Van Assche *et al.*[6] These γ rays of Fig. 2, together with the associated protons, were used to obtain time-delay spectra for levels in Sc^{46}.

The lifetime of the 52 keV first excited state in Sc^{46} is expected to be in the μsec region if the transition is of $E2$ multipolarity. On the other hand, several of the other levels shown in Fig. 2 are estimated to have lifetimes of hundreds of psec. While these values are based on single-particle estimates and might be changed significantly if nuclear-structure details were considered, it is obvious that with this large a difference in expected lifetimes, somewhat different techniques must be used in the various lifetime measurements. For the 52-keV first excited state, the γ rays were detected with a 5-cm-diam by 2-mm-thick NaI scintillator with a thin Be window. The protons from the

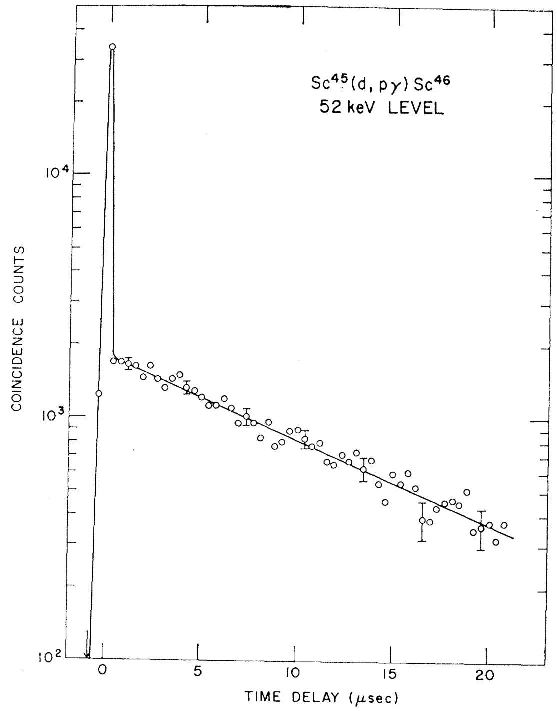

FIG. 3. The experimental decay curve for the 52-keV level of Sc^{46} as obtained with the $Sc^{45}(d,p\gamma)Sc^{46}$ reaction. The slope of the decay curve corresponds to a half-life for this state of $t_{1/2}=8.8\pm0.4$ μsec. The sharp peak which represents the time resolution function is a result of prompt events that satisfy the energy requirements.

$Sc^{45}(d,p\gamma)Sc^{46}$ reaction that populate this level were detected at 45° to the deuteron beam axis in a 25-mm² silicon surface-barrier solid-state detector. Elastic deuterons were stopped before the detector by an Al foil. The γ-ray detector was positioned perpendicular to the reaction plane and the front face about 1 cm from the target. The 1.5 mg/cm² Sc metal target and the deuteron bombarding energy of 3.2 MeV that were used for the γ-ray singles run were also used for all of the timing measurements.

Timing for this measurement was achieved from the zero crossover of bipolar pulses. The proton and γ-ray pulses marked, respectively, the population and decay of the state. A start-stop time-to-amplitude converter (TAC) with maximum time range of 30 μsec was used to convert the time delays to a pulse-height spectrum. With pulse-height windows accepting the protons and γ rays appropriate to the 52-keV level, the resulting time spectrum shown in Fig. 3 was observed. The prompt resolution function, as indicated by the narrow peak at zero time, was more than adequate for this measurement. Pulses related to other levels that fell in the acceptance windows produced the prompt peak. Time calibration was checked against a crystal oscillator. A least-squares fit to the observed slope resulted in a half-life for the 52-keV level in Sc^{46} of $t_{1/2}=8.8\pm0.4$ μsec.

For the faster timing, the γ rays were detected in a Pilot B plastic scintillator coupled to an XP1020 photomultiplier tube, while the protons were detected in a silicon solid-state counter chosen for a collection time of about 1 nsec. Logic signals were obtained from 100 MHz leading-edge discriminators coupled to a TAC. An inductive pickoff circuit was employed to obtain a fast signal from the solid-state detector without affecting the energy resolution. Slow-coincidence requirements were used in conjunction with the fast timing to isolate the excitation region of interest and to minimize time jitter. The details of this particular fast-slow timing apparatus have been discussed previously.[13] Under favorable conditions, the time resolution for a 1-MeV γ ray with this apparatus is about 350 psec full width at half-maximum with a slope which falls a factor of 2 in approximately 75 psec. For lower γ-ray energies and under high counting rates, the resolution width increases. Time calibration was made with air-dielectric trombone delay lines.

The fast-timing survey was done for two different proton energy regions. One included protons at high energy which populated states in Sc^{46} up to approximately 1-MeV excitation and the other was a wider channel which accepted lower-energy protons representing the excitation region from 1 to about 5 MeV in Sc^{46}.

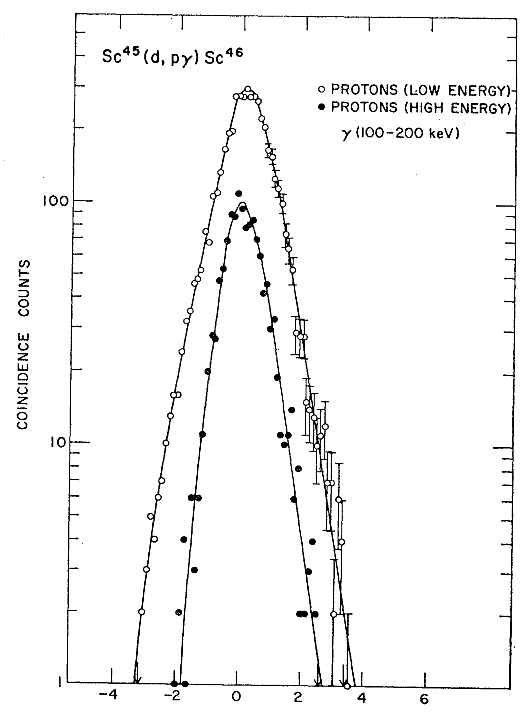

FIG. 4. Spectra of time delays between protons and γ rays for a γ-ray channel from 100–200 keV as obtained with the $Sc^{45}(d,p\gamma)Sc^{46}$ reaction. Open circles represent data for the low-energy proton channel and filled circles represent data for the high-energy proton channel.

[13] D. B. Fossan and A. R. Poletti, Phys. Rev. 152, 984 (1966).

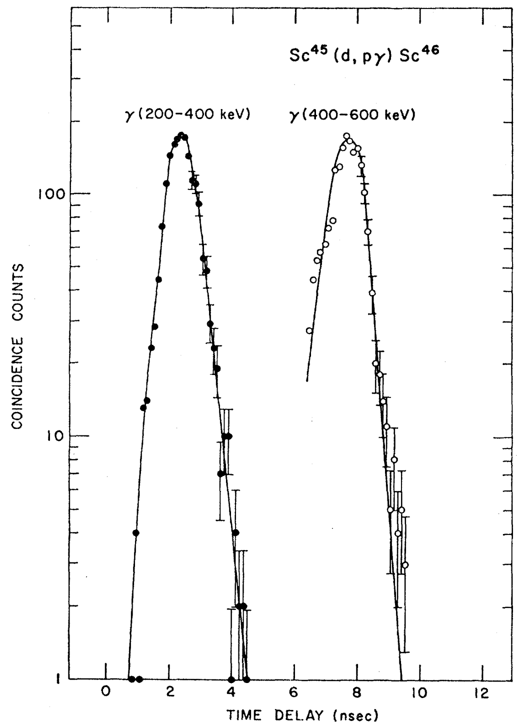

FIG. 5. Spectra of time delays between protons and γ rays for the high energy proton channel as obtained with the $Sc^{45}(d,p\gamma)Sc^{46}$ reaction. Open circles represent data for a γ-ray channel from 400–600 keV and filled circles represent data for a γ-ray channel from 200–400 keV. An arbitrary zero time is used.

The reason for using two proton channels was that from a coincidence measurement some of the low-lying levels were found to be only weakly populated in a direct manner but were populated in a prompt manner via cascades from higher energy levels with sufficient strength for timing measurements. For each of these proton channels, three different energy regions of the γ-ray spectrum were used in the timing survey. The three channels included γ rays of energies 100–200, 200–400, and 400–600 keV. Of course, the γ-ray pulse-height channels were set to the appropriate Compton region of the plastic-scintillator spectrum, where a given channel would see a portion of the Compton events initiated by higher-energy γ rays in addition to events expected for the channel.

Timing information could be obtained for only those levels in Sc^{46} whose de-excitation γ rays represented at least 10% of the coincident pulses in one of the γ-ray channels. The γ rays that are believed to satisfy this criterion are shown in Fig. 2. Thus, lifetime limits that were obtained for a given γ-ray channel would apply to those levels in Fig. 2 having de-excitation γ rays in that channel.

The observed time spectra for the 100–200 keV γ-ray window are shown in Fig. 4. The filled data points represent the time spectrum where high-energy protons (low excitation) marked the time of population of the levels in Sc^{46} while the open circles relate to the low-energy protons (high excitation). The lines drawn through the time-delay data on the right of each time spectrum correspond to a half-life of 380 psec. The right side of these time spectra contains a low-intensity wing due to the high γ-ray singles rates which are associated with deuteron-induced reactions, despite the fact that the deuteron beam current was kept below 10 nA. This effect, in general, increases the width of the prompt-resolution function and puts a lower limit on the lifetime that can be measured. The results shown in Fig. 4 indicate a half-life limit of $\leq$380 psec for levels that decay by 100–200 keV γ rays and that are populated significantly (see Fig. 2).

Figure 5 shows the time-delay spectra for the high-energy proton channel (low excitation) and the γ-ray windows of 200–400 and 400–600 keV. The slopes drawn through the data correspond to a half-life of 270 and 200 psec, respectively. The corresponding time spectra for low-energy protons (high excitation) yielded similar slopes with better statistics; however, since these time spectra include prompt events from levels in the high-excitation region with greater efficiency they have not been shown. Considering both sets of data, upper limits for half-lives corresponding to the 200–400 and 400–600 keV γ-ray windows (Fig. 2) are 270 and 200 psec, respectively.

III. DISCUSSION

A summary of the experimental lifetime information obtained for the low-lying levels in Sc^{46} is given in Table I. The levels listed with lifetime limits are only those that are populated with sufficient strength by the $Sc^{45}(d,p)Sc^{46}$ reaction (see Fig. 2). For comparison with the present experimental results, transition-probability calculations have been made using Sc^{46} configurations of lowest seniority. With the exception of the $2^- \rightarrow 1^-$ $M1$ transition, the initial and final configurations were of seniority 2, namely, an uncoupled neutron and proton. The positive-parity configurations were assumed to involve only $f_{7/2}$ particles $(\nu f_{7/2})(\pi f_{7/2})$, while the negative-parity configurations were made up of an $f_{7/2}$ neutron particle and a $d_{3/2}$ proton hole $(\nu f_{7/2})(\pi d_{3/2})^{-1}$.

TABLE I. Lifetime results for states in Sc^{46}.

E(keV)	J^{π} [a]	$t_{1/2}$
52	6^+	8.8±0.4 μsec
143	1^-	20 sec[b]
228	3^+	<270 psec
281	5^+	<270 psec
290	2^-	<380 psec
444	2^+	<270 psec
585	3^-	<270 psec
627	$(3,4)^+$	<200 psec
835	$(4,5)^+$	<200 psec

[a] P. Van Assche, U. Gruber, B. P. Maier, H. R. Koch, and O. W. B. Schult, Nucl. Phys. **84**, 661 (1966).
[b] M. Goldhaber and C. O. Muelhause, Phys. Rev. **74**, 1877 (1948).

TABLE II. $M1$ transitions in Sc^{46}.

E_i (keV)	$J_i^\pi \to J_f^\pi$	E_γ (keV)	$B(M1)$ (nm^2) expt	$B(M1)$ (nm^2) theory	Hindrance
228	$3^+ \to 4^+$	228	$>1.3\times10^{-2}$	7.8	<600
281	$5^+ \to 6^+$	228	$>1.3\times10^{-2}$	4.4	<350
444	$2^+ \to 3^+$	216	$>1.5\times10^{-2}$	9.4	<600
627	$\{3^+, 4^+\} \to 4^+$	627	$>8.6\times10^{-4}$	{7.8, 1.5}	{<9000, <1700}
835	$\{4^+, 5^+\} \to 5^+$	554	$>1.2\times10^{-3}$	{6.2, 2.2}	{<5000, <1800}
290	$2^- \to 1^-$	147	$>3.5\times10^{-2}$	0.4	<10
585	$3^- \to 2^-$	295	$>6.1\times10^{-3}$	0.15	<25

Only the uncoupled neutron and proton then compete in the γ transitions. The spins, parities, and γ branching information for Sc^{46} of Van Assche *et al.*[6] were used in these calculations.

The experimental conversion coefficient[6] for the 52-keV γ ray from the first-excited state in Sc^{46} implies an $E2$ multipolarity for this transition. The theoretical transition probability calculated for a $6^+ \to 4^+$ transition of 52 keV is $B(E2)=1.05\times10^{-52}(e_p+e_n)^2$ cm^4, where e_p and e_n are, respectively, the proton and neutron effective charges. The experimental half-life of $t_{1/2}=8.8\pm0.4$ μsec and the theoretical conversion coefficient $\alpha=4.4$ imply a $B(E2)=3.10\times10^{-51}e^2$ cm^4. A comparison of these two results gives $e_p+e_n=5.43e$. An $E2$ enhancement of this size is not uncommon for the $f_{7/2}$ shell. The present lifetime result is thus consistent with an $E2$ transition and the 6^+ assignment for the 52-keV state. Kästner *et al.*[14] recently reported the observation of a 52-keV γ ray from the $Sc^{45}(n,\gamma)Sc^{46}$ reaction with a half-life of $t_{1/2}=10.6\pm0.6$ μsec. This γ ray probably corresponds to the decay of the first excited state of Sc^{46}.

The theoretical $M1$ transition probabilities for the low-lying levels in Sc^{46} are listed in Table II. In calculating the experimental transition probabilities $B(M1)$ from the lifetime information, the transitions indicated are all assumed to be $M1$. From branching ratios, the $E1$ transitions between the positive- and negative-parity levels are hindered relative to single-particle estimates by about 1000, which is a manifestation of the different configurations.[6] The experimental $B(M1)$ and the resulting hindrance $H=B(M1)_{\text{theory}}/B(M1)_{\text{expt}}$ are both listed for each transition in Table II. None of these hindrance limits for the $M1$ transitions in Sc^{46} is as unusually large as those that have been observed for two transitions in Sc^{46} by Ristinen and Sunyar.[11] These differences would indicate that the positive-parity configurations of Sc^{44} and Sc^{46} are more complex than simply $(\pi f_{7/2})(\nu f_{7/2})^{\pm3}$. With the somewhat normal speeds measured for the $M1$ transitions, no large seniority-forbidden effects have been seen. Thus nothing definite can be stated regarding seniority mixing.[12]

[14] R. Kästner, A. Andreef, and P. Manfrass, in *International Conference on the Study of Nuclear Structure with Neutrons* (North-Holland Publishing Co., Amsterdam, 1966), p. 515.