Excitation of Low-Lying States of ^{89}Zr by the (p,n) Reaction on ^{89}Y†

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Neutrons from the (p,n) reaction on ^{89}Y were investigated for the incident proton energies 5.503 and 5.770 MeV. The angular distributions of the neutrons corresponding to the (p,n) transitions to five low-lying states of ^{89}Zr were measured by the time-of-flight method in conjunction with a pulsed proton beam. The energies of the populated states are: ground state, 595±10, 1095±10, 1465±10, and 1645±10 keV. A spin and parity of $\frac{3}{2}^-$ was determined for the 1095-keV state.

INTRODUCTION

Several low-lying states have been observed in ^{89}Zr; however the spin-parities are known[1] only for the ground state $(\frac{9}{2}^+)$ and the excited state at 588 keV $(\frac{1}{2}^-)$. A second excited state has been observed by Goodman[2] at 1100 keV. He reported the l transferred in the ^{90}Zr$(p,d)^{89}$Zr neutron pick-up reaction to be unity. Since the spin-parity of the target is 0^+, it follows that the spin-parity of the 1100-keV excited state of ^{89}Zr must be either $\frac{1}{2}^-$ or $\frac{3}{2}^-$. This level has also been observed through the (p,n) reaction studies on ^{89}Y targets.[3–5]

We have investigated the energy spectra and the angular distribution of the neutrons from the (p,n) reaction of an ^{89}Y target at incident energies $E_p=5.503$ and 5.770 MeV. The spin and parity of the 1100-keV state of ^{89}Zr were determined by eliminating one of the two possible assignments established through the (p,d) investigation. This was done by comparing the shape and magnitude of the neutrons feeding the 1100-keV state $(I^\pi=\frac{1}{2}^-$ or $\frac{3}{2}^-)$ to those neutrons feeding the known 588-keV, $I^\pi=\frac{1}{2}^-$ state.

RESULTS

Except for the incorporation of a γ-ray discrimination feature to the time-of-flight neutron detection system, the experimental procedure used for the present investigation was identical to that reported.[6] A representative neutron flight-time spectrum is shown in Fig. 1. The average values of the excitation energies are determined from ten neutron spectra (at the same incident energy but with different angles). Assuming that the reaction Q-value is -3.625 MeV, (see Ref. 7) they are 595±10, 1095±10, 1465±10, and 1645±10 keV. These values are in excellent agreement with the previously measured values.[3]

The angular distributions of the neutron groups were obtained from the flight-time spectra. These were corrected for the neutron energy dependence of the detection efficiency. The resulting relative differential cross-sections $\sigma(\theta)$'s are shown in Figs. 2–4. Because of the difference in thickness for the targets used at different incident energies, the units shown for $\sigma(\theta)$'s are not the same. However, a common relative unit is taken for the different neutron groups for a given incident energy. The data by Lightbody *et al.* for the $E_p=5.51$ MeV are also illustrated along with the 5.503-MeV data. The present results are in reasonable agreement with the previous ones.

We have performed a least-squares analysis of the $\sigma(\theta)$'s in terms of the Legendre polynomial. This analysis did not require any odd Legendre functions. We, therefore, take the result of this analysis as reasonable evidence that the $\sigma(\theta)$'s are symmetric around $\theta=90°$. This is as expected if the reaction goes by the statistical compound nucleus process.

The angular distributions of the neutron groups feeding the three low-lying states of ^{89}Zr are essentially the same for the two bombarding energies. As we shall shortly see, it is of considerable interest to note that the $\sigma(\theta)$ for the 1095-keV state is practically isotropic while the $\sigma(\theta)$ for the 595-keV $(I^\pi=\frac{1}{2}^-)$ state is very anisotropic. Also it is evident from Figs. 2 and 3 that the neutron yields to the 1095-keV state are greater than the yields to the 595-keV $(\frac{1}{2}^-)$ state for both incident energies employed.

DISCUSSION

We shall assume that the (p,n) reaction on ^{89}Y for the relevant incident energies proceeds mostly via statistical compound nucleus process. There are several arguments which support the assumption. The detailed experimental data of the reactions ^{89}Y$(p,n)^{89}$Zr(g.s.) and ^{89}Y$(p,n)^{89}$Zr* (595-keV), available for the incident energy range 4 to 6 MeV, revealed that: (a) the angle integrated reaction cross sections vary smoothly with the bombarding energy,[8] (b) the angular distributions of the

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[1] *Nuclear Data Sheets*, compiled by K. Way *et al.* (U. S. Government Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington, D. C.), NRC 60-3-85.

[2] C. D. Goodman, Bull. Am. Phys. Soc. **9**, 106 (1964).

[3] D. B. Lightbody, G. E. Mitchell, and A. Sayres, Phys. Letters **15**, 155 (1965).

[4] G. S.Mani and G. C. Dutt, Phys. Letters **16**, 50 (1965).

[5] C. H. Johnson and R. L. Kernell, Oak Ridge National Laboratory Report No. ORNL-3778, 1965 (unpublished).

[6] H. J. Kim and R. L. Robinson, Phys. Rev. **151**, 920 (1966).

[7] This Q value is taken from L. A. Koening, J. H. E. Mattauch, and A. A. Wapstra, *Nuclear Data Tables* (U. S. Government Printing Office, Washington, D. C., 1960).

[8] C. H. Johnson, R. L. Kernell, and S. Ramavataram (to be published).

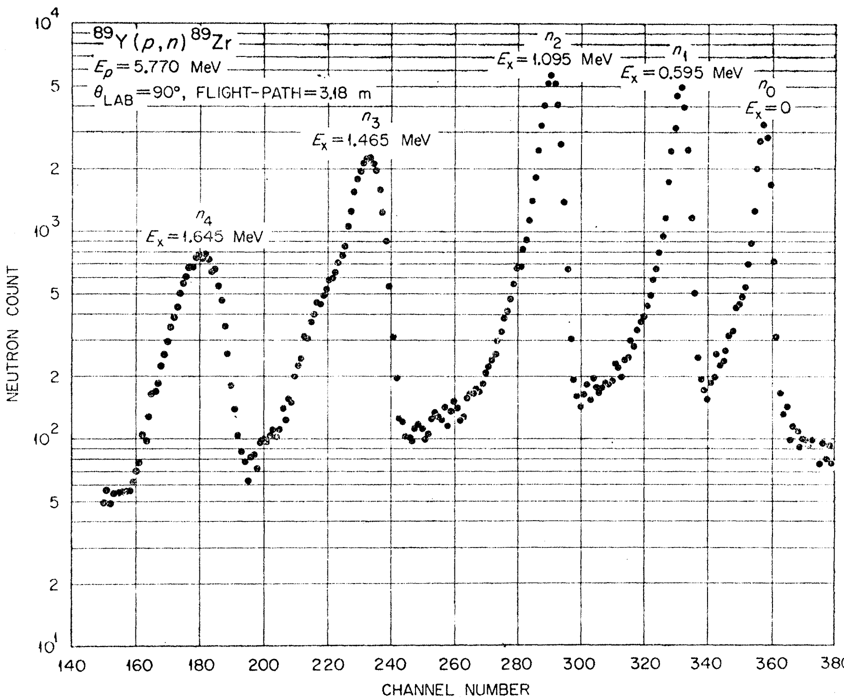

FIG. 1. A neutron time-of-flight spectrum for the $^{89}Y(p,n)^{89}Zr$ reaction. The flight time increases from right to left. The apparent shoulder shown for n_3 is due to the instrumentation used and not due to another neutron group.

neutrons feeding the ground state as well as the 595-keV state of ^{89}Zr are symmetric[4,6,9] about $\theta_{c.m.} = 90°$, (c) the ratio of the differential cross-sections leading to the above two states show smooth energy dependence,[2,3,9] and (d) the angular distributions can be fitted[6,9] by the Hauser-Feshbach theory.[10] The above features are the expected angle and energy dependence of the cross-section if the dominant reaction mechanism is the statistical compound nuclear reaction process.[11–13] This process can also explain the shape of the analogue resonance as well as the resonance angular distribution observed in the study of the $^{89}Y(p,n)^{89}Zr$ reaction mechanism via the isobaric-spin analog resonances.[6]

Consider the branching ratio and the angular distributions of neutrons feeding two residual states of the

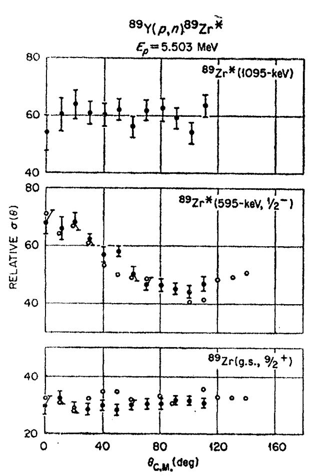

FIG. 2. Relative differential cross sections for $E_p = 5.503$ MeV. The data points without the error-flags are from Ref. 8. See text for the meaning of the relative unit used.

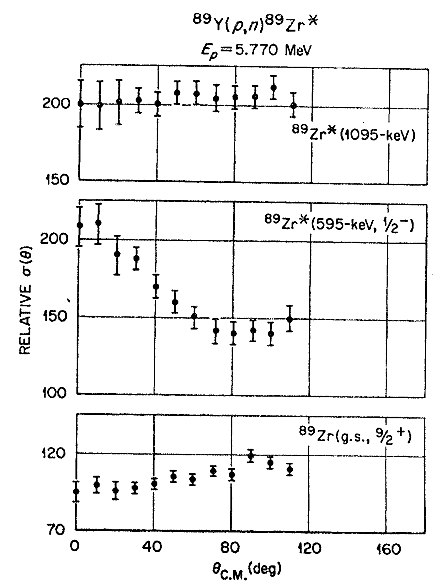

FIG. 3. Relative differential cross sections for $E_p = 5.770$MeV. See text for the meaning of the relative unit used.

[9] D. B. Lightbody, A. Sayres, and G. E. Mitchell, Phys. Rev. **153**, 1214 (1967).
[10] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952).
[11] H. Feshbach, in *Nuclear Spectroscopy*, edited by F. Ajenberg-Selove (Academic Press Inc., New York, 1960), Part B, p. 661.
[12] E. Sheldon, Rev. Mod. Phys. **35**, 795 (1963).
[13] M. A. Preston, in *Physics of the Nucleus* (Addison-Wesley Publishing Company, Inc., Reading, Massachussetts, 1962), p. 508.

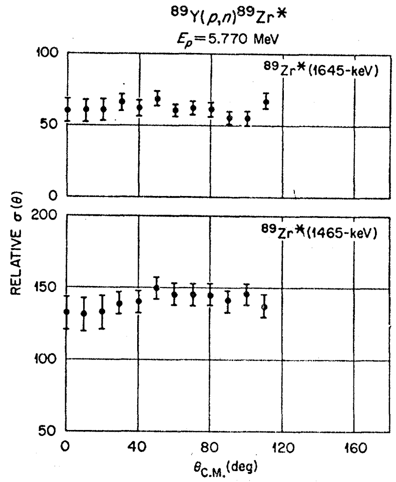

FIG. 4. Relative differential cross sections for $E_p=5.770$ MeV. See text for the meaning of the relative unit used.

same spin-parity I^π but with slightly different excitation energies. The branching ratio should favor the neutron emission to the state with lower excitation energy. This is because the branching ratio is given in terms of the neutron transmission coefficients, as shown in Eqs. 1 and 2 of the Appendix, and the neutron-transmission coefficients for the emitted neutron energies ~1 MeV increase with energy. In regard to the angular distributions, we have already seen the shapes of the differential cross-sections did not change with the small change of the incident energy (see Figs. 2 and 3). Thus, we would expect[14] that the neutrons to two states with the same spin-parity would have the same angular distrbution but greater yield to the lower state.

It follows from the above qualitative discussions that: since the neutron yield to the 1095-keV state is greater than the neutron yield to the 595-keV ($I^\pi=\frac{1}{2}^-$) state, and since the $\sigma(\theta)$ for the former is isotropic while the $\sigma(\theta)$ for the latter is very much peaked away from the symmetry angle $\theta=90°$, the spin and parity of the 1095-keV state is not $\frac{1}{2}^-$. The only remaining spin and parity consistent with the work of Goodman[2] is $\frac{3}{2}^-$. A similar comparison of the $\sigma(\theta)$'s for the 1465-keV state (see Figs. 3 and 4) to the ground state ($\frac{9}{2}^+$) and the 595-keV state ($\frac{1}{2}^-$), with the same type of arguments as used above, indicates that this state does not have $I^\pi=\frac{1}{2}^-$ or $\frac{9}{2}^+$.

COMPARISON TO THEORY

The general and qualitative aspect of the predictions of the statistical compound nuclear reaction theory was introduced and used in the preceding section in order to make some restricted inquiry concerning the spins and parities of relevant states. In this section we shall investigate the quantitative feature of the predictions of this reaction theory by using the Hauser-Feshbach theory[10] in conjunction with the nucleon transmission coefficients derived from the optical model theory. The discussion of the theory can be found in various review articles.[11–13]

The angular distributions and the branching ratios were calculated with the generalized Hauser-Feshbach (H-F) computer code[15] which includes the spin-orbit effect. The optical-model potentials adopted are; the local equivalent nonlocal potential of Perey and Buck[16] as given by Wilmore and Hodgson[17] for the emitted neutron channels, and the potential determined by fitting the absolute experimental (p,n) reaction cross-section of ^{89}Y for the incident energy range 3.7 to 5.4 MeV for the incident proton channels.[7] The details of the calculation including the open channels considered are given in the Appendix and the parameters of the optical-model potentials used are given in Table I. The calculated differential cross-sections are normalized using a single normalization factor and compared with the data. The normalization factor was so chosen that the calculated $\sigma(\theta)$'s for the (p,n) transitions to the two residual states with known I^π, the ground state ($\frac{9}{2}^+$) and the 595-keV ($\frac{1}{2}^-$) state, give a good visual fit to the experimental results. Theoretical $\sigma(\theta)$'s adjusted in this way are shown along with the data in Figs. 5 and 6.

It is remarkable that the theory predicts not only the shapes of the $\sigma(\theta)$'s but also gives correct branching ratios of the neutron yields to these two known states. The theoretical results support the spin-parity choice of $\frac{3}{2}^-$ for the 1095-keV state, made in the previous section. For an assumed $I^\pi=\frac{1}{2}^-$, the calculated result does not agree at all with the data, as can be readily seen in Fig. 5.

TABLE I. Parameters of the optical-model potentials.[a]

	V(MeV)	r_V(F)	a_V(F)	W(MeV)	r_W(F)	a_W(F)	V_{s-0}(MeV)
Proton	56.60	1.25	0.650	5.00	1.25	0.470	7.50
Neutron	46.50	1.34	0.660	8.50	1.30	0.480	7.20

[a] The shape of the potentials as well as the definition of the various quantities are the same as in Ref. 17.

[14] It is implied here that the small change of the incident energy essentially introduced no other changes but the excitation energy of the compound nucleus, hence the emitted neutron energy.
[15] W. R. Smith, Oak Ridge National Laboratory Report No. ORNL-TM-930, 1964 (unpublished).
[16] F. G. Perey and B. Buck, Nucl. Phys. **32**, 353 (1962).
[17] D. Wilmore and P. E. Hodgson, Nucl. Phys. **55**, 673 (1964).

The theoretical $\sigma(\theta)$'s also suggest that the $I^{\pi}=\frac{3}{2}^{+}$ or $\frac{3}{2}^{-}$ for the 1465-keV state and $I^{\pi}=\frac{5}{2}^{+}, \frac{5}{2}^{-}, \frac{7}{2}^{+}$, or $\frac{7}{2}^{-}$ for the 1645-keV state.

In the course of the present calculation, we have noticed that the shape as well as the magnitude of the calculated $\sigma(\theta)$ depends very strongly on the assumed spin of the residual state (see Fig. 5 for an example) but are quite insensitive to the assumed parity.

CONCLUSION

Experimental data support the assumption that the (p,n) reaction on ^{89}Y mainly proceeds by the statistical compound nuclear reaction mechanism for the incident proton energy of about 5.5 MeV. The present experimental results are consistent with the general predictions of this reaction mechanism if the spin and parity of the 1095-keV state of ^{89}Zr is $\frac{3}{2}^{-}$; however, they are inconsistent with the only other choice, namely, $\frac{1}{2}^{-}$, compatible with the (p,d) studies of Goodman.[2]

The Hauser-Feshbach formalism used in conjunction with the transmission coefficients derived from the optical-model theory and reasonable optical-model potentials correctly predicts the branching ratio and the angular distributions of the neutrons from the reactions $^{89}Y(p,n)^{89}Zr$ (g.s., $\frac{9}{2}^{+}$) and $^{89}Y(p,n)^{89}Zr^{*}$ (595-keV, $\frac{1}{2}^{-}$) for incident proton energies 5.503 and 5.770 MeV. The neutron yields and the angular distributions for these energies from the (p,n) transition to the 1095-keV state of ^{89}Zr are in agreement with the result of the above calculation if the spin-parity of this state is $\frac{3}{2}^{-}$ and they do not agree at all if the spin-parity is $\frac{1}{2}^{-}$. It is also concluded that the spin-parity of the 1465-keV state cannot be $\frac{1}{2}^{-}$ or $\frac{9}{2}^{+}$; the spin of this state is very likely $\frac{3}{2}$ rather than $\frac{5}{2}$ or $\frac{7}{2}$.

ACKNOWLEDGMENTS

We are grateful to W. R. Smith for use of his H-F code and we acknowledge the useful comments from C. H. Johnson.

APPENDIX

The theoretical angular distributions are calculated using a computer code by W. R. Smith.[15] The differential cross section in the notation given in Ref. 12 for the transition $i \longrightarrow f$ is

$$\sigma(\theta)=\frac{\lambda\!\!\!^{-2}}{8}\sum\frac{2J+1}{2I_i+1}\sigma(Jj_ij_f)\eta_\nu(j_ij_iI_iJ)\times\eta_\nu(j_fj_fI_fJ)P_\nu(\theta)\,. \quad (1)$$

The summation indicated includes sum over all allowed values j_i, j_f, J and ν. The partial reaction cross section $\sigma(Jj_ij_f)$ is related to the optical-model transmission coefficients $T(Jlj)$ by

$$\sigma(Jj_ij_f)=\frac{T(Jl_ij_i)T(Jl_fj_f)}{\sum T(Jl_sj_s)}\,, \quad (5)$$

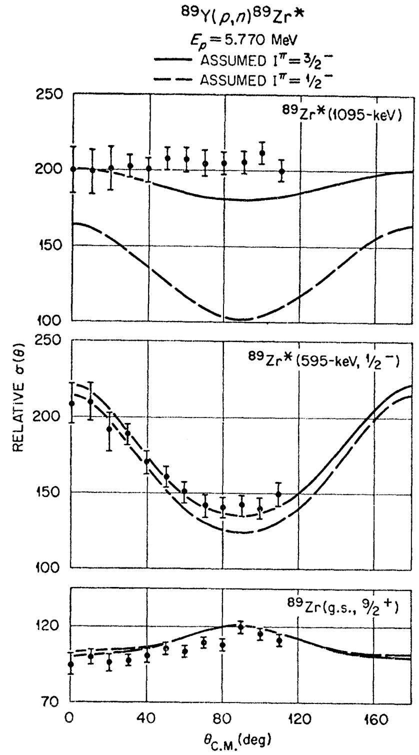

FIG. 5. Comparison of the experimental $\sigma(\theta)$, shown in Fig. 3, to the results of the Hauser-Feshbach calculation. Solid lines are for $I^{\pi}=\frac{3}{2}^{-}$ and the broken curves are for $I^{\pi}=\frac{1}{2}^{-}$.

where the summation shown accounts for the competition from all the open reaction channels s.

The open channels considered were the compound elastic, (p,p'), (p,n), and (p,α) channels. Of these open channels, we neglect all charged particle channels except the compound elastic and (p,p') to the first excited state (915 keV, $\frac{9}{2}^{+}$) of ^{89}Y. The other charged particle

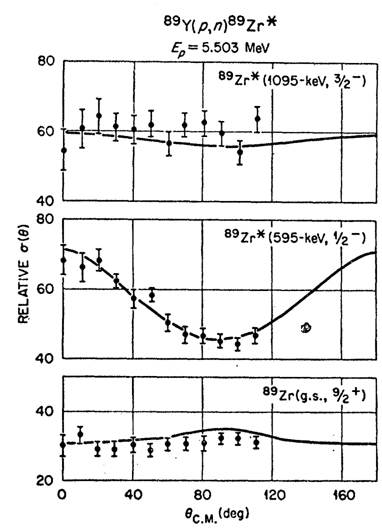

FIG. 6. Comparison of calculated $\sigma(\theta)$ to the experimental data. Solid curves are for $I^{\pi}=\frac{3}{2}^{-}$.

channels do not contribute much (less than few percent) to the proton reaction cross section since the energies involved are considerably below the respective Coulomb barrier. We included the (p,n) channels leading to the ground state $(\frac{3}{2}^+)$, 595-keV state $(\frac{1}{2}^-)$, 1095, 1465, and 1645-keV states.

The differential cross section for a given channel is coupled to the rest of the open channels through Eq. (2). Therefore, in general, $\sigma(\theta)$ for a particular channel depended on the assumed I^π's of the relevant open channels. However, we found, by actual calculations assuming different spin-parities for the unknown states, that, insofar as the shapes and branching ratios of the $\sigma(\theta)$'s to the three low-lying states were concerned, the assumed values of the spin-parities did not matter. On the other hand, the absolute values of $\sigma(\theta)$ did change noticeably with particular choice of the I^π. The differential cross-sections shown in Figs. 5 and 6 are calculated assuming $I^\pi=\frac{3}{2}^+$ for the 1465-keV state and $I^\pi=\frac{5}{2}^+$ for the 1645-keV state.

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Nuclear Structure of Na^{22}. II. Some Gamma-Ray Doppler-Shift and Correlation Measurements*

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Levels of Na^{22} below an excitation energy of 4.4 MeV have been investigated through the $F^{19}(\alpha,n\gamma)Na^{22}$ and $Ne^{20}(He^3,p\gamma)Na^{22}$ reactions. Using the first reaction, initiated in a CCl_2F_2 gas target, the Doppler shifts of γ-ray transitions from the 0.891-, 2.211-, and 2.572-MeV levels were measured using α energies between 4 and 7 MeV. From these results upper limits were placed on the lifetimes of the three initial states. Combining these upper limits with previously obtained lower limits yields the following restrictions on the mean lifetimes (in psec) for these three levels: $8<\tau<52$, $11<\tau<42$, and $10<\tau<42$, respectively. Proton-γ angular correlations were measured at $E_{He^3}=6.56$ MeV using the $Ne^{20}(He^3,p\gamma)Na^{22}$ reaction. These results gave information on γ-ray branching and multipole-mixing ratios and served to limit the possible spin-parity assignments of some of the levels.

I. INTRODUCTION

IN this report we present further results in a continuing experimental investigation into the properties of the energy levels of the nucleus Na^{22}. Information available on the quantum numbers of the first 18 levels of Na^{22} and the first 3 levels of Ne^{22} is shown in Fig. 1. The figure is taken from a previous report[1] on the levels of Na^{22} with some additions. Recent results from γ-ray linear polarization measurements[2] are included. These fixed the 1.528-MeV level as $J^\pi=5^+$ and determined the parity of the 2.211-MeV level to be odd. The results of the present work are also included.

In our previous report[1] we presented results bearing on the levels below an excitation energy of 3.1 MeV. The emphasis in this report is on the levels between 2.5 and 4.4 MeV. These levels were studied by proton-γ angular-correlation measurements via the $Ne^{20}(He^3,p\gamma)Na^{22}$ reaction. The interpretation of these results was aided by γ-γ coincidence measurements obtained with both NaI(Tl)-NaI(Tl) and NaI(Tl)-Ge(Li) γ-ray detector combinations.

In addition to these correlation measurements, we also present the results of Doppler-shift measurements on the most intense γ rays originating from each of the three levels at 0.89, 2.21, and 2.57 MeV. These measurements were analyzed to give upper limits on the lifetimes of these three levels. Combining them with previously obtained[1] lower limits results in fairly limited ranges of allowed values for the lifetimes of the three states.

II. LIFETIME MEASUREMENTS

A. Experimental Procedure and Results

Levels of Na^{22} were populated via the $F^{19}(\alpha,n)Na^{22}$ reaction. The target consisted of CCl_2F_2 gas at a pressure of 1 atm, which was confined by a 0.1-mil Ni foil. The α beam passed through this foil, through 2 cm of gas, and was stopped in tantalum. Gamma rays were detected in an 8-cc Ge(Li) detector placed 10 cm from the gas target and at angles θ_γ to the beam axis of 0° and 90°. Gamma-ray spectra were recorded using a 4096-channel digitally stabilized analog-to-digital converter in conjunction with a Technical Measurements Corporation (TMC) 16384 pulse-height analyzer.

The three γ-ray transitions studied were: $0.891\rightarrow 0$, $2.211\rightarrow 0.657$, and $2.572\rightarrow 0$. For each level studied

* Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] E. K. Warburton, J. W. Olness, and A. R. Poletti, Phys. Rev. **160**, 938 (1967).
[2] A. R. Poletti, E. K. Warburton, and J. W. Olness, Phys. Rev. (to be published).