(p,t) Reaction on the Isotopes of Sm and Nd, $N=88$ and 90†

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The (p,t) reaction on targets of $Sm^{150,152}$ and $Nd^{148,150}$ has been investigated using the 40-MeV beam of the University of Minnesota Linear Accelerator. Angular distributions have been measured for the low-lying levels in the range 5° to 40°. These nuclei are interesting in that they have $N=88$ and 90, and span the rather sharp transition from a region of spherical to deformed nuclei. Three equally strong $L=0$ transitions are observed in the $Sm^{152}(p,t)Sm^{150}$ spectrum corresponding to the excitation of 0^+ states in Sm^{150} at 0, 0.78, and 1.28 ($\pm$0.05 MeV). The $L=0$ transition to a 0^+ state at 1.28 MeV in Sm^{150} appears to correspond to the excitation of a deformed state in a nucleus with an approximately spherical ground state. One might expect the (p,t) reaction to excite such a state because the target nucleus, Sm^{152}, is deformed. The 0.78-MeV group in the $Sm^{152}(p,t)Sm^{150}$ spectrum probably corresponds to the excitation of the known 0^+, "two-phonon," state at 0.743 MeV. In the $Sm^{150}(p,t)Sm^{148}$ reaction, where both the target and residual nuclei have spherical ground states, the ground-state $L=0$ transition is the only state observed with significant strength below 1.45 MeV. A group at 1.45 MeV, which probably includes some $L=0$ strength, is observed with about $\frac{1}{3}$ the strength of the ground-state transition. The Nd^{150} and $Nd^{148}(p,t)$ spectra are similar to the two Sm spectra with the same neutron number. Comparison is made with the existing (t,p) data on the same Sm nuclei.

I. INTRODUCTION

THE isotopes of samarium are a particularly interesting sequence of nuclei in that they span the transition region from spherical to deformed nuclei. The transition from spherical to deformed nuclei occurs rather sharply between $_{62}Sm^{150}$ and $_{62}Sm^{152}$ with neutron number 88 and 90, respectively. The samarium nuclei have been studied extensively through (d,p) and (p,p') reactions[1,2] and more recently by means of the (t,p) reaction.[3] In this paper an investigation is made of the (p,t) reaction on Sm^{150} and Sm^{152} with particular emphasis on the comparison of results for the $Sm^{152}(p,t)Sm^{150}$ and $Sm^{150}(p,t)Sm^{148}$ reactions. The $_{60}Nd^{150}$ and $_{60}Nd^{148}(p,t)$ reactions have also been investigated because these nuclei have the same neutron number as the above samarium nuclei and may show the same rather sharp transition from spherical to the deformed ground states.

II. EXPERIMENTAL METHOD AND RESULTS

The experimental method has been described previously[4] and will be discussed only briefly. The 40-MeV beam from the University of Minnesota Linear Accelerator was focused onto the target in the scattering chamber with an energy spread of about 150 keV. The energy spread in the beam is due about equally to the size of the collimator after the beam-analyzing magnet and to the spread in energy loss of the beam as it passes through two windows separating the linear-accelerator vacuum system and the scattering-chamber–spectrometer vacuum system. Tritons from the (p,t) reaction were analyzed with a 40-in., $n=\frac{1}{2}$, magnetic spectrometer and detected with an array of 32 solid-state detectors in the focal plane.[5] The over-all resolution of the system was about 250 keV. The targets used for the investigation were oxides of samarium and neodymium enriched in the particular isotope of interest and were obtained from the Isotopes Division of Oak Ridge National Laboratory. They were prepared as powdered oxides in a binder of polystyrene by a method described elsewhere.[6]

The triton spectra are shown to several MeV of excitation in Fig. 1, the angular distributions of the low-lying triton groups in Figs. 2–5. The error bars on the angular distribution data reflect the counting statistics and the unfolding uncertainties. The latter in fact are the limiting errors for the triton groups at 1.45 MeV in Sm^{148} and at 0.96 MeV in Nd^{148}. The vertical scales on the angular distributions give the relative cross sections in the *same* (arbitrary) units. Absolute cross sections have not been measured. The relative target thicknesses were determined by measuring the yield of 40-MeV protons elastically scattered from each of the four targets over the maximum in the angular distribution near 45°. The relative yields were measured to better than 10% accuracy, and all targets were assumed to have the same cross section to Rutherford ratio for the thickness comparison.

Transitions of about equal strength are observed to the ground-state and excited-state groups at 0.78 and 1.28 MeV in Sm^{150} (all energies are determined to $\pm$50 keV). The ground states of Sm^{152} and Sm^{150} both

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[1] R. A. Kenefick and R. K. Sheline, Phys. Rev. **133**, B25 (1964); **135**, B939 (1964).
[2] R. A. Kenefick and R. K. Sheline, Phys. Rev. **139**, B1497 (1965).
[3] S. Hinds, J. H. Bjerregaard, O. Hansen, and O. Nathan, Phys. Letters **14**, 48 (1965).
[4] G. Bassani, N. M. Hintz, and C. D. Kavaloski, Phys. Rev. **136**, B1006 (1964).
[5] University of Minnesota Linear Accelerator Laboratory Progress Report, 1964, p. 126 ff (unpublished).
[6] G. Bassani, N. M. Hintz, J. R. Maxwell, and G. M. Reynolds, University of Minnesota Linear Accelerator Laboratory Progress Report, 1964, p. 83 (unpublished).

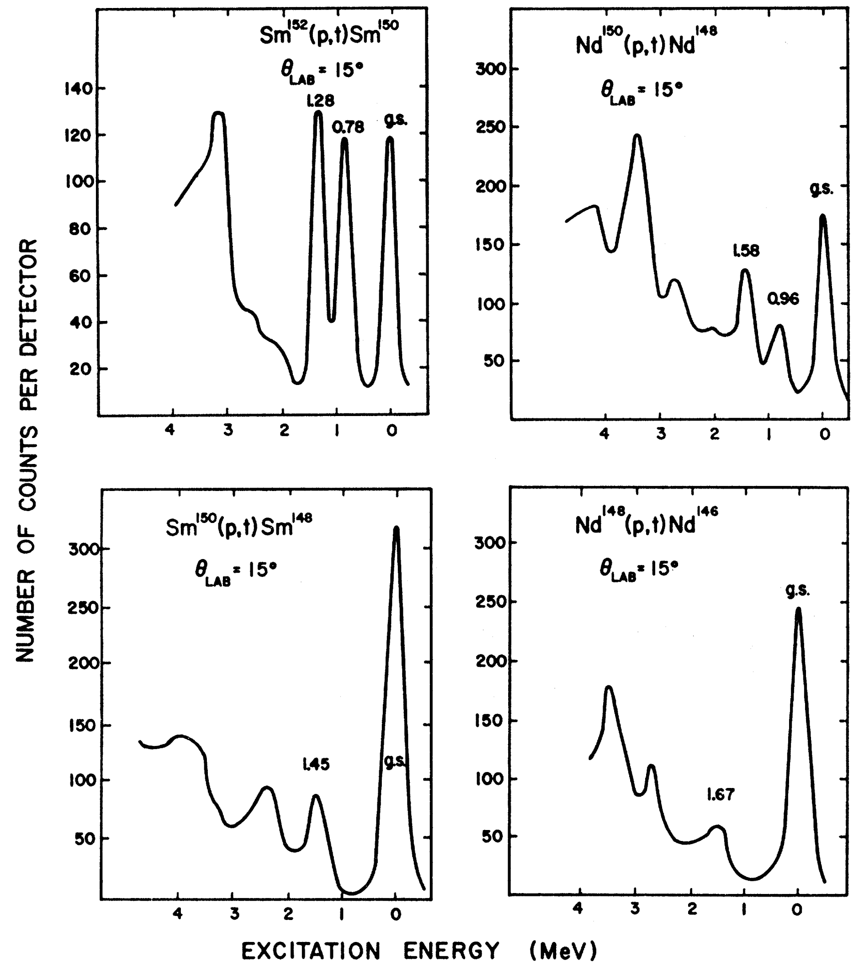

FIG. 1. Energy spectra of tritons from the (p,t) reaction on Sm^{152}, Sm^{150}, Nd^{150}, Nd^{148} targets at a proton energy of 40 MeV (g.s. ≡ground state).

have spin zero so that the orbital angular momentum of the transferred neutron pair is $L=0$ according to the selection rules for the (p,t) reaction.[4] The ground-state angular distribution for the $Sm^{152}(p,t)Sm^{150}$ reaction is shown in Fig. 2 and is very similar to the $L=0$ transitions observed in the tin and cadmium[7] as well as the calcium-to-zinc[4] regions of the periodic table. In addition, the 0.78 and 1.28-MeV angular distributions, also shown in Fig. 2, are very similar to that for the ground state, indicating the strong excitation of two spin-zero excited states in Sm^{150}.

The $Sm^{150}(p,t)Sm^{148}$ spectrum, shown in Fig. 1, is very different from the $Sm^{152}(p,t)Sm^{150}$ spectrum in that there are no low-lying states excited as strongly as the ground state. The ground-state transition shows a typical $L=0$ angular distribution (Fig. 3). The 1.45-MeV group, also shown in Fig. 3, has only about $\frac{1}{3}$ the strength of the ground-state transition. The group at 1.45 MeV seems to include some $L=0$ strength, but more than one state is being excited since the cross section does not decrease at small angles.

[7] G. Bassani, N. M. Hintz, C. D. Kavaloski, J. R. Maxwell, and G. M. Reynolds, Phys. Rev. **139**, B830 (1965).

The neodymium spectra of Fig. 1 seem to have features similar to the spectra of the samarium isotopes having the same neutron number. Three strong groups are observed in the $Nd^{150}(p,t)Nd^{148}$ spectrum, the ground-state and excited-state groups at 0.96 and 1.58 MeV. The ground-state transition is expected to be a pure $L=0$. However, the angular distribution shown in Fig. 4 seems to include some contribution from the known 0.300-MeV 2^+ first excited state which could not be resolved.[8] The 0.96-MeV group, although not well resolved, seems to include some $L=0$ strength to a spin-zero state in Nd^{148} with roughly 50% of the strength of the ground state. The 1.58-MeV group is stronger than the 0.96-MeV group but was not sufficiently well resolved from other triton groups at higher excitation for an angular distribution to be taken. The $Nd^{148}(p,t)Nd^{146}$ spectrum, in contrast to the $Nd^{150}(p,t)$-Nd^{148} and similar to the $Sm^{150}(p,t)Sm^{148}$ spectrum, shows

[8] Energies, spins, and parities of Sm nuclei have been taken from Refs. 1, 2, 3, and references quoted therein; of Nd nuclei from *Landolt-Börnstein Tables*, edited by K. H. Hellwege (Springer-Verlag, Berlin, 1961), Vol. 1.

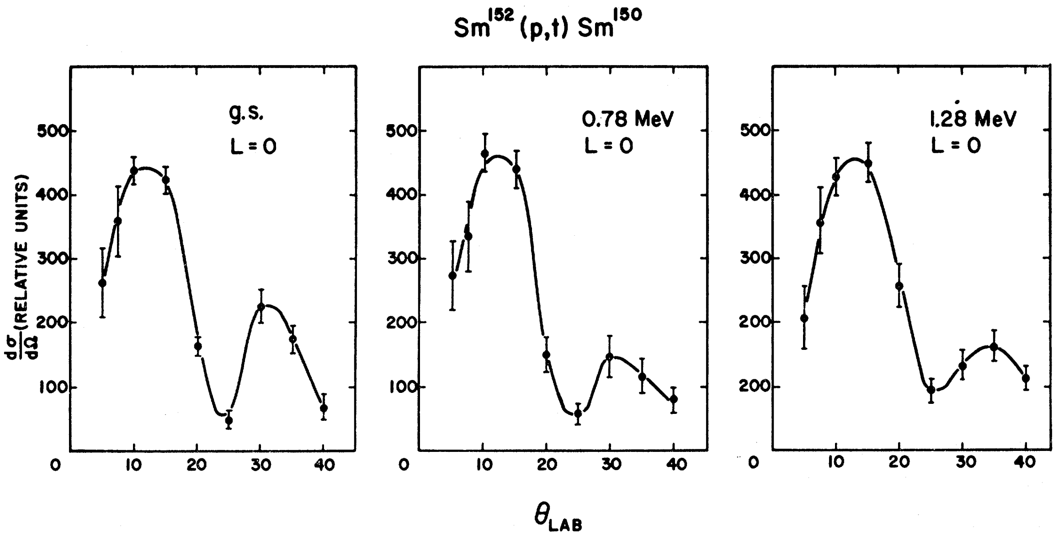

FIG. 2. Angular distributions of ground state, 0.78- and 1.28-MeV triton groups from $Sm^{152}(p,t)Sm^{150}$. The vertical scales on these angular distribution data as well as the angular distribution data of Figs. 3, 4, and 5 are given in the same (relative) units.

only the strong ground-state transition with a weakly excited triton group at 1.67 MeV.

The 2^+ state at 0.334 MeV in Sm^{150} is not well resolved from the ground state and the group at 0.78 MeV, but it appears that the state is only very weakly excited, and similarly for the 2^+ state at 0.560 MeV in Sm^{148} and at 0.453 MeV in Nd^{146}. However, the 0.300-MeV 2^+ state in Nd^{148} may be quite strongly excited as can be seen from the shape of the angular distribution of the ground and unresolved 0.300-MeV state in Fig. 4.

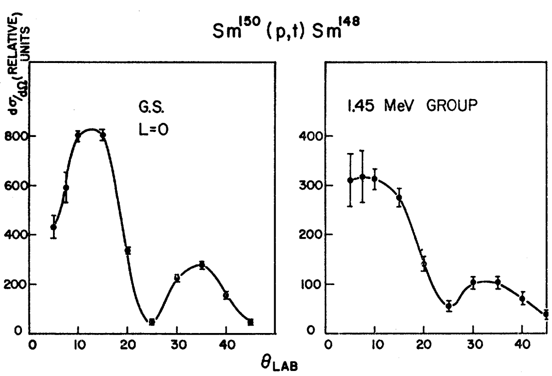

FIG. 3. Angular distributions of ground-state and 1.45-MeV triton groups from $Sm^{150}(p,t)Sm^{148}$.

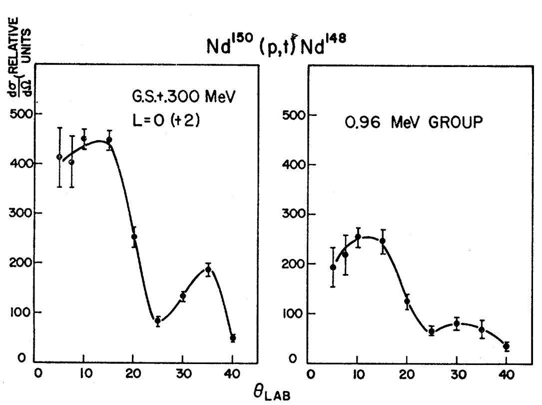

FIG. 4. Angular distributions of ground-state 0.300- and 0.96-MeV triton groups from $Nd^{150}(p,t)Nd^{148}$.

III. DISCUSSION OF RESULTS

The most interesting feature of the $Sm^{152}(p,t)Sm^{150}$ data is that 3 $L=0$ transitions, of about equal strength, are observed in the spectrum below 1.28 MeV. Although the evidence is less convincing, a similar situation seems to exist for $Nd^{150}(p,t)Nd^{148}$ at the same target neutron number ($N=90$). The situation seems to be very different for the $Sm^{150}(p,t)Sm^{148}$ and $Nd^{148}(p,t)Nd^{146}$ spectra (N target$=88$) where the bulk of the $L=0$ strength is to the ground states. The latter is similar to earlier (p,t) results on Ca to Zn nuclei[4] and the Sn isotopes[7] where no strongly excited $L=0$ transitions, except the ground state, have been observed up to 4–5-MeV of excitation. Exceptions are the $L=0$ transitions to $T=T_z+2$

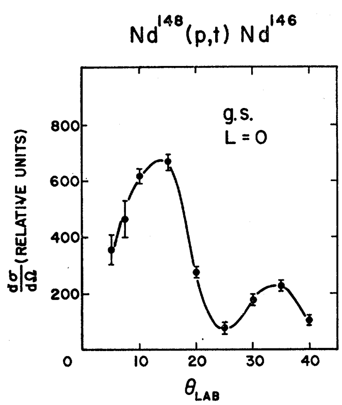

FIG. 5. Angular distribution of ground-state transition from $Nd^{148}(p,t)Nd^{146}$.

TABLE I. Cross sections to levels observed in the (p,t) reaction at $\theta_{lab}=15°$ in the same (relative) units. (g.s.≡ground state.)

Residual nucleus							
Sm^{150}		Sm^{148}		Nd^{148}		Nd^{146}	
Level (MeV)	$d\sigma/d\Omega$	Level (MeV)	$d\sigma/d\Omega$	Level (MeV)	$d\sigma/d\Omega$	Level (MeV)	$d\sigma/d\Omega$
g.s.	424	g.s.	802	g.s.+0.300	449	g.s.	667
0.78	439	1.45	275	0.98	247		
1.28	452						

ground-state analog levels[9] in several nuclei with large transition strengths at $\geqq 9$ MeV, and more recently to (presumably) $J=\frac{1}{2}^-$ excited states in the $Fe^{57}(p,t)Fe^{55}$ reaction below 4 MeV.[10] The general rule has been, however, that most of the $L=0$ strength is concentrated in the ground-state transition, in agreement with the coherence in the cross section expected in the pairing-force approximation.[11]

Analogous effects have been observed in (t,p) reactions. In the cadmium and uranium regions of the periodic table no strong low-lying $L=0$ transitions have been observed other than the ground state.[12] In the $Sm^{150}(t,p)Sm^{152}$ reaction, however, 3 $L=0$ transitions below 1.1 MeV are observed with about equal strength.[3] It appears that the change in nuclear coupling scheme as one goes from the spherical nuclei, $N\leqq 88$, to the deformed nuclei, $N\geqq 90$, is responsible for these strong, excited $L=0$ transitions. The nucleus Sm^{150} is thought to be approximately spherical and Sm^{152} more or less spheroidal. In the (t,p) reaction, the 0^+ ground state and the 0^+, "β-vibrational" state at 0.685 MeV in Sm^{152}, which are deformed states, appear to be excited in (t,p) through deformed components of Sm^{150}. One might expect, with a spherical target nucleus, to find in the (t,p) reaction a 0^+ spherical excited state in Sm^{152}. It is believed that the $L=0$ transition at 1.091 MeV observed in the $Sm^{150}(t,p)Sm^{152}$ reaction corresponds to this state.[3] There is evidence to support this interpretation from two-neutron separation-energy data[13] which indicate a spherical state would exist at 1 MeV.[3]

In the $Sm^{152}(p,t)Sm^{150}$ reaction one might in the same way expect to see an excited, deformed 0^+ state corresponding to the spherical 0^+ state found in Sm^{152} at 1.091 MeV. The state which is observed at 1.28 MeV is perhaps such a state. The deformed character of this state is also suggested by the results of (d,p) and (p,p') studies where the state is not excited and not expected to be because of the large change in shape.[2] Further, this 1.28-MeV state is *not* seen in the $Sm^{148}(t,p)Sm^{150}$ reaction[14] where it would be expected to be weak since the target nucleus is well into the spherical region.

The transitions to the ground state and first 0^+ excited state in Sm^{150} probably include strength from amplitudes of spherical and deformed components in these states of Sm^{150} and in the ground state of Sm^{152}. Apparently both of the first 0^+ states in Sm^{150} and Sm^{152} are mixtures of a β vibration of the deformed component and a two-phonon excitation of the spherical component in the ground states. The energies of these states, at 0.743 MeV in Sm^{150} and 0.685 MeV in Sm^{152}, are about equally low. Farther from the $N=88$ and 90 transition region the first 0^+ excited states are higher in energy, at 1.120 MeV in Sm^{148} and 1.020 MeV in Sm^{154}, where either the pure spherical two-phonon or the pure deformed β-vibrational model is a better description.

The $Sm^{150}(p,t)Sm^{148}$ spectrum does not exhibit the strong excited $L=0$ transitions. The ground-state transition has about twice the strength of the $Sm^{152}(p,t)Sm^{150}$ ground-state transition. The 15° peak cross sections for the various transitions are given in Table I in the same (relative) units. Apparently, as the deformed amplitudes in the ground state decrease in going away from the deformed region, the total $L=0$ strength goes increasingly to the ground state. The weaker $L=0$ transition to a state at 1.45 MeV may correspond to a deformed state in Sm^{148}, higher in energy and with smaller transition probability as expected.

Although the neodymium data are less complete, similarities to the samarium isotopes with the same neutron number suggest that the transition from the region of spherical to deformed nuclei also occurs at $N=88$ and 90 for neodymium.

[9] G. T. Garvey, J. Cerny, and R. H. Pehl, Phys. Rev. Letters **12**, 726 (1964).
[10] J. R. Maxwell, G. M. Reynolds, and N. M. Hintz, Phys. Letters (to be published).
[11] S. Yoshida, Nucl. Phys. **33**, 685 (1962).
[12] R. Middleton and D. J. Pullen, Nucl. Phys. **51**, 77 (1964); R. Middleton and H. Marchant, in *Proceedings of the Second International Conference on Nuclidic Masses, Vienna, 1963*, edited by Walter H. Johnson, Jr. (Springer-Verlag, Vienna, 1964), p. 329.
[13] R. C. Barber, H. E. Duckworth, B. G. Hogg, J. D. Macdougall, W. McLatchie, and P. Van Rookhuyzen, Phys. Rev. Letters **12**, 597 (1964).
[14] O. Hansen (private communication).