^{148}Gd$(p,t)^{146}$Gd reaction: Neutron states in ^{146}Gd

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We have used the ^{148}Gd$(p,t)^{146}$Gd reaction with protons of 34.6 and 24.9 MeV to study levels in ^{146}Gd below $E_x = 5.6$ MeV. The radioactive target material was deposited on the carbon support foil from an isotope separator. Triton spectra were analyzed by a magnetic quadrupole-dipole-dipole-dipole spectrometer (Q3D) at 11 angles between 10° and 60°. By comparing the angular distributions with the results of distorted-wave Born approximation calculations we obtained definitive L-transfer values for 11 excited states, including a strongly populated 0^+ state at 4534 keV, and approximate L values for about 50 additional states. A search for members of the two-octupole-phonon quartet of states expected to occur at $\sim$3.2 MeV of excitation (twice the single-phonon energy) revealed no convincing evidence of the 0^+ component, but the 2^+ component could be one of the four new 2^+ states identified in this region. A comparison between the most strongly populated low-lying states of ^{142}Sm in the ^{144}Sm(p,t) reaction and states in the pairing-vibrational region of ^{146}Gd reveals a possible set of states whose energies and (p,t) cross sections are in reasonable agreement with predictions of the harmonic pairing-vibration model.

I. INTRODUCTION

The nucleus ^{146}Gd has been shown[1] to exhibit many of the features of a doubly closed-shell nucleus. This unique situation, which suggests an important shell closure at $Z=64$, has led to extensive efforts, both experimental and theoretical, to understand the nuclei in the region around ^{146}Gd. The level structure of ^{146}Gd has been studied most extensively[1-3] by in-beam e^- and γ-ray spectroscopic techniques with the Sm(α,xn) reactions. The recent work by Yates *et al.*[2] using the ^{144}Sm$(\alpha,2n)$ reaction provides a summary of the present knowledge of the levels up to 4700 keV of excitation and gives an extensive bibliography of earlier work. Nearly all of the levels that have been characterized by these in-beam experiments are proton configurations. This reflects the fact that the shell gap at 82 neutrons is larger than the gap at 64 protons, and therefore the neutron states lie farther above the yrast line, where experimental identification is much more difficult. Furthermore, ^{146}Gd cannot be studied by single-nucleon transfer reactions because the adjacent nuclides are too unstable for use as targets.

Significant features of the ^{146}Gd level structure are the occurrence of a collective octupole vibrational state ($J^\pi=3^-$) at 1579 keV as the first excited state, the high excitation energy of the 2_1^+ quadrupole vibrational phonon at 1972 keV, and the relatively high energies of the 2p2h pairing vibrational (pv) states with respect to the systematics in this region. The neutron monopole and quadrupole pv states occur[4] at 3020 and 3383 keV, respectively, and the lowest-lying 1p1h neutron state is believed[5] to be the $\nu(f_{7/2}d_{3/2}^{-1})_{3^-}$ state at 3423 keV. A two-octupole-phonon quartet $(3^-\times3^-)_{0,2,4,6}$ of states is also expected in this energy region, at approximately twice the energy of the single-phonon 3^- state. There would be great interest in identifying any of these two-phonon states, which so far have been identified[6,7] only in ^{147}Gd and ^{148}Gd, weakly coupled to the extra-core neutrons. Above $\sim$3.5 MeV one expects increasing numbers of neutron excitations in addition to seniority two and four proton excitations.

The availability of ^{148}Gd targets[8,9] prepared from material irradiated at the Los Alamos Meson Physics Facility (LAMPF) has made it possible to study ^{146}Gd with the (p,t) reaction. This reaction strongly populates states of two neutron holes in the target nucleus, and it has a strong selection rule against populating states of unnatural parity. The first experiments[4] performed with a ^{148}Gd target led to the identification of the neutron monopole and quadrupole pv states and confirmed the $J^\pi=3^-$ nature of the first excited state. There was also an indication that some of the quadrupole pv strength lies at higher excitation energies than the maximum of $\sim$3.5 MeV that was explored. Furthermore, calculations by Chasman[10] predict a splitting that was not observed in the monopole pv state.

In the present work we used an improved ^{148}Gd target and explored the region of excitation energies up to 5.6 MeV. With the improved sensitivity provided by a thicker target we hoped to find evidence of the two-octupole-phonon multiplet by detecting the 0^+ or 2^+ components,

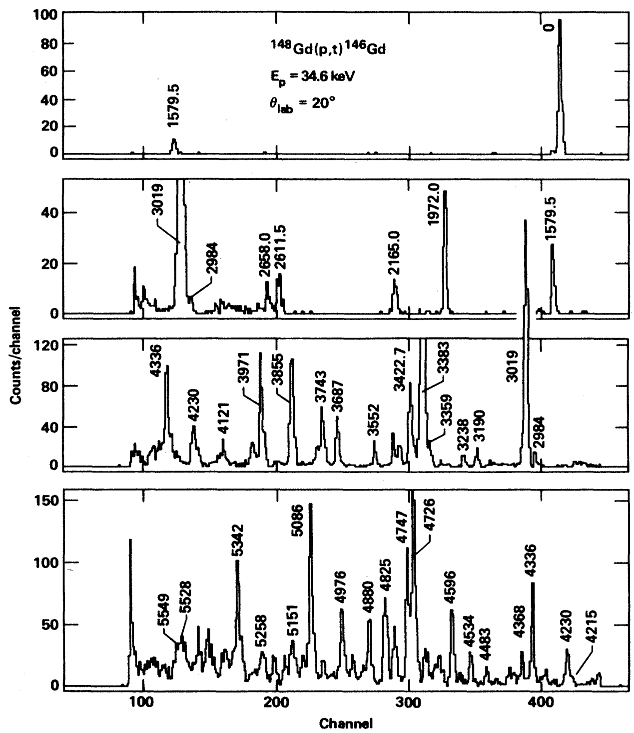

FIG. 1. Triton spectra obtained with the Q3D spectrometer at $\theta_{\rm lab}=20°$ for the ^{148}Gd$(p,t)^{146}$Gd reaction. Selected peaks are labeled with their excitation energies obtained from γ-ray data, to the nearest 0.1 keV, or from the present work, to the nearest keV.

which might contain some admixture of the nearby strongly populated pv states. We also wanted to examine the region of excitation energy above 3.5 MeV for additional pv strength and for comparison with the systematics of two-neutron states in other nuclei in this region.

II. EXPERIMENTS AND DATA ANALYSIS

We carried out the ^{148}Gd$(p,t)^{146}$Gd experiments at the Princeton University AVF cyclotron facility. The proton beam energy was 34.6 MeV in one set of experiments and 24.9 MeV in a later, less extensive, run. Beam currents were between 200 and 250 nA during the 34.6-MeV experiments and between 250 and 600 nA in the 24.9-MeV experiments. The tritons were momentum analyzed in a quadrupole-dipole-dipole-dipole (Q3D) spectrometer[11] operated at its maximum aperture of 14.5 msr. The full width at half maximum (FWHM) energy resolution was approximately 15 keV in the 34.6-MeV experiments and 13 keV in the 24.9-MeV experiments. The position-sensitive particle detector covered a useful range of about 6.2% in triton energy. Therefore, the range of excitation energies in ^{146}Gd that could be examined in a single run was between 1300 and 1600 keV, depending on the excitation energy, in the 34.6-MeV experiments, and 850 keV at 3.2 MeV of excitation in the 24.9-MeV experiments.

The target consisted of 0.93 μg of ^{148}Gd deposited on a 50-μg/cm^2 carbon foil. The target spot covered (nonuniformly) an area of 3 to 4 mm^2. However, the beam spot was considerably larger than the target, thus reducing the effective areal density of Gd. Depending on the quality of the beam spot, the effective target thickness was in the range of 7–11 μg/cm^2 during these experiments.

Material for the target was produced by spallation reactions in a tantalum target at the LAMPF accelerator.[8] After a total irradiation of the order of 1000 C with 750-MeV protons the initial chemical separations were performed at the Los Alamos National Laboratory (LANL). Further chemical purification of the Gd fraction was carried out at the Lawrence Livermore National Laboratory (LLNL). Sources for the LLNL Nuclear Chemistry Isotope Separator were then prepared by electrodeposition on tungsten strips, and the final targets were collected on carbon foils in the isotope separator.[9]

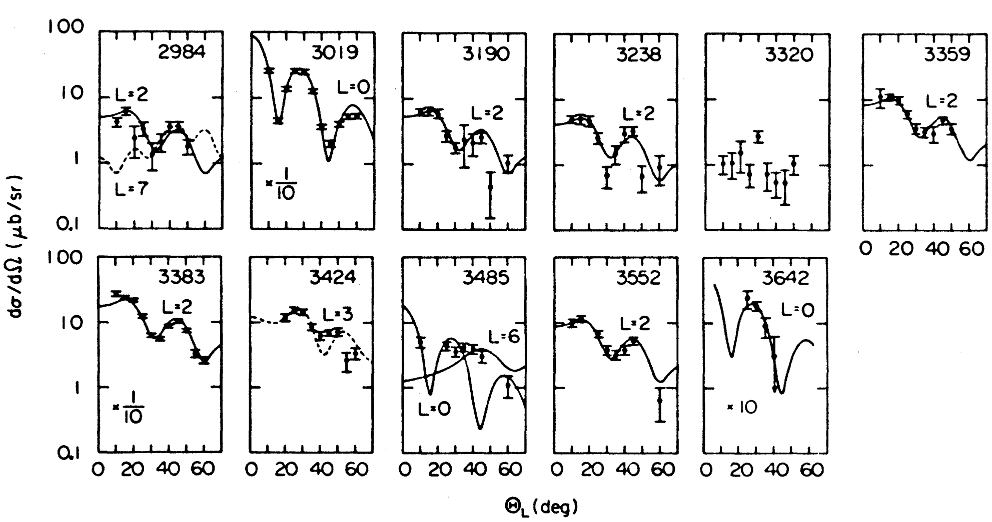

FIG. 2. Triton angular distributions and DWBA calculations for the ^{148}Gd$(p,t)^{146}$Gd reaction at $E_p=24.9$ MeV. Solid lines are for even L and dashed lines for odd-L transfer. The notation $\frac{1}{10}$ means the data are plotted at 0.1 times the measured values.

In the experiments with 34.6-MeV protons we collected energy spectra and angular distributions in the energy range from 0 to ~6 MeV of excitation in ^{146}Gd. This wide energy range required runs at five different spectrometer settings, with sufficient overlap between adjacent energy bites to permit the relative intensities to be normalized to a common intensity scale. The spectrometer was calibrated for reaction cross sections by comparing the calculated elastic cross section with the counting rates of elastically scattered protons detected in the Q3D at forward angles. In a separate set of angular distribution runs for excitation energies around 3.5 MeV we used a Si(Li) detector at a scattering angle of 120° to provide better beam-current monitoring. All the data from the other energy bites were normalized to this set of runs by using peaks in the overlap region between adjacent bites.

The data for peak energy determinations were obtained from longer runs of several hours at 20° and were calibrated by peaks of known energy in the Cu and Ti (p,t) reactions. Several peaks with accurately known excitation energies, at 1579.5, 1972.0, 2165.0, 2611.5, 2658.0, 3020, and 3422.7 keV in ^{146}Gd, provided the reference points for normalizing the Gd spectra to the calibration curves. In order to obtain an accurate Q-value measurement[12] for the ^{148}Gd (p,t) reaction, we ran the calibration targets immediately before and after the Gd in the 3.5-MeV energy bite, so that the effects of drift in the proton beam energy would be minimal.

Light-element impurity peaks obscured the data in the important 3- to 4-MeV excitation region of the angular distribution experiments performed at 34.6-MeV bombarding energy. Therefore, we repeated the angular dis-

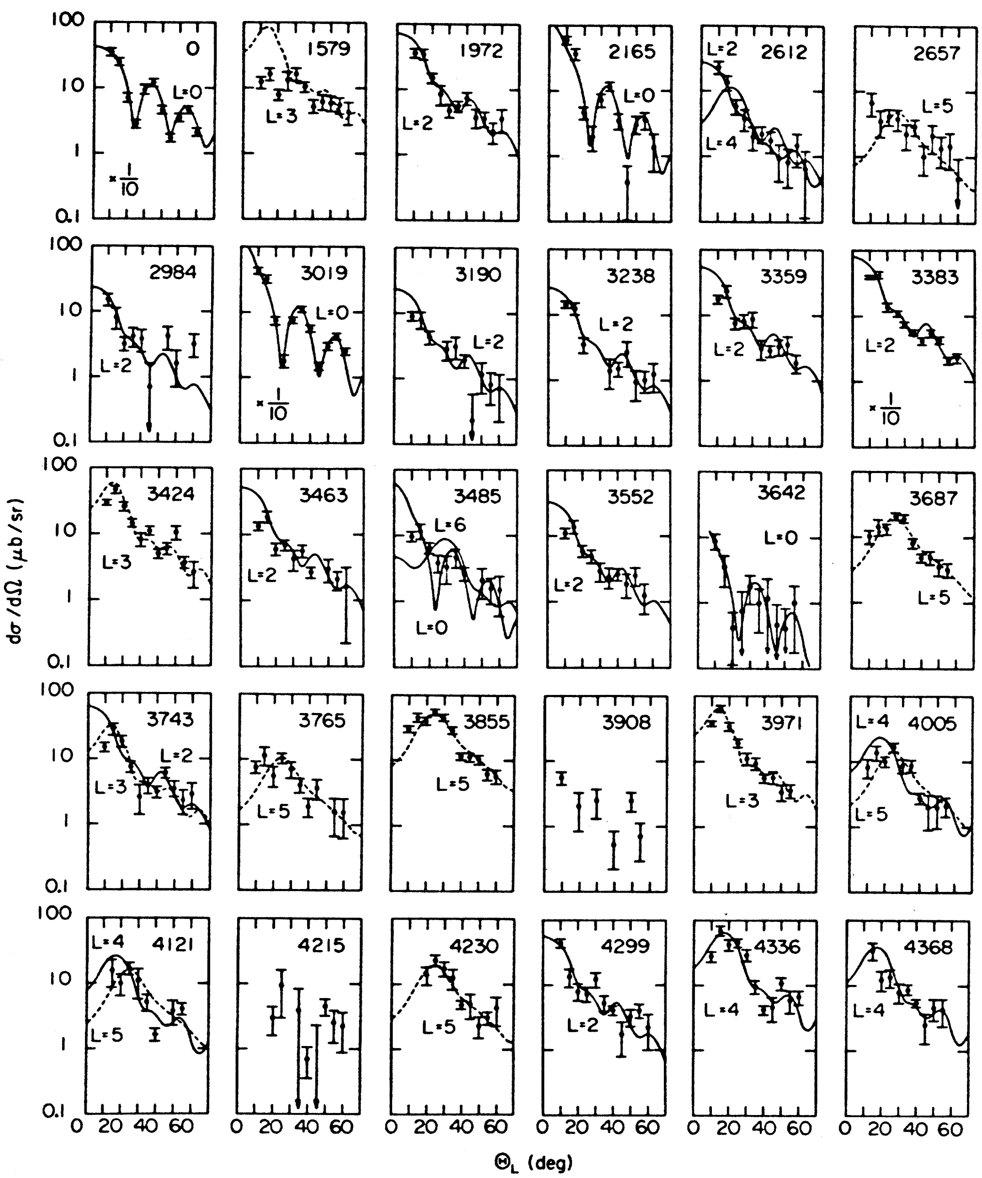

FIG. 3. Same as Fig. 2, except $E_p = 34.6$ MeV.

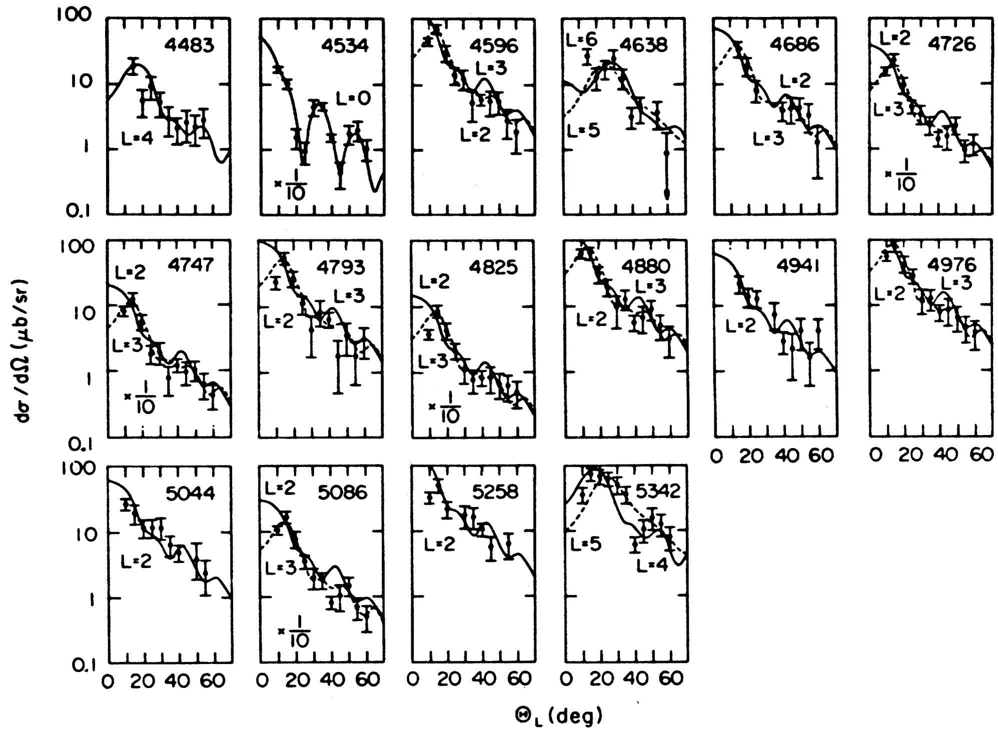

FIG. 3. (*Continued*).

tribution measurements in the 3.5-MeV excitation region, using protons of 24.9 MeV to shift the energies of the impurity peaks relative to the Gd peaks. In these experiments a BGO scintillation detector at 120° was used to monitor elastically scattered protons. This detector did not exhibit the radiation damage problems that we found with the Si(Li) beam monitor. The resolution, while not as good as with Si(Li), was sufficient for resolving the Gd peak from the C and O peaks.

Figure 1 presents triton energy spectra obtained at 20° in the 34.6-MeV bombardments. The spectra from four different settings of the spectrometer, covering the range of excitation energies from 0 to 5.6 MeV in ^{146}Gd, are shown. The analysis for peak energies and intensities was carried out with the aid of a computer using the spectrum analysis and energy calibration codes FITEK (Ref. 13) and CALIB.[14]

Figures 2 and 3 show selected angular distributions compared with distorted-wave Born approximation (DWBA) calculations for the 24.9- and 34.6-MeV bombardments, respectively. The calculations were performed in the zero-range approximation with no lower radial cutoff, and using standard optical-model potentials that have previously been applied successfully in this region.[4,15] The potential for the bound state was adjusted for each single-particle wave function to give the correct average single-neutron separation energy, $S(2n)/2=8.15$ MeV. There is generally good agreement with the DWBA curves for $L=0$ and $L=2$ transfer. The angular distribution associated with the 3^- state at 1579 keV is clearly anomalous at the forward angles, as Flynn *et al.*[4] found, and the distribution for the 4^+ state at 2612 keV resembles $L=2$, also in agreement with Flynn *et al.* The structures of both of these states are primarily proton 1p1h, so it is not surprising if their population in the (p,t) reaction involves multistep processes.

III. RESULTS AND DISCUSSION

The states that are populated most strongly in the (p,t) reaction are those formed by pickup of a correlated pair of neutrons. For a ^{148}Gd target these include the ground state and the neutron pv states in ^{146}Gd. Other two-neutron states will be populated with various strengths, and we expect to see many of them in the region above 3.5 MeV of excitation. The states below 3.5 MeV are primarily two-proton configurations and therefore are only weakly populated. However, the 2_1^+ and 3_1^- collective vibrational levels should be more strongly populated through their neutron 1p1h components. The first (p,t) experiments[4] showed that most of the known states up to 3 MeV are populated in the (p,t) reaction, with cross sections of a few μb or more.

Much of the (p,t) strength above 3.5 MeV should come from pickup of one valence neutron from the $f_{7/2}$ shell and one neutron from the filled orbitals below the $N=82$ shell closure. In general, we cannot expect to identify specific configurations among the large number of experimental levels in this region. However, we will point out a few speculative possibilities in the following discussion.

The results of our analysis for excitation energies, L-values, and (p,t) cross sections are shown in Table I. We

TABLE I. Energy levels in ^{146}Gd observed with the ^{148}Gd(p,t) reaction.

Known[a]		^{148}Gd$(p,t)^{146}$Gd Flynn *et al.*[b]		Present work		Integral cross section (μb)[d]		$d\sigma/d\Omega$[e] at 20°
E_x(keV)	J^π	E_x(keV)	L	E_x(keV)[c]	L	34.6 MeV	24.9 MeV	(μb/sr)
0	0^+	0	0	0	0	221		71
1579.5	3^-	1580	3	1576	3	27		8.0
1972.0	2^+	1971	2	1971	2	25		15
2165.0	0^+	2162	0	2160	0	23		4.7
2611.5	4^+	2615		2612	2,(4)	9.6		5.9
2658.0	5^-	2658		2657	(5)	6.9		4.1
2968	$4^+(2^+)$							
2982	7^-							
2986[f]	(2^+)	2985		9284	(2)	10	7.9	3.2
2997	4^-							
3020[f]	0^+	3016	0	3019	0	229	310	74
3031	3^+							
3099	6^-							
3182	8^-							
		3181		3190	2	6.7	17	4.3
		3231		3238	2	8.6	6.8	3.5
3287	$3^+(4^+,5^+)$							
3290	7^-							
3294	8^-							
3313	5^-							
				3320			3.0	
		3354		3359	2	17	14	7.6
		3378	2	3383	2	263	294	137
3384	6^-							
3389	3,4							
3412	(4^+)							
3416	4							
3422.7	$3^-,4^-$	3417		3424	3	35	26	26
3428	9^-							
3436	3							
		3442						
3456	(5^-)							
3457	6^+							
3460	(5^-)							
3463	(4)			3463	(2)	14		6.1
3485(D)[f]	$6^+,0^+$			3485		11		6.6
				3552	2	10	14	5.9
3639[f,g]	0^+			3642	(0)	3.8		0.4
3660	6^+							
				3687	(5)	25		13
				3743	(2,3)	20		19
				3765	(5)	13		5.6
3779	8^+							
3784	$(5^+,6^+)$							
3854	7^-							
				3855	(5)	69		40
3864	10^+							
				3908				2.0
				3971	(3)	38		35
				4005	(4,5)	18		10
4107	8^+							
				4121	(4,5)	20		10
				4215				3.0
				4230	(5)			14

TABLE I. (*Continued*).

Known[a] E_x(keV)	Known[a] J^π	Flynn *et al.*[b] E_x(keV)	Flynn *et al.*[b] L	^{148}Gd$(p,t)^{146}$Gd Present work E_x(keV)[c]	L	Integral cross section (μb)[d] 34.6 MeV	Integral cross section (μb)[d] 24.9 MeV	$d\sigma/d\Omega$[e] at 20° (μb/sr)
4248	(9)							
				4299	(2)	21		8.0
				4336	(4)	56		43
				4368	(4)	27		12
				4394				4.8
				4409				5.6
				4483	(4)	14		5.6
4501	10							
				4534	0	91		15
4541	10^+							
				4596	(2,3)	38		32
				4638	(5,6)	29		13
				4656				9.4
4667	(11,12)							
				4686	(2,3)	22		19
4719	4^-							
				4726	(2,3)	121		94
				4747	(2,3)	63		54
				4793	(2,3)	28		27
4828	5^-			4825	(2,3)	48		43
				4880	(2,3)	44		30
				4905				8.0
				4941	(2)	21		13
				4976	(2,3)	50		41
				5044	(2)	23		12
				5086	(2,3)	86		77
				5115				14
				5151				25
				5177				11
				5217				15
				5258	(2)	43		22
				5289				9.4
				5342	(4,5)	90		69
				5388				23
				5443				34
				5482				27
				5528				23
				5549				25

[a]Reference 2.
[b]Reference 4.
[c]Energy uncertainties (standard deviations) are ±3 keV for levels up to ~3800 keV of excitation and ±6 keV for levels above ~4000 keV.
[d]Integrated cross section from 7.5° to 62.5°. The estimated uncertainty is ±50% for the ground state and ±25% for the other levels.
[e]E_p = 34.6 MeV.
[f]Reference 18.
[g]Reference 17.

also show in Table I the energies and the J^π values for states in ^{146}Gd as summarized in Ref. 2, and the results from the earlier (p,t) experiments of Flynn *et al.*[4] We see all the known states of natural parity below the 3290-keV state, except for those levels where the sensitivity is severely impaired because of closely spaced multiplets or proximity to the intense neutron pv peak at 3020 keV. At higher excitation energies there is very little correspondence between the states we see, which are primarily two-neutron configurations, and the states identified in other reactions, primarily (α,xn), that favor yrast states which are primarily proton configurations.

A. 0^+ states

The proton and neutron monopole pv states have been identified at 2165 and 3020 keV of excitation, respectively.[4,16] In addition to the pv states, proton pair excitation within the 51 to 82 shell will produce five more 0^+ states, three of which are predicted to occur below 5 MeV of excitation energy (cf. Fig. 9, Ref. 2). The (p,t) reaction should populate these proton states only very weakly. We also expect a two-phonon 0^+ state at close to twice the single-octupole phonon energy of 1579.5 keV, due to the 0^+ coupling of two octupole phonons. This state might be detectable in our experiments if there is some mixing with the strongly populated neutron pv state, which is nearby in energy. Excitation of neutron pairs out of the 51 to 82 shell produces many more 0^+ states, most of which will occur at excitation energies well above the limit of ~ 5.5 MeV explored in our experiments. These neutron 2p2h states are expected to be only weakly populated because of destructive interference associated with two-neutron transfer.

In addition to the proton and neutron monopole pv states, we observed a new state that is clearly identified as $L=0$ transfer at an excitation energy of 4534 keV. This state is strongly populated in the (p,t) reaction. Only the ground state and the neutron pv states have substantially larger integrated cross sections in the experiments with 34.6-MeV protons. The nature of the 4534-keV state is unclear, but the strong (p,t) population suggests that it is a two-neutron state, either one of the incoherent 2p2h states or possibly associated with a splitting of the pv state. Calculations by Chasman[10] suggest such a splitting which is strongly dependent on the quadrupole interaction strength. However, for the interaction strength that he uses, Chasman obtains a much smaller energy splitting.

The triton angular distribution of the weakly populated level at 3190 keV in the 34.6-MeV data (Fig. 3) suggested an $L=0$ transfer and therefore that this state could be the $(3^- \times 3^-)_{0^+}$ two-phonon excitation. However, the data at 25°, which is a key point in the $L=0$ distribution, were obscured by a silicon impurity peak. Therefore, we repeated the experiment using 24.9-MeV protons. The data at this energy (Fig. 2) agree well with $L=2$ transfer and clearly reject the $L=0$ possibility.

In-beam conversion-electron spectroscopy experiments have recently revealed two other 0^+ states, at 3639 and 3485 keV of excitation.[17,18] In addition, the $(\alpha,2n)$ study[2] showed a 6^+ state at 3485 keV, so at this energy there is a doublet that would be unresolved in the (p,t) experiments. The 3639-keV state was first observed by the Jyväskylä group[17] in the $(^3\text{He},n)$ reaction, and the $E0$ decay of both 0^+ states was seen with the $(\alpha,2n)$ reaction at our in-beam spectroscopy facility at LANL. We find rather convincing evidence in both the 34.6 MeV and the 24.9 MeV bombardments for very weak (p,t) population of the 3639-keV level. The measured energy agrees well with 3639 keV, and the limited angular distribution data suggest $L=0$ transfer. The level that we observe at 3485 keV exhibits a very inconclusive triton angular distribution. This may be the result of weak population of both the 0^+ and 6^+ members of the 3485-keV doublet.

Both of these 0^+ states occur at higher excitation than the prediction of ~ 3.2 MeV for the 0^+ member of the two-phonon multiplet. Therefore they are more likely associated with the incoherent proton 2p2h states, as suggested in Ref. 2.

B. 2^+ States

We clearly see the well known collective quadrupole phonon state at 1972 keV and the neutron quadrupole pv state at 3383 keV which was identified in the earlier (p,t) experiments. Several other levels that show clear $L=2$ angular distributions occur at 3190, 3238, 3359, and 3552 keV. These four states are all weakly populated, and their low excitation energies, with the possible exception of the 3552-keV state, suggest that they are proton states. No levels corresponding to these states have been observed in any other reaction or decay experiments. However, in their summary of the level information Yates *et al.*[2] indicate the excitation energies expected on theoretical considerations for proton states that have not yet been identified experimentally. There are four such states with $J^\pi=2^+$ predicted in the energy region below 3.5 MeV. In the order of increasing predicted energies, they arise from the $d_{5/2}^{-2}$ configuration, the two-octupole-phonon vibration, and the $d_{3/2}d_{5/2}^{-1}$ and $d_{3/2}g_{7/2}^{-1}$ configurations. A reasonable speculation might be to associate the four $L=2$ levels that we see with these four states.

A possible 2^+ state at 2986 keV was seen in the $(\alpha,2ne^-)$ experiments,[18] and there is also a well known 7^- level at 2982 keV in the yrast sequence. We see a level weakly populated at 2984 keV with an angular distribution that agrees well with $L=2$ in both the 34.6- and the 24.9-MeV data. This peak provides some confirmation of the 2986-keV level seen in the $(\alpha,2n)$ experiments. The 2^+ state from the $\pi h_{11/2}^2$ configuration is expected near this energy.[2]

Other definite $L=2$ assignments cannot be made from our data, but $L=2$ or 3 are the only reasonable assignments for a number of the peaks between ~ 3.5 and 5 MeV (see Table I and Fig. 3).

C. Higher-spin states

The 3_1^-, 4_1^+, and 5_1^- states at 1579, 2611, and 2658 keV, respectively, are well known from the in-beam spectroscopic studies. We observe weak population of each of these states, which are primarily proton configurations. The angular distribution associated with the 3_1^- state (1579 keV) in the 34.6-MeV bombardments deviates from the $L=3$ DWBA calculations at forward angles in a fashion similar to what was observed for both ^{146}Gd and ^{144}Sm in the earlier (p,t) experiments[4] with 25-MeV protons. Likewise, the 4_1^+ state (2611 keV) shows an anomalous angular distribution at the forward angles, in agreement with earlier observations.[4]

The lowest-lying neutron state, except for the pv states, is believed to be the 3^- state of the $f_{7/2}d_{3/2}^{-1}$ configuration which was observed in the β decay of ^{146}Tb at 3423 keV of excitation.[5] The peak we see at 3424 keV is probably from this state. Its population by the (p,t) reaction is several times greater than is seen for the lower-lying proton states, and the angular distribution at both bombarding energies is best fitted by $L=3$, without the anomaly that is observed for the 3_1^- state. The most likely candidate for the 5^- state of this configuration, $\nu(f_{7/2}d_{3/2}^{-1})_{5^-}$, is the level that we see at 3855 keV. This speculation is based on the indicated $L=5$ angular distribution and on the expected energy dependence. Two other peaks in this region, at 3687 and 3765 keV, also have reasonable fits to the $L=5$ distribution.

A level at 4828 keV in ^{146}Gd has been identified in the ^{146}Tb β-decay experiments[5] as the $\nu(h_{9/2}d_{3/2}^{-1})_{5^-}$ state. This state should be populated in the (p,t) reaction more weakly than the $\nu(f_{7/2}d_{3/2}^{-1})_{5^-}$ state because of smaller occupancy of the $h_{9/2}$ orbital in the target. Therefore, the level we see at 4825 keV is probably not this state; the observed cross section is too large and the angular distribution is much more suggestive of $L=2$ or 3 than of $L=5$. Also weakly populated in the β decay of ^{146}Tb is a level at 3313 keV which is assigned on the basis of energy systematics and its decay properties as the $\pi(h_{11/2}g_{7/2}^{-1})_{5^-}$ state.[2] We see a level at 3320 keV, very weakly populated in the (p,t) reaction with 24.9-MeV protons. This peak may be due to the 3313-keV state, even though, because of poor statistics, the angular distribution is not distinctive and the energy agreement is somewhat worse than we expect in this region of excitation.

IV. COMPARISON WITH THE HARMONIC PAIRING VIBRATION MODEL

The doubly magic features indicated by the low-energy structure of ^{146}Gd suggest that we should examine the strongly populated states at higher excitation energies in analogy to other doubly magic nuclei such as ^{208}Pb. There is a wealth of two-nucleon transfer data for lead because several isotopes of Pb are on or near the line of stability and can be used as targets. These data are summarized in a review article by Broglia *et al.*,[19] who show that there is strong evidence for the validity of the harmonic pairing vibration model[20] in the region near ^{208}Pb. For a doubly magic nucleus A, the model predicts the excitation energies of monopole and quadrupole pairing vibrations in terms of the binding energies of a neutron pair in the A and $A+2$ isotopes. This gives, in terms of the (p,t) Q values, $E_{pv}(A)=Q_{p,t}(A+2)-Q_{p,t}(A)$ for the pair removal vibration. The intensity is just the intensity of the (p,t) reaction to the corresponding state in the A-2 isotope.

The data on gadolinium will be much less extensive than for lead because ^{146}Gd is far from the line of stability. However, with the ^{148}Gd target it is relatively straightforward to identify the monopole and quadrupole pair removal vibrations in ^{146}Gd by means of their large (p,t) cross sections and their $L=0$ and $L=2$ angular distributions. Flynn *et al.*[4] did this with an earlier target and made comparisons with states seen in the other $N=82$ isotones. In particular, they noted the systematics of the ratios of pairing vibrational intensities to the ground-state intensities.

The intensity ratios we would like to have for comparison with the pairing vibration model are those for the pv states in ^{146}Gd relative to the low-lying states in ^{144}Gd, but these ratios are not available because of the difficulties in fabricating the necessary ^{146}Gd target. Therefore, we have examined the strongly populated states in the pv region of ^{146}Gd in comparison with states populated by the $^{144}Sm(p,t)^{142}Sm$ reaction[21] at very nearly the same bombarding energy, $E_p=34.5$ MeV. The ^{144}Sm target differs from the desired ^{146}Gd only by having two fewer protons. We expect that the strongly populated states of lowest excitation energy would have similar (p,t) cross sections for these two targets.

Figure 4 shows the six most strongly populated low-lying states in ^{142}Sm compared with selected high-lying states in ^{146}Gd. The excitation energy scales have been shifted to aid the visual comparison of energy spacings by matching the 768-keV ^{142}Sm level and the 3383-keV ^{146}Gd level. Also, since the two lowest states in ^{142}Sm were not measured in Ref. 21, their cross sections at 34.5 MeV have been inferred by scaling the 42-MeV data of Struble *et al.*[15] according to the energy dependence of the strongly populated triplet of levels around 2350 keV.

The prediction of the harmonic model for the excitation energies of the monopole and quadrupole pv states is 3.9 and 4.7 MeV, respectively. These states, clearly identified by their angular distributions and large cross sections, are found at 3.0 and 3.4 MeV. The energy difference of 363 keV is only about one-half of the expect-

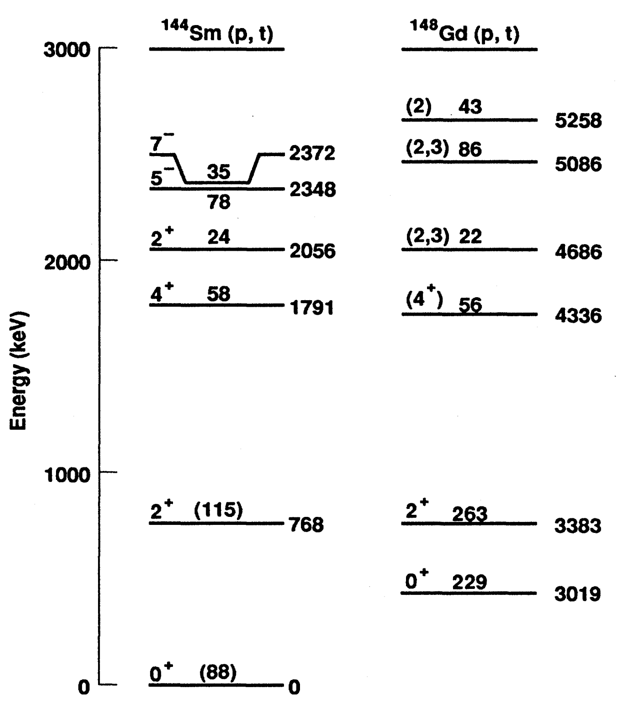

FIG. 4. Comparison of levels of ^{146}Gd and ^{142}Sm populated by the (p,t) reaction with 34.6-MeV protons. States are labeled with their J^π values, excitation energies in keV, and (p,t) cross sections in μb. The energy scales have been shifted to facilitate the comparison of ^{146}Gd levels in the pv region with the low-lying ^{142}Sm levels.

ed separation based on the excitation energies of the 2_1^+ states in ^{144}Gd (743 keV) and ^{148}Gd (784 keV). This might result from the residual force between the neutrons, which could mix the nearly degenerate $0_p^+ \times 2_h^+$ and $2_p^+ \times 0_h^+$ configurations strongly. As Flynn *et al.*[4] pointed out, the observed energies are well below the harmonic prediction but well above the expectation based on systematics of the other $N=82$ isotones. Thus, they indicate a significant, but less complete than in ^{208}Pb, double-shell closure.

In ^{146}Gd, the integrated cross sections for populating the pv states are similar to the ground-state cross section but much larger than the harmonic prediction. (The inference made in Ref. 4 that there is missing quadrupole strength above the 3.4 MeV region, based on the differential cross sections at 25°, is not substantiated by the integrated cross sections.) If the (p,t) cross sections for populating the 0_1^+ and 2_1^+ states in ^{142}Sm are approximately equal to the harmonic predictions, then the cross sections we observe for the monopole and quadrupole pv states in ^{146}Gd are respectively 2.6 and 2.3 times greater than the model prediction.

The situation with respect to the enhanced quadrupole pv strength may be similar to that encountered in the lead region. There the quadrupole pair addition phonon strength is a factor of 2 larger than is predicted by the harmonic model. Broglia *et al.*[19] argue that this strength may come from mixing with the many additional 2^+ states that exist at these high excitation energies. This argument cannot be used, however, to explain the large strength to the 0^+ states.

In addition to the two lowest states in ^{142}Sm, there are four other strongly populated levels, with excitation energies of 1791, 2056, 2348, and 2372 keV and J^π values of 4^+, 2^+, 5^-, and 7^-, respectively. The excitation energies and J^π values have been confidently determined from decay data[22] and the (p,t) experiments.[21] The dominant structures in the negative-parity states, which have to involve the $h_{11/2}$ neutron hole, are expected to be the $\nu(s_{1/2}^{-1}h_{11/2}^{-1})_{5^-}$ and $\nu(d_{3/2}^{-1}h_{11/2}^{-1})_{5^-,7^-}$ configurations.[22] It is apparent from Fig. 4 that there is good agreement between the energy spacings and cross sections of these four states in ^{142}Sm and states we observe in ^{146}Gd, but the angular distribution data for the 5086- and 5258-keV peaks do not support this correlation. However, the (p,t) angular distributions may be anomalous for these two levels. A similar situation seems to occur in the ^{144}Sm(p,t) reaction, where the angular distributions for the known $J^\pi=5^-$ and 7^- levels at 2348 and 2372 keV are also not characteristic of $L=5$ and $L=7$ transfer. The excitation energies of 5086 and 5258 keV in ^{146}Gd are very close to the predictions for the $(\nu s_{1/2}^{-1}h_{11/2}^{-1})_{5^-}$ and $(\nu d_{3/2}^{-1}h_{11/2}^{-1})_{7^-}$ configurations, respectively, based on the neutron-hole energies obtained from ^{147}Gd data.[23]

Figure 4 suggests that the monopole pv state is ~ 0.4 MeV too high relative to the other two-neutron-hole states in ^{146}Gd. This might be caused by mixing of the pv state with the ground state or the 0^+ proton state at 2165 keV. All the ^{146}Gd states in Fig. 4 are $\gtrsim 1$ MeV below the energies predicted by the harmonic model.

Two other states that are of special interest because of the large (p,t) cross sections feeding them are the 0^+ state at 4534 keV and the state at 4726 keV populated by $L=2$ or 3 transfer. We observe that the ratio of cross sections populating these two states, 1.33, is similar to the ratios of 1.15 for the 2^+ and 0^+ pv states and 1.30 for the 2_1^+ and 0_1^+ states in ^{142}Sm. Assuming the 4726-keV state has $J^\pi=2^+$, this might suggest that configuration mixing has fragmented the total pair removal phonon strength. However, this would not explain the very high pv strength relative to the harmonic prediction. In fact, it would make the disagreement worse.

Recent calculations by Chasman[10] may offer an alternative explanation for the 4534-keV state. Chasman has calculated the spectrum of 0^+ states in ^{146}Gd by using a nonorthogonal basis that includes a very deformed prolate configuration. For one choice of parameters, he finds the deformed state only a few hundred keV above the pv state and containing 37% of the pv strength. This intensity is similar to what we observe for the higher 0^+ state, but the energy is about 1 MeV too low. However, Chasman points out that the energy of the deformed 0^+ state is extremely sensitive to the values of certain parameters used in the calculation. It would be interesting to see if this approach could produce agreement with both the excitation energy and the (p,t) cross section for the 0^+ state at 4534 keV.

The other possibility for producing a 0^+ state near 5 MeV of excitation would be the 4p4h state formed by a coupling of the neutron and proton 2p2h pairing vibrational excitations. The unperturbed energy would be at the sum of the neutron and proton pv 0^+ states (5185 keV). Heyde[24] has suggested that such a state might be strongly populated by the (p,t) reaction.

In summary, we have observed (p,t) population of a large number of levels in ^{146}Gd in the region between 0 and 5.5 MeV of excitation. Our results up to $E_X \approx 3.5$ MeV are in substantial agreement with those obtained from the $(\alpha,xn\gamma)$ reactions. Above 3.5 MeV, most of the levels we find are new, and many of them will be difficult to characterize beyond their excitation energies, (p,t)-population cross sections, and approximate spins based on the L-transfer values. We identified four new 2^+ states in the region below ~ 3.5 MeV of excitation, weakly populated by the (p,t) reaction, which could be the four previously unobserved proton states with $J^\pi=2^+$ expected in this region. One of them could be the two-octupole-phonon state $(3^- \times 3^-)_{2^+}$ predicted to occur at ~ 3.2 MeV. We found no evidence for the 0^+ state of this multiplet. A 0^+ state at 4534 keV is strongly populated by the (p,t) reaction. The nature of this state is not understood. Finally, a comparison with the ^{144}Sm$(p,t)^{142}$Sm reaction data shows a set of states in ^{146}Gd that are in qualitative agreement with the harmonic pairing vibrational model, supporting the doubly magic nature of ^{146}Gd. However, certain details of the comparison show large deviations from this picture.

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