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Collective excitations in ^{148}Gd populated in the pp'-reaction on a radioactive target

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Collective excitations in the two-particle nucleus ^{148}Gd up to 2.9 MeV have been investigated by the pp'-reaction at 25 MeV beam energy, and angular distributions have been analyzed with standard DWBA calculations. It is found that ^{148}Gd has larger octupole- than quadrupole collectivity in the energy range investigated. The 3^- strength distribution is in quantitative agreement with predicted results for the levels formed by the coupling of two valence particles to the ^{146}Gd core octupole phonon.

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1. Introduction

Quite extensive data exist on the ^{148}Gd nucleus. Its high-spin excitations were recently investigated in various in-beam γ-ray studies [1–3] where the nucleus was produced through compound-evaporation reactions with different angular momentum inputs. Knowledge on low-spin excitations above the yrast line came from γ-spectroscopic investigations [4] of the ^{148}Tb 2^- and 9^+ β-decay isomers. From these data a rather detailed picture of the structural properties of ^{148}Gd emerged, where in particular the high-spin states reveal many features characteristic of a spherical nucleus with two valence particles and their couplings to the ^{146}Gd core excitations. In all these studies the ^{148}Gd nucleus however could only be excited through processes that are not selective for specific structural configurations, with the exception of ^{148}Tb 9^+ Gamow-Teller decay which firmly identified the ^{148}Gd $(\nu h_{9/2}\ \nu f_{7/2})\ 8^+$ state.

The rather long 75-y half life of the ^{148}Gd ground state made it possible to prepare a target from the radioactive material suitable for high-resolution nuclear reaction studies. With this target the collective excitations built on the ^{148}Gd ground state become accessible through inelastic scattering experiments, and we report here the results of such measurements using the pp' reaction with 25 MeV protons. First results of the present investigation were earlier communicated in [5].

2. Experimental

The radioactive target material was produced [6] through spallation with $\approx 0.4 A \times h$ of $\simeq 750$ MeV protons on $2\frac{1}{2}$ lbs of tantalum in the LAMPF beam dump. After cooling and chemical separation the target for nuclear reaction measurements was prepared [7] by direct deposition of the radioactive isotopes on a 50 μg/cm^2 carbon-foil in the LLNL mass separator. The final target consisted of ≈ 0.9 μg ^{148}Gd which was invisible and deposited with unknown density distribution within an area of 2 to 5 mm^2.

The measurements were carried out at the QQDDQ Big Karl Magnet Spectrograph with 25 MeV protons from the Jülich cyclotron. The momentum-analyzed scattered protons were detected in a 90 cm Morris-type delay-line-readout drift chamber [8] where the vertical detector aperture was limited in the off-line sorting of the data, which significantly reduced the background in the spectra. The detector covered ^{148}Gd excitation energies from 0.75 to 3.25 MeV in a single magnet setting; a typical spectrum is shown in Fig. 1. We also took data with a magnet setting covering excitation energies up to 4 MeV where the spectra became highly complex, but above 2.8 MeV we did not observe any individual peak with a cross section exceeding 0.1 mb at 30°. The reaction products were recorded at eight angles between 15° and 60°. The energy resolution obtained was 12 keV FWHM.

The poorly known target properties made absolute cross section determination as well as normalization of spectra measured at different angles difficult. Absolute cross sections were obtained through comparison of the yield of elastically scattered particles measured at 30° to the elastic scattering cross section calculated from the DWBA described below. The elastic scattering yield was measured in separate short exposures before and after the long exposure. For the normalization of spectra at

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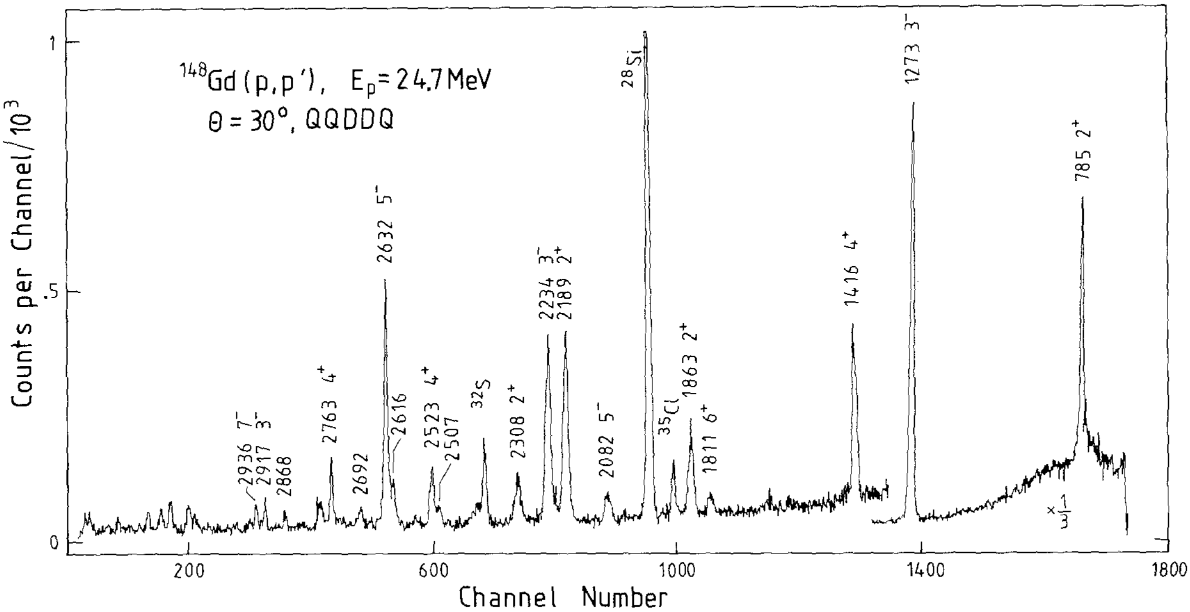

Fig. 1. Proton spectrum from the ^{148}Gd (p, p') reaction. Excitation energies are given in keV; spin-parity values deduced in the present experiment are also specified

different angles we have used the theoretical $l=3$ angular distribution[1] and the pp'-peaks for the 1.273 MeV 3^- state. With this procedure $l=2$ angular distributions were in good agreement with calculated curves for the independently assigned 1.863 and 2.189 MeV 2^+ states. Similarly, consistent angular distributions were obtained for the known 4^+ and 5^- levels at 1.416, 2.082, and 2.632 MeV. Here, however, the 15° and 20° cross sections lie higher than calculated, which was also found in a similar pp' study [9] of ^{142}Nd. This did not severely impede l-assignment, which could be made for levels populated with cross sections as low as ~3% of the 0.785 MeV 2^+ cross section. The so normalized angular distributions are shown in Fig. 2 where they are compared with the calculated DWBA curves. The results are compiled in Table 1. The uncertainties in the relative cross sections as shown in the figure are of statistical nature only; the error in the absolute normalization is estimated to be ~20%.

3. DWBA calculations and deformation parameters

The calculations were performed in the zero-range approximation with the DWBA code DWUCK using the (p, p') parameters of Fabrici et al. [10]. Values of β_λ^2 were extracted [11] by adjusting the calculated angular distributions to the data points. Following a widespread tradition, we also include in Table 1 the $E\lambda$-strengths given in single particle units evaluated as

$$\frac{B_\lambda}{(B_\lambda)_w}=\frac{Z^2}{4\pi}\frac{(3+\lambda)^2}{(2\lambda+1)}\beta^2.$$

[1] At 50°, where the 3^- peak was obscured by a light-mass target contamination, we used the 0.785 MeV 2_1^+ intensity

These values are often considered to be proportional to the electromagnetic transition strength and are indicative of the collectivity of the states.

4. Discussion

The present measurements identify three 2^+ levels above the 0.785 MeV 2_1^+ state which is largely formed by the two valence neutrons in $f_{7/2}$. The next two-neutron 2^+ level is the $\nu f_{7/2}\, p_{3/2}$ excitation which should be strongly excited in pp'. This aligned singlet coupling configuration is expected to lie a few hundred keV below the 2.8 MeV unperturbed energy as extracted from the $p_{3/2}$ excitation energy [12] in ^{147}Gd and the pertinent [13] ground state masses. However, it is also known that proton core excitations are observed in ^{148}Gd at similar energies to those in the ^{146}Gd N = 82 nucleus [14], where the lowest 2^+ state lies at 1.972 MeV, clearly lower than the expected two-neutron 2^+ energy. We therefore identify the 1.863 MeV state in ^{148}Gd as the proton core excitation and suggest $\nu f_{7/2}\, p_{3/2}$ for the 2.189 MeV 2^+ level. The larger cross section observed for that level is in accord with this suggestion.

Interesting support for the assignment of the 1.863 MeV state as proton 2^+ core excitation derives from β-decay [4] of the ^{148}Tb $(\pi d_{3/2}\ \nu f_{7/2})\, 2^-$ ground state. This state cannot decay by a Gamow-Teller transition. Instead the $\pi g_{7/2} \rightarrow \nu f_{7/2}$ pseudoscalar first forbidden transition should here be the strongest β-decay. This transition populates the $(\pi d_{3/2}\ \pi g_{7/2}^{-1}\ \nu f_{7/2}^2)\, 2^+$ configuration, where a small fraction resides in the lowest $(\pi d_{3/2}\ \pi g_{7/2}^{-1})_{2^+} \times (\nu f_{7/2}^2)_{0^+}$ coupling which is a principal component of the 1.863 MeV proton core excitation. In fact that state has the largest β-strength observed in ^{148}Tb 2^- decay.

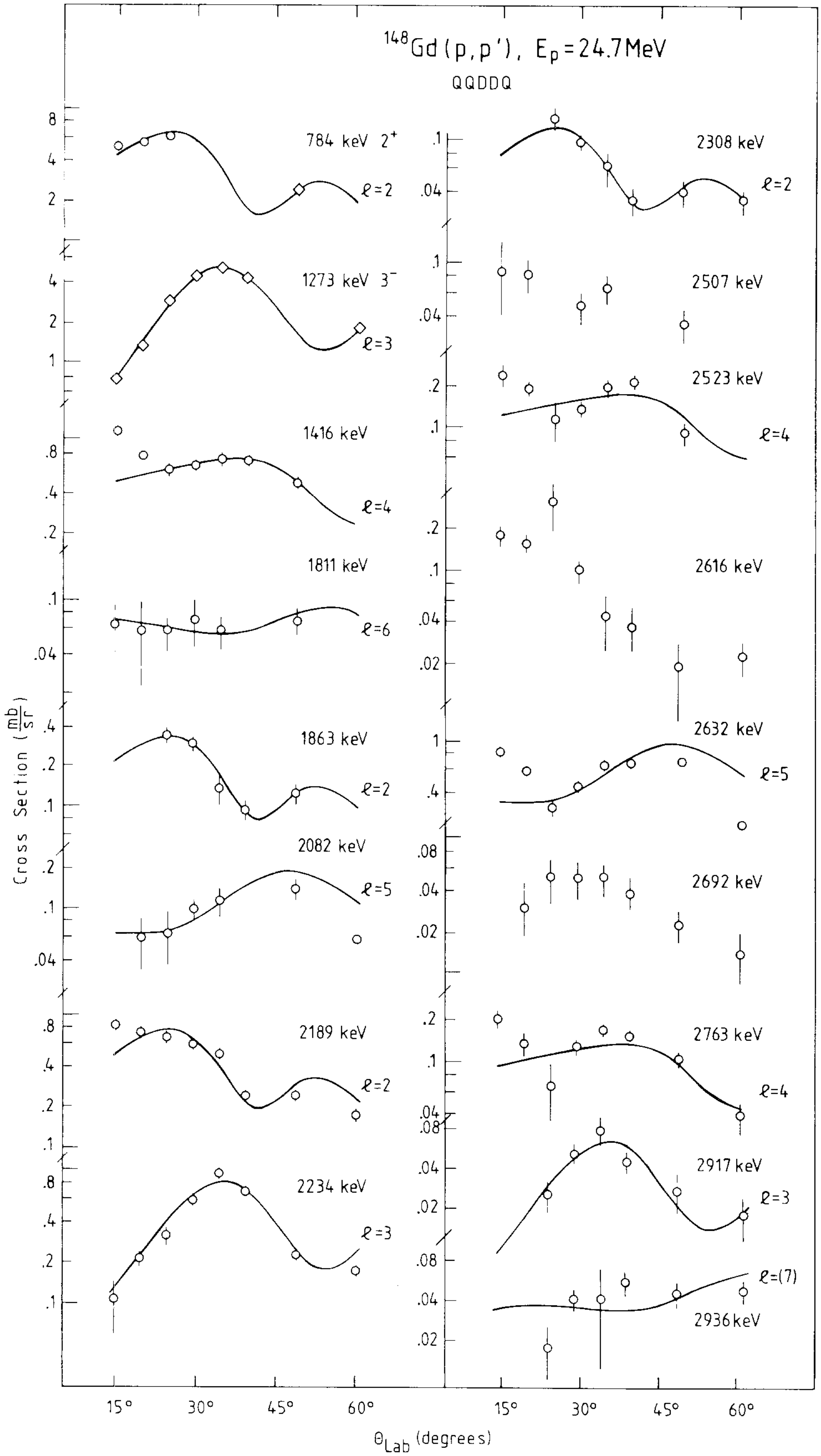

Fig. 2. Comparison of calculated and measured proton angular distributions. Data points used for angular normalization are shown as diamonds (see text)

The next higher-lying 2^+ states formed by the two valence neutrons could be the $\nu f_{7/2}\ \nu h_{9/2}$ and $\nu f_{7/2}\ \nu f_{5/2}$ spin-flip excitations at about 3 MeV [1] which however should have little $E2$ strength. The couplings of the low-lying 2_1^+ state with the proton core 0^+ or 2^+ excitations could even lie slightly below 3 MeV, but none of these states is expected as low as 2.3 MeV. Since however strong mixing of the 2^+ levels is anticipated the rather

Table 1. Levels in ^{148}Gd populated in the pp' reaction at 24.7 MeV

E_x (keV)		l	$I^{\pi\,ab}$	$\frac{d\sigma^c}{d\Omega}\left(\frac{mb}{sr}\right)$	$\beta_\lambda^2 \times 10^2$	$\frac{B(E\lambda, \lambda \to 0)}{B(E\lambda, \lambda \to 0)_{SP}}$ (B_w)	Proposed Configuration[d]
pp'	γ-ray data[ab]			$\theta = 30°$			
785(1)	784.5	2	2^+	obsc.	1.5	30	$\nu f^2_{2^+}$
1273(1)	1273.5	3	3^-	4.42	2.5	42	$\nu f^2_{0^+} \times 3^-$
1416(1)	1416.4	4	4^+	0.61	0.49	7.9	$\nu f^2_{4^+}$
1811(2)	1811.0	6	6^+	0.07	0.13	2.4	$\nu f^2_{6^+}$
1863(3)	1863.4	2	2^+	0.28	0.10	1.5	$\nu f^2_{0^+} \times 2^+$
2082(2)	2082.0	5	5^-	0.09	0.14	2.5	$\nu f^2_{2^+} \times 3^-$
2189(3)	2188.7	2	2^+	0.58	0.20	3.6	$\nu f p$
2234(3)	2233.6	3	$(3, 2)^-$	0.55	0.35	6.2	$\nu f^2_{2^+} \times 3^-$
2308(5)	2310.9	2	$(2^+, 1)$	0.09	0.04	0.6	
2507(4)	2503.9		(2^-)	0.05			$\nu f^2_{2^+} \times 3^-$
2523(4)	2522.0	4		0.15	0.16	2.5	$\nu f^2_{0^+} \times 4^+$
2616(4)	2615.0		(1^-)	0.10			$\nu f^2_{2^+} \times 3^-$
2632(1)	2631.7	5	5^-	0.43	0.85	17	$\nu f^2_{0^+} \times 5^-$
2692(4)				0.06			
2763(3)		4		0.12	0.09	1.9	$\nu f p$
2868(3)				0.03			
2917(3)	2915.3	3	$(3)^-$	0.05	0.03	0.5	$\nu f^2_{4^+} \times 3^-$
2936(4)	2937.0	(7)	7^-	0.04	0.12	(2.6)	$\nu f^2_{0^+} \times 7^-$

[a] Piiparinen et al. (1990), Ref. [1]
[b] Nuclear data sheets (1984), Ref. [4]
[c] Absolute cross section uncertainty 20%, relative cross section errors purely statistical
[d] From present work and Piiparinen et al., Ref. [1]. I^π-values specify the proton core excitations

low 2.308 MeV excitation of the observed 2_4^+ state is not unreasonable.

The pp' data for the 2^+ and 3^- states show that in the ^{148}Gd nucleus the octupole collectivity is larger than the quadrupole collectivity. This result is in accord with the data for many other spherical nuclei.

The 3^- states in ^{148}Gd are of particular interest because this nucleus provides an instructive example of the coupling of two valence particles to an octupole phonon. This coupling will give rise to a complex family of – altogether twenty – $\nu f_{7/2}^2 \times 3^-$ states with spins from 1^- to 9^-. It has been shown [1] that the properties of these levels can be quantitatively explained from the $\nu f_{7/2} \times 3^-$ one-particle × phonon spectrum observed in ^{147}Gd, where the $(\nu f_{7/2} \times 3^-)\ 13/2^+$ state couples to the $\nu i_{13/2}$ level through a large matrix element. This coupling has to be explicitely treated in a calculation of the ^{148}Gd octupole states. In the two-particle nucleus one thus obtains five 3^- levels, four from the $\nu f_{7/2}^2 \times 3^-$ family which all couple to the $(\nu f_{7/2}\ i_{13/2})\ 3^-$ state. The microscopic compositions of these 3^- levels are obtained through matrix diagonalization in the analysis given in [1], where all the empirical one-particle × phonon anharmonicities and 2.1 MeV $\nu i_{13/2}$ single particle energy are used as input data.

Our pp' data unambiguously locate the second and third 3^- excitation in ^{148}Gd, at 2.234 and 2.917 MeV, with 15% and ~1% of the 1.273 MeV 3_1^- strength. The two states are predicted at 2.218 and 2.936 MeV, both within 20 keV of experiment. The 3_2^- state is of predominant $(\nu f_{7/2}^2)_{2^+} \times 3^-$ character but it mixes – primarily through the high-lying $(\nu f_{7/2}\ i_{13/2})\ 3^-$ level – with the $(\nu f_{7/2}^2)_{0^+} \times 3^-$ state, and this admixture is populated in the pp' process. The 3_3^- state is mainly $(\nu f_{7/2}^2)_{4^+} \times 3^-$.

Two components contribute to the $3^- \to 0^+$ strength in ^{148}Gd, namely the 37(2) B_w core octupole- and the 8.1(25) B_w $\nu i_{13/2} \to \nu f_{7/2}$ single particle $E3$-transition. The latter is extracted [1] from the half life of the $13/2^+$ first excited state in ^{147}Gd. With the respective amplitudes of the 3^- state compositions as obtained in the $I=3$ diagonalization [1] the $B(E3)$ values are calculated as

$$B^{th}(E3, 3_1^- \to 0^+) = \{0.86\sqrt{37(2)} + 0.36\sqrt{\tfrac{1}{2}8.1(25)}\}^2\, B_W = 35.8(22)\, B_w$$

and

$$B^{th}(E3, 3_2^- \to 0^+) = \{0.45\sqrt{37(2)} - 0.23\sqrt{\tfrac{1}{2}8.1(25)}\}^2\, B_w = 5.2(6)\, B_w.$$

The calculated transition strength ratio is

$$\frac{B^{th}(E3, 3_1^- \to 0^+)}{B^{th}(E3, 3_2^- \to 0^+)} = 6.9(9).$$

These predictions are in good agreement with our experimental values of

$$B(E3, 1273\text{ keV}) = 42(9)\, B_w$$

and

$$B(E3, 2234\text{ keV}) = 6.2(12)\, B_w,$$

and also with the more accurately determined strength ratio

$$\frac{B(E3,1273\ \text{keV})}{B(E3,2234\ \text{keV})}=6.8(3).$$

The three highest 3^- states are predicted to have much smaller cross sections, also in agreement with experiment.

We mention here that the two states at 2.616 and 2.507 MeV, weakly excited in pp', could well be the lowest $(\nu f_{7/2}^2 \times 3^-)$ 1^- and 2^- states predicted close to these energies. They are also populated in ^{148}Tb2^- decay and the γ-ray data would be in accord with these assignments. The states cannot be directly excited in pp', and their unspecific angular distributions might indicate two-step processes. We note that the $(\nu f_{7/2}^2 \times 3^-)$ 5^- yrast state at 2.082 MeV is also weakly excited in pp' with $l=5$. We will return to that state later.

The most strongly excited $l=4$ state is the 1.416 MeV 4_1^+ level of mainly $\nu f_{7/2}^2$ character. Two higher-lying 4^+ states are identified, at 2.523 and 2.763 MeV. Two-neutron 4^+ excitations in ^{148}Gd should occur only above 2.8 MeV, except for the $(f_{7/2}^2)_{4^+}$ state. However, the 4^+ proton core excitation in ^{146}Gd lies at 2.612 MeV. As in other similar cases, this core configuration might account for the 2.523 MeV 4^+ state in ^{148}Gd. Of the anticipated ν^2 4^+ states the $f_{7/2}$ $p_{1/2}$ configuration is expected to be strongly excited, but is estimated to lie above 3 MeV, whereas the observed 2.763 MeV state is quite close to the $\nu f_{7/2}$ $p_{3/2}$ zero interaction energy where the 4^+ multiplet member should approximately lie. We prefer this assignment but keep in mind that also the 4^+ states mix.

Another interesting result of the present study is the distribution of the 5^- strength in ^{148}Gd. We observe two 5^- states, at 2.082 and 2.632 MeV. Of these, the higher-lying level is the third-strongest state populated by pp', after the low-lying 2_1^+ and 3_1^- states. The data show that its collectivity is seven times larger than the 5_1^- collectivity. This unusual result becomes clear from the microscopic structure of the two 5^- states. We interpret the intense 2.632 MeV level as a proton core excitation analogous to the ^{146}Gd 5^- yrast state at 2.658 MeV. The level in ^{148}Gd is the lowest 5^- two-quasiparticle excitation and therefore will carry the collective $E5$ strength. The 2.082 MeV $(\nu f_{7/2}^2 \times 3^-)$ 5^- level in contrast is a four-quasiparticle state and should not have significant $E5$ collectivity, in agreement with the present pp' result. The weak but positively observed $l=5$ excitation rather suggests a small admixture of the higher-lying two-proton state.

Finally, the pp' data even give a 6^+ collectivity from the population of the dominant $\nu f_{7/2}^2$ 6^+ state at 1.811 MeV. The level is excited with a small cross section having an angular distribution in accord with $l=6$ that gives an $E6$-strength of $2.4 B_w$. The known [1] 2.564 MeV ^{148}Gd $(\nu f_4^2 \times 3^-)$ 7^- level as expected is not observed in pp', but the γ-ray data suggest the lowest proton $1p\,1h$ 7^- core excitation at 2.937 MeV. The proton spectrum is complicated in this region, but a state at that energy is clearly observed at backwards angles with a cross section that would give a hekatoneikosioctopole-strength of the order of $3 B_w$.

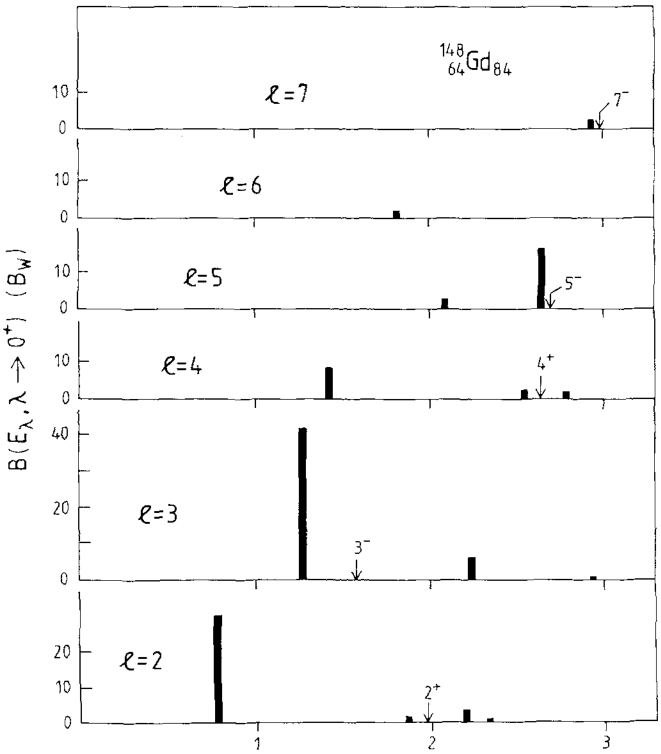

Fig. 3. Collective strengths, in B_w, for low-lying states in ^{148}Gd$_{84}$ excited in pp'. The arrows mark the respective proton $1p$-$1h$ core excitations in ^{146}Gd$_{82}$

The results of the present pp' measurements are summarized in Fig. 3. We note the larger strength for odd-parity excitations in ^{148}Gd than for those of even parity, a result which reflects the significance of proton core excitations across $Z=64$ into the $h_{11/2}$ shell. The figure also clearly shows that the odd-l collective states lie close to the respective ^{146}Gd proton particle-hole core-excitations whereas the even-l vibrations occur markedly lower in energy. This is a natural consequence of the high 2.1 MeV neutron $i_{13/2}$ single particle energy [1] at $N=83$. In ^{148}Gd the two valence neutrons can form low-lying positive parity excitations that will attract the collective strength. For odd parity, the lowest two-neutron excitation – $\nu f_{7/2}$ $i_{13/2}$ – will lie above 3 MeV, significantly higher than the proton core excitations and therefore these latter states will carry the collectivity.

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