Pramāṇa, Vol. 12, No. 6, June 1979, pp. 653-664, © printed in India

Isobaric analogue resonances in ^{71}As through proton elastic scattering on ^{70}Ge

C R RAMASWAMY, N G PUTTASWAMY and M G BETIGERI*
Department of Physics, Bangalore University, Bangalore 560 001
*Nuclear Physics Division, Bhabha Atomic Research Centre, Bombay 400 085

MS received 26 September 1978; revised 11 April 1979

Abstract. The analogues of the low-lying levels in ^{71}Ge have been observed as resonances in the compound nucleus ^{71}As through proton elastic scattering on ^{70}Ge in the energy range E_p=3·5 to 5·3 MeV. The excitation functions cover the analogue resonances corresponding to states upto 2·3 MeV excitation in ^{71}Ge. The sub-structures in the 5·06 MeV resonance, first observed by Temmer and co-workers have been confirmed in the present experiment. The present investigation reveals similar sub-structures in the 4·13 MeV resonance lending further support to the existence of intermediate structure near an isobaric analogue resonance. The resonance parameters and the spectroscopic factors (for the corresponding parent states) have been extracted. The results are compared with the information available from the ^{70}Ge(d, p) ^{71}Ge reaction.

Keywords. Isobaric analogue resonances; proton elastic scattering on ^{70}Ge; levels in ^{71}As; spectroscopic factor; intermediate structure.

1. Introduction

In a study of (p, p) and $(p, p'e)$ reactions on ^{72}Ge, Betigeri *et al* (1969, 1972a and 1972b) have observed the isobaric analogue states of ^{73}Ge as compound nuclear resonances in ^{73}As. In addition to these isobaric analogue resonances (IAR's), a number of $T_<$ states with typical widths of 20 keV have been observed at excitation energies both above and below the threshold for the analogue states. Temmer *et al* (1970 and 1971) have reported the presence of similar structures of 20 keV width within the broad l=0 resonances which are analogues of the 2·22 MeV and 2·96 MeV states in ^{71}Ge and ^{73}Ge respectively. These 'sub-structures' also show typical l=0 shapes. From a knowledge of the widths and level spacings, it has been concluded that the sub-structures are neither fine structure levels nor Ericson fluctuations but give evidence for the existence of 'intermediate structure', i.e., structure intermediate between the gross IAR structure and the ultimate fine structure.

Information concerning the low-lying levels in the parent nucleus ^{71}Ge has come mainly through the ^{71}Ga (p, n) ^{71}Ge, ^{71}Ga $(p, n\gamma)$ ^{71}Ge and ^{70}Ge (d, p) ^{71}Ge reactions. From a study of the (p, n) and the $(p, n\gamma)$ reactions, Malan *et al* (1970) have assigned spins and parities for the states in the residual nucleus ^{71}Ge. Similar results have also been obtained by Murray *et al* (1971) from a study of gamma transitions following the beta decay of ^{71}As. The (d, p) reactions on ^{70}Ge have provided, in addition, the l values and spectroscopic factors for many of these states (Goldman 1968; Yoh *et al* 1976).

In the present study, we report the elastic scattering of protons on ^{70}Ge in the energy range of 3·5 to 5·3 MeV. The excitation function reveals resonances corresponding to states in ^{71}As which are identified as isobaric analogues of low-lying states in ^{71}Ge. In addition to the l values for these states, we present evidence for intermediate structure near E_p=4·13 MeV corresponding to the analogue of the 1·34 MeV (l=0) level in ^{71}Ge.

2. Experimental techniques

The proton beam was obtained from the 5·5 MeV van de Graaff accelerator at the Bhabha Atomic Research Centre, Bombay. A thin target of ^{70}Ge was prepared by evaporating isotopically enriched GeO_2 onto a thin carbon film. The percentage composition of the target material was as follows:

$$^{70}\text{Ge} = 84{\cdot}62\%,\ ^{72}\text{Ge} = 5{\cdot}54\%,\ ^{73}\text{Ge} = 1{\cdot}47\%$$

$$^{74}\text{Ge} = 6{\cdot}36\%, \text{ and } ^{76}\text{Ge} = 2{\cdot}01\%.$$

The target thickness was estimated by Rutherford scattering of 2 MeV alphas on the target and was found to be 15 μ gm/cm^2. The elastically scattered protons were analysed for energy by silicon surface barrier detectors mounted inside the scattering chamber at angles of 90°, 125°, 149° (which correspond to zeros of the Legendre polynomials P_{odd}, P_2 and P_4 respectively) and 165° with respect to the incident beam. The resolution of the detectors used ranged from 35 keV to 50 keV. For energy calibration, in addition to the usual calibration using the ^{7}Li(p, n) ^{7}Be threshold energy, the known resonance in ^{12}C(p, p) at 4·808 MeV was used (Reich *et al* 1956).

The electronics set-up used in the present experiment consists, in particular, of a scanning unit for the automatic scanning of the excitation function (Bhalerao *et al* 1974). With this unit the complete excitation function between two energy limits of about 100 keV width is recorded at the same time; this procedure avoids the error due to the variation in the target thickness and non-uniformity in the beam. The energy variation of the beam is achieved by automatically varying the analysing magnet current through a linearly increasing sawtooth voltage. The output pulses from the detectors are amplified and fed to single channel analysers (SCA's) to select the elastic peak of interest. The logic output of each SCA is routed to the memory router unit of the 4096 channel multi-channel analyser (MCA) through a multi-discriminator unit. The fan-in signal from the multi-discriminator unit is given to the gate generator of the scanning unit, the output of which is fed to the analog-to-digital converter unit of the MCA. The excitation functions at the different angles are recorded simultaneously in different parts of the MCA. To normalise the yield obtained with respect to the charge collection, the current integrator counts are also recorded in one part of the MCA. The excitation functions are covered in several ' runs ' each having a range of about 3 hr and the duration of each cycle during scanning was approximately one minute. The beam current on the target was approximately 300 nA.

3. Results and analysis

The excitation functions from 3·5 to 5·3 MeV are measured with targets of roughly the same thickness. Figures 1 and 2 show the excitation functions from 3·5 to 4 MeV and 4 to 4·7 MeV respectively; in these figures the yield (arbitrary units) on the ordinate represents the ratio of counts recorded in the detector to the counts in the current integrator. The frequency (MHz) on the abscissa refers to the resonance frequency of the NMR probe. The arrows in the figures indicate the energy positions of the IAR's and the numbers refer to the excitation energies for the corresponding parent states.

The relative error on the cross sections is found to be less than 2% and represents the error due to statistics only. The absolute error on the cross sections is estimated to be 15%. A number of resonances have been observed in the excitation function and their positions are marked in the figures. Using the known resonance at 5·055 MeV corresponding to the 2·22 MeV state in ^{71}Ge (Temmer *et al* 1971), these resonances are identified as the IAR's in ^{71}As corresponding to the low-lying bound states in ^{71}Ge. Except the two resonances at 4·13 and 5·055 MeV all the other resonances have been observed to be weak.

3.1. *Resonance parameters*

The l value of the resonance is determined by inspection of the angular distribution i.e., from the lack of resonant structure at the angle corresponding to the zero of the lth Legendre polynomial. With this l value, together with initial guesses for the resonance parameters, the computer programme ANSPEC (Thompson and Adams 1967) is used to vary the values of the total width Γ and the proton partial width Γ_p to get the best fit to the excitation function data at each resonance.* The goodness of fit is measured by the minimum χ^2 condition. The excitation function is fitted independently at all the angles for each resonance. In figure 4 the typical theoretical fits obtained at different angles are shown for two of the resonances. The values of the resonance parameters E_R, l, Γ and Γ_p obtained for each resonance are listed in table 1; the level positions and the l values obtained from (d, p) study of Goldman (1968) and Yoh *et al* (1976) are also listed. The absolute energy E_R, of each resonance is estimated to be accurate to $\pm$ 10 keV. The optical-model parameter set used in the present analysis (Perey and Perey 1974) is given below:

$$V_{\text{real}} = 50{\cdot}3 \text{ MeV}, \; W_{\text{surface}} = 11{\cdot}4 \text{ MeV},$$

$$r_{\text{real}} = r_{\text{im}} = 1{\cdot}24 \text{ fm}, \; r_{\text{coul}} = 1{\cdot}25 \text{ fm},$$

$$a_{\text{real}} = 0{\cdot}65 \text{ fm and } a_{\text{im}} = 0{\cdot}57 \text{ fm}.$$

*The ANSPEC fit does not include contributions from compound elastic (CE) scattering. This contribution has however been estimated for the IAR's in ^{71}As using the programme HAUFEC of Kailas *et al* (1976). For the 4·6 MeV resonance at 165°, the CE cross section is found to be only about 8% of the experimental value; the contribution is still less at smaller angles and lower energies. This is however well within the absolute error of 15% in the experimental cross section.

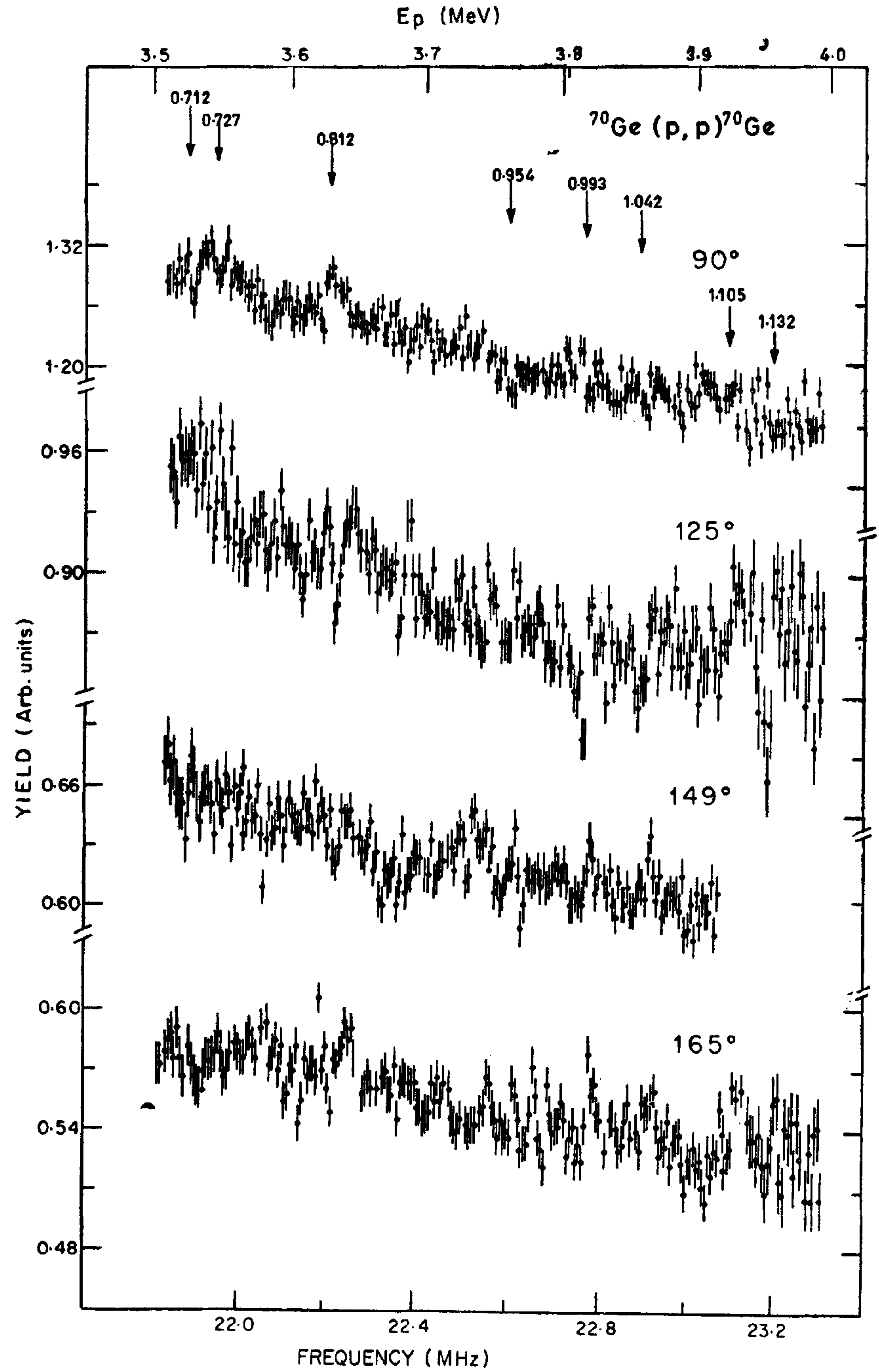

Figure 1. Excitation function for the $^{70}Ge(p, p)$ reaction at laboratory angles of 90°, 125°, 149° and 165° in the energy region from 3·5 to 4·0 MeV.

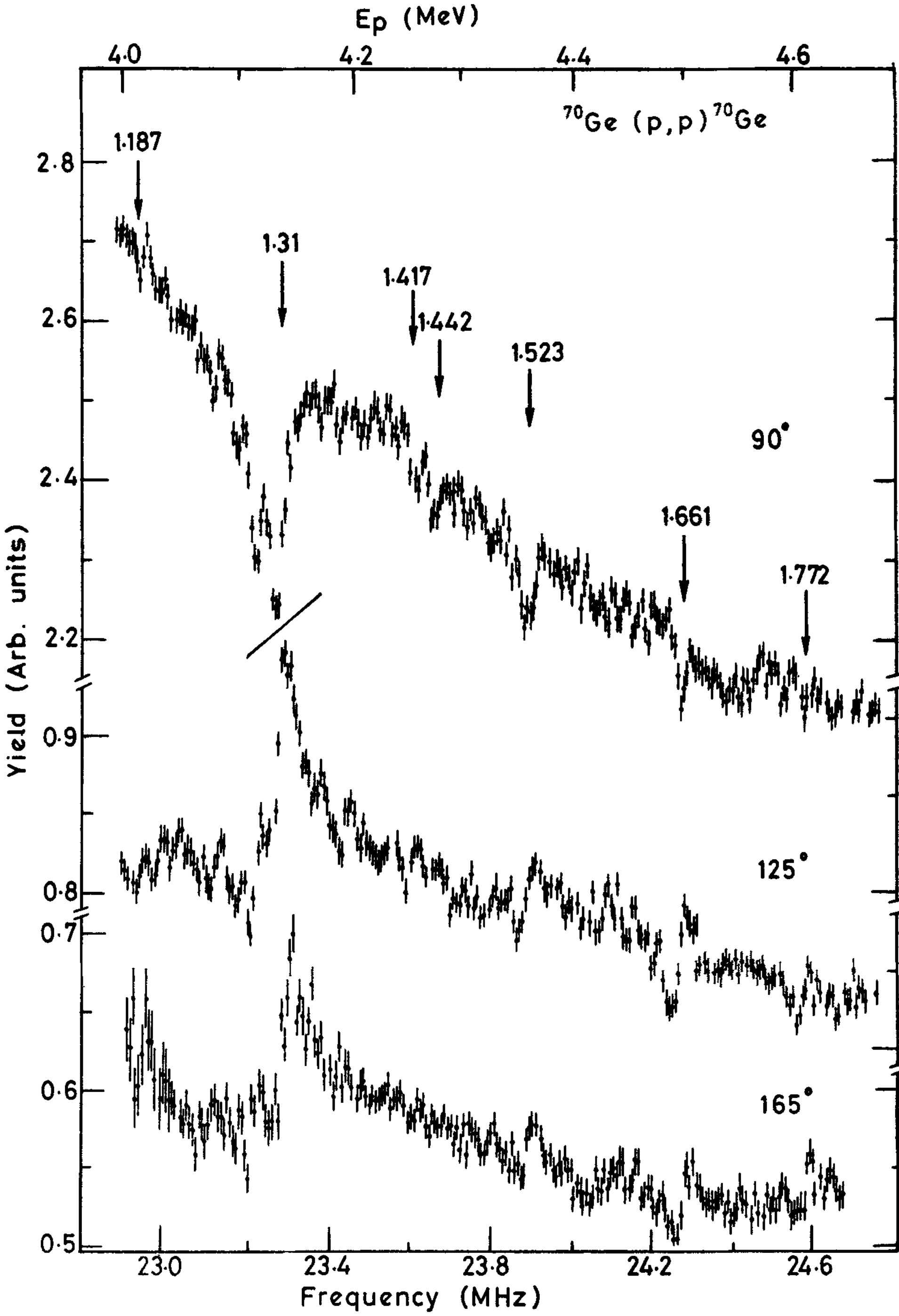

Figure 2. Excitation function at laboratory angles of 90°, 125° and 165° in the energy region from 4·0 to 4·7 MeV.

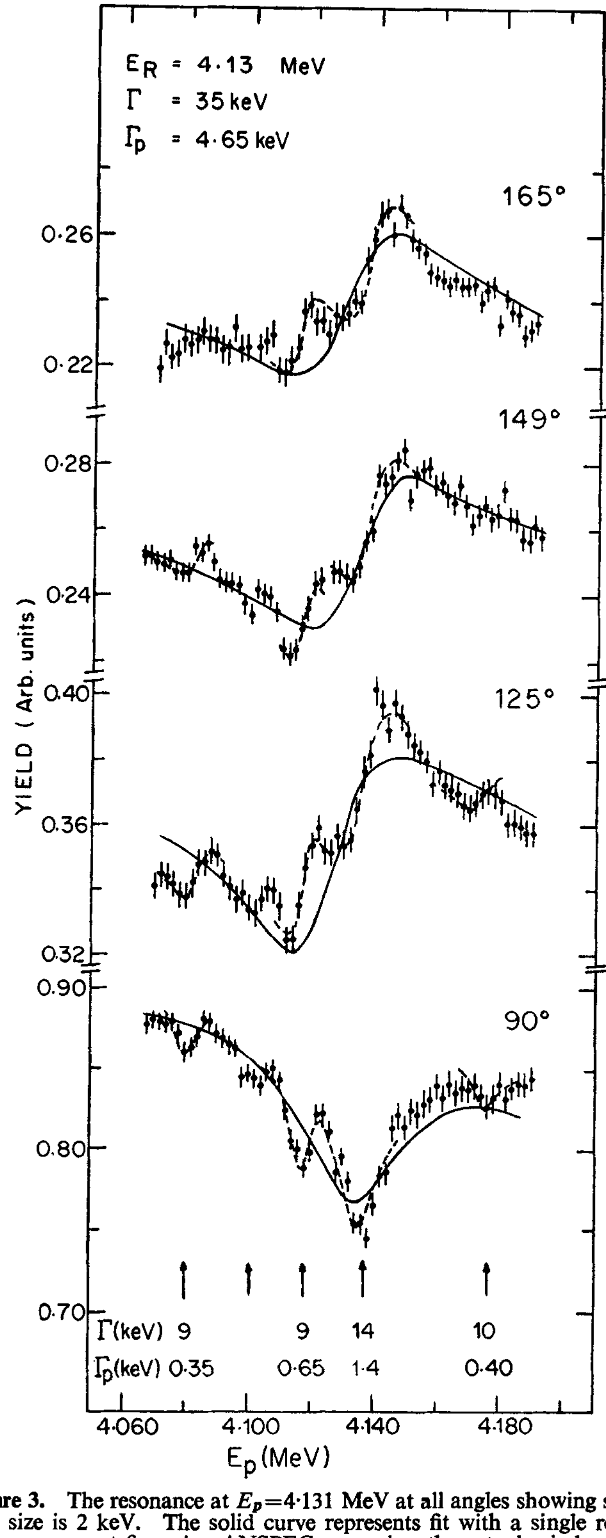

Figure 3. The resonance at E_p=4·131 MeV at all angles showing sub-structures. The step size is 2 keV. The solid curve represents fit with a single resonance. Dashed curves represent fits using ANSPEC, assuming them to be independent. The positions of the sub-structures are indicated by arrows and their parameters are given at the bottom of the figure.

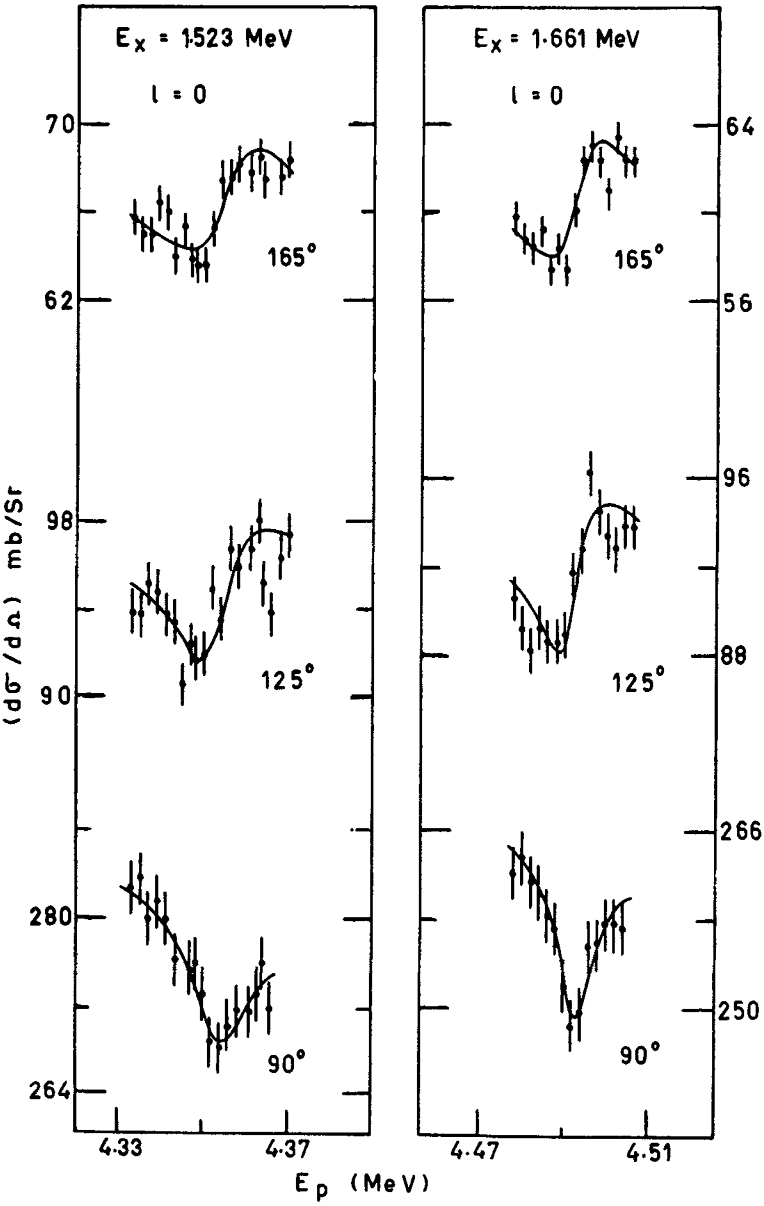

Figure 4. Fits to the resonances at E_p=4·353 and 4·492 MeV observed in the ^{70}Ge (p, p) reaction. Solid curves represent fits from ANSPEC.

The resonance observed at E_p=4·13 MeV exhibits a number of smaller structures *within* it. The shape of these sub-structures at all angles is indicative of l=0 resonances; the theoretical fits to them using ANSPEC, shown in figure 3, also suggest the values l=0. The solid curves represent the fits assuming Γ=35 and Γ_p=4·65 keV. The resonance at E_p=5·055 MeV of width Γ=62 keV as observed by Temmer *et al* (1971) is reproduced in our study in every detail.

Table 1. Resonance parameters for states in ^{71}As which are analogues of states in ^{71}Ge.

Res. No.	E_{res} (MeV)	^{71}As E_{exc} (MeV)	E_x (^{71}Ge) (MeV)		l (J^{π})			Γ; Γ_p (keV)	(2J+1)S		
				A		A	B			A	B
1	3·631	8·204	0·812	0·81	1	—	—	8; 0·3	0·03	—	
2	3·815	8·385	0·993	0·97	0(1/2+)	—		7; 0·35	0·01	—	
3	3·928	8·497	1·105	1·095	1	1		9; 0·45	0·06	0·1	
					0(1/2+)			10; 0·30	0·01	—	
4	4·131	8·703	1·304	1·34	0(1/2+)	0?	0	35; 4·65	0·10	0·093	0·185
5	4·353	8·915	1·523	1·50	0(1/2+)	(2)		17; 0·8	0·02	0·057	
6	4·492	9·053	1·661	1·69	0(1/2+)	(3)		12; 0·6	0·01	0·63	
7	4·605	9·164	1·772	1·78	0(1/2+)	(1)		12; 0·55	0·01	0·013	
8	5·055	9·608	2·216	2·22	0	0	0	65; 18·9	0·26	0·25	0·431

A = Goldman (1968).
B = Yoh *et al* (1976).

3.2. *Coulomb energy difference*

The Coulomb energy difference $\triangle E_c$ has been extracted from the present data using the relation

$$\triangle E_c = (E_R)_{\rm cm} + B_n - E_{\rm ex}, \tag{1}$$

where $(E_R)_{\rm cm}$ is the centre-of-mass energy at resonance, B_n is the neutron separation energy and $E_{\rm ex}$ is the excitation energy of the corresponding state in the parent nucleus. B_n is taken to be 7·413 MeV in the present work (Wapstra and Gove 1971). The average value of $\triangle E_c$ found in this way is 10·18$\pm$0·02 MeV which agrees well with the value of 10·234 MeV obtained from an empirical formula (Janecke 1969).

3.3. *Spectroscopic factors*

The single-particle spectroscopic factors for the corresponding parent state is given by

$$S_n = (2\,T_0+1)\,\gamma_p^2/\gamma_n^2, \tag{2}$$

where T_0 is the isospin of the target. γ_p^2, the reduced width for the resonance scattering is defined by $\gamma_p^2 = \Gamma_p/2P_0$ where P_0 is the optical penetrability factor. The neutron reduced width, γ_n^2, is given by

$$\gamma_n^2\,(a_c) = \frac{\hbar^2}{2ma_c}\,\frac{U_n^2\,(a_c)}{\int_0^{a_c} U_n^2\,(r)\,dr}. \tag{3}$$

Because S_n is a function of the matching radius a_c, the best value of S_n obtained from ANSPEC is taken to be its minimum value and this is quoted in table 1 for each resonance.

4. Discussion

The resonances observed in the present experiment (table 1) correspond to the low-lying states in ^{71}Ge. This correspondence is established (i) from Coulomb energy difference, and (ii) by assuming the resonance observed at 5·055 MeV to be the analogue of 2·216 MeV l=0 state in ^{71}Ge as seen in the ^{70}Ge(d, p) ^{71}Ge reaction by Goldman (1968). The identification of resonances in ^{71}As with the corresponding parent states in ^{71}Ge is seen to be accurate to within 20 keV. Our $(2J+1)S$ values are in good agreement with the values of Goldman (1968). The values given by Yoh *et al* (1976) for the analogue states at 1·34 and 2·22 MeV are found to be a factor of two larger and are presumably due to the different set of optical-model parameters used by them. We have extended the excitation function to the range of energy E_p=2·83 to 3·5 MeV so as to cover the analogue of the ground state of ^{71}Ge. However, the resonances are very weak and hence the excitation function is not included in the figures. In the range of our study, we have fitted the data to the theoretical calculations for only those resonances which are strong. We discuss only these states below. Each resonance is referred to by the incident proton energy and its analogue state in ^{71}Ge whose excitation energy is given in parenthesis.

4.1. 3·631 *MeV* (0·812 *MeV*)

This resonance is interpreted to correspond to $l=1$ in our analysis. The (d, p) data do not assign any l-value for this state at 0·81 MeV. Thus the spin value of this state is restricted to $(1/2, 3/2)^-$.

4.2. 3·815 *MeV* (0·993 *MeV*)

Our analysis indicates an $l=0$ assignment to this state, thus making it a $1/2^+$. No corresponding l-assignment has been made from (d, p) study.

4.3. 3·928 *MeV* (1·105 *MeV*)

The (d, p) study to the 1·09 MeV state indicates an $l=1$ assignment. Our data analysis indicates that both $l=0$ and 1 are possible. The values calculated for both the l-values are given in table 1.

4.4. 4·131*MeV* (1·304 *MeV*)

Our analysis of this resonance (figure 3) indicates it to be an $l=0$, $1/2^+$ state. On the basis of the l value and the spectroscopic strength, this resonance is identified as the analogue of the level at 1·34 MeV observed in the (d, p) study. The (d, p) study of Goldman (1968) has indicated the presence of two levels at 1·28 and 1·38 MeV in ^{71}Ge in the vicinity of the main resonance. The 1·38 MeV level is reported to be an $l=2$ level and is very weak. No l assignment has been made for the 1·28 MeV level; however, possible spin assignment of 1/2 or 3/2 has been made by Malan *et al* (1970).

The resonance parameters are found to be $\Gamma=35$ keV and $\Gamma_p=4{\cdot}65$ keV. Riding on this broad resonance at 4·131 MeV are sub-structures at 4·080, 4·102, 4·118, 4·137 and 4·176 MeV typically with $\Gamma=10$ to 15 keV at a spacing of 20 to 40 keV and are correlated at different angles (table 2). The shapes of the resonances at different angles for each of the sub-structure levels are characteristic of $l=0$. From a knowledge of the $T_<$ level density at this excitation energy ($D=3$ per keV and $\Gamma=20$ eV;

Table 2. Resonance parameters for the 'gross and sub-structures' of the $l=0$ $(J=1/2)$ resonance in ^{71}As at 4·13 MeV proton energy in the ^{70}Ge(p, p) reaction

Structure	$(E_R)_{\text{Lab}}$ (MeV)	T	Γ (keV)	Γ_p (keV)
Gross structure	4·131	7/2	35	4·65
Sub-structure 1	3·080	5/2	9	0·35
,, 2	4·102	5/2	—	—
,, 3	4·118	5/2	9	0·65
,, 4	4·137	5/2	14	1·40
,, 5	4·176	5/2	10	0·40

Maruyama *et al* 1970) it can be concluded that these structures are not due to fine-structure levels. Further, their specific $l=0$ shapes and their correlation at different angles point out that they are not Ericson fluctuations. The observed structures therefore seem to suggest the existence of intermediate structure with widths in between those of the isobaric analogue states and the usual $T_<$ states. However, for a conclusive evidence of the presence of intermediate structure, the $1/2^+$ spin values of the sub-structures have to be confirmed through independent studies such as $(p, p'\gamma)$ and $(\vec{p}, p)$ reactions; further confirmation through correlation of these sub-structures in other channels such as the inelastic channel would also be necessary.

4.5. 4·353 *and* 4·605 *MeV* (1·523 *and* 1·772 *MeV*)

The present analysis indicates the shapes of the excitation function at different angles to be characteristic of an $l=0$ transfer (figure 4). The (d, p) study suggests $l=2$ and 1 respectively. We reassign the two states to be $1/2^+$.

4.6. 4·492 *MeV* (1·661 *MeV*)

The resonance angular distribution (figure 4) is clearly indicative of an l value of zero for this resonance. The nearest level observed in the (d, p) study at 1·69 MeV is known to be an $l=4$ (Yoh *et al* 1976). The resonance is therefore identified as the analogue of the 1·63 MeV level observed in the $(p, n\gamma)$ study (Malan *et al* 1970) and is assigned $1/2^+$.

4.7. 4·8 *MeV* (1·96 *MeV*)

The resonance corresponding to the 1·96 MeV state in ^{71}Ge could not be studied since at this incident energy of 4·808 MeV, a strong resonance in ^{13}N covers this completely. In fact, this strong resonance in ^{12}C (p, p) is used for energy calibration in the present experiment.

4.8. 5·055 *MeV* (2·216 *MeV*)

This resonance has been first studied by Temmer *et al* (1971). The main resonance and the sub-structures at 4·97, 5·01, 5·04 and 5·07 MeV were found to have characteristic $l=0$ shapes. From a knowledge of the widths and level spacings, these structures were interpreted as giving evidence of 'intermediate structure' near the analogue resonance. Based on their (p, p') data these sub-structures were considered to be hallway states (possibly $5p$-$4h$ states in the particle-hole hierarchy). Our data reproduce the detailed shape of this broad resonance at all angles; using the values of Γ and Γ_p given by Temmer *et al* (1971) the fit obtained for our data at 90°, is satisfactory. Recent evidence by Terry *et al* (1978) based on the $(p, p'\gamma)$ angular correlation measurements and analysing power measurements in the $(\vec{p}, p)$ has indicated that the sub-structures at 5·01 and 5·07 MeV have spin $1/2^+$ and the other two structures at 4·97 and 5·04 MeV have spins $3/2^-$ and $5/2^+$ respectively, instead of the previously assigned $1/2^+$ values, thus casting doubt on the interpretation of the resonance as an example of intermediate structure. The structure at 5·04 MeV is very close to the main resonance at 5·055 MeV and hence the spin assignment $1/2^+$ can only be regarded as tentative. The anomaly corresponding to the state at 4·97 MeV exists at all angles (including 90°) in our data and in the data of Temmer *et al* (1971). The assignment of $3/2^-$ for this structure by Terry *et al* (1978) therefore appears to be contradictory; moreover the analysing power at this energy in their data deviates only slightly from zero. In any case, the sub-structures at 5·01 and 5·07 MeV remain as strong candidates for the intermediate-structure interpretation.

It is of interest to note that such structures of about 20 keV width have also been observed below the threshold of IAR in ^{72}Ge(p, p) (Betigeri *et al* 1969), ^{72}Ge(p, $p'e$) (Betigeri *et al* 1972a), ^{72}Ge(p, γ) (Baba *et al* 1976) and ^{90}Zr(p, $p'e$) (Nessin *et al* 1962). It has been pointed out by Baba *et al* (1976) that such widths and spacings typically occur at about 6 MeV excitation. Since the energy of excitation in this region is around 9 MeV, it is tempting to associate these levels with structures in a second potential well which is separated from that of the ground state by about 3 MeV. Lifetime measurements by Baba *et al* (1976) for such a probable level have proved inconclusive.

Acknowledgements

The authors wish to thank Dr C V K Baba for his help and guidance during the experiment and also for many useful discussions. Thanks are also due to Dr G M Temmer for the exchange of ideas during the initial stages of the experiment. One of the authors (CRR) wishes to thank the Department of Atomic Energy (DAE) for providing a research fellowship. This work has been supported in part by a research grant from the DAE.

References

Baba C V K, Betigeri M G, Datar V M, Bharati S M and Roy A 1976 *Nucl. Phys. Solid State Phys. (India)* **B19** 23
Betigeri M G, Lamba C M, Sarma N, Sood D K and Thampi N S 1969 *Nucl. Phys.* **A133** 465
Betigeri M G, Lamba C M, Sood D K and Thampi N S 1972a *Nucl. Phys.* **A185** 330
Betigeri M G, Thampi N S, Varma L P and Vaze M Y 1972b *Nucl. Phys. Solid State Phys. (India)* **B15** 31
Bhalerao P J, Vaze M Y, Gupta S K and Baba C V K 1974 *Nucl. Phys. Solid State Phys. (India)* **B17** 285
Goldman L H 1968 *Phys. Rev.* **165** 1203
Janecke J 1969 in *Isospin in nuclear physics* ed D H Wilkinson (Amsterdam: North Holland) p. 341
Kailas S, Gupta S K and Mehta M K 1976 BARC Report/I-360 (unpublished)
Malan J G, Tepel J W and Devilliers J A M 1970 *Nucl. Phys.* **A143** 53
Maruyama M, Tsukada K, Ozawa K, Fujimoto F, Komaki K, Mannami M and Sakurai T 1970 *Nucl. Phys.* **A145** 581
Murray G, Sanderson N E and Willmott J C 1971 *Nucl. Phys.* **A171** 435
Nessin M, Kruse T H and Eklund K E 1962 *Phys. Rev.* **125** 639
Perey C M and Perey F G 1974 *Atomic Nucl. Data Tables* **13** 293
Reich C W, Phillips G C and Russel Jr J L 1956 *Phys. Rev.* **104** 143
Temmer G M, Maruyama M, Mingay D W, Petrascu M and van Bree R 1970 in *Statistical properties of nuclei* ed. J B Garg (New York: Plenum) p. 563
Temmer G M, Maruyama M, Mingay D W, Petrascu M and Van Bree R 1971 *Phys. Rev. Lett.* **26** 1341
Terry G H, Hausman H J, Donoghue T R, Suiter H R and Wallace P H 1978 *Phys. Rev. Lett.* **41** 934
Thompson W J and Adams J L 1967 Technical Report No. 10 Florida State University
Wapstra A H and Gove N B 1971 *Nucl. Data* **A9** 314
Yoh W A, Darden S E and Sen S 1976 *Nucl. Phys.* **A263** 419