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A study of the reaction $^{19}F(\alpha, n)^{22}Na$ in the bombarding energy range 2·6 to 5·1 MeV

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Abstract. The total (α, n) reaction cross section for ^{19}F has been measured as a function of alpha energy in the energy range 2·6 to 5·1 MeV with a thin target. The excitation function exhibits a large number of resonances. The prominent amongst these for which the J^{π} values are known have been analysed to extract the partial widths Γ_{α} and Γ_n. Statistical analysis of the data in terms of strength function and average level spacing distribution has also been performed.

Keywords. (α, n) reaction; ^{19}F target; E=2·6 to 5·1 MeV; measured total $\sigma_{\alpha,n}$; extracted Γ_{α}, γ_{α}^2 and $\bar{S_{\alpha}}$.

1. Introduction

Considerable theoretical effort has been expended on the structure calculations for nuclei in the *s-d* shell and experimental information on nuclei in this shell is needed to verify these calculations. The compound nucleus ^{23}Na, in the present case, belongs to the *s-d* shell and provides a suitable spectrum to this region. Since it is an odd-even nucleus, the excitation function would show resonances which are more complicated than that for even-even nuclei in this mass region, for a corresponding range of excitation energy. The experimental information available can also be made use of in extracting the values of interaction matrix elements (del Campo *et al* 1975). The (α, n) reaction on light nuclei has been utilised to obtain information on excited states of corresponding compound nuclei through resonance analysis (Sekharan *et al* 1967, Balakrishnan *et al* 1975). It is also a reaction of importance for the consideration of nucleosynthesis processes in astrophysics as it is one of the reactions through which heavier nuclides could be built up from lighter species (Fowler *et al* 1955).

In continuation of our programme of (α, n) reaction studies on light elements (Sekharan *et al* 1967, Balakrishnan *et al* 1975) with the above described motivation in mind, the reaction of $^{19}F(\alpha, n)^{22}Na$ has been studied and is described in this paper. It may be noted that $^{19}F(\alpha, n)$ reaction has been used as a neutron source utilising natural alpha emitters and fluorine compounds (Szilvasi *et al* 1960, Massand and Venkatraman 1974).

Experimentally low lying levels in ^{23}Na have been studied extensively (Endt and Van der Leun 1973). In a low resolution study of the reaction $^{25}Mg\ (d, \alpha)^{23}Na$ Hansen *et al* (1964) have shown that the total cross sections averaged over bombarding energy to definite states in ^{23}Na is approximately proportional to $(2I+1)$. Duboi

(1967) has investigated the energy levels in ^{23}Na again by means of ^{25}Mg (d, α)^{23}Na (target thickness $\sim$100 μgm/cm^2) reaction up to an excitation of 7·75 MeV. More recently resonance strengths, branching ratios and mean life times of nuclear energy levels in ^{23}Na, in the region of excitation 10 to 10·5 MeV have been measured by der Toit *et al* (1971) using ^{22}Ne (p, γ) ^{23}Na reaction. Freeman and Mani (1964) have studied the yield of gamma rays following the alpha particle bombardment on ^{19}F targets for incident energies ranging from 3·95 to 4·92 MeV. They used NaI (Tl) crystal to detect gamma-rays. From elastic and inelastic scattering of protons on ^{22}Ne, Katori *et al* (1967) have identified a total of 75 resonances, corresponding to levels in ^{23}Na, between 9·7 and 12·8 MeV. Several pronounced resonances, including $T=3/2$ isobaric analogues, are analysed using the single level approximation of the dispersion formula and level parameters assigned. Williamson *et al* (1960) have also studied ^{19}F(α, n) ^{22}Na reaction up to about $E_\alpha=3·5$ MeV.

A preliminary study of this reaction carried out at this laboratory has been described earlier (Sekharan *et al* 1965). The present study was undertaken to achieve finer resolution and better accuracies. After the manuscript for this paper was prepared, the work of Van der Zwan and Geiger (1977) has been published which describes the differential cross section measurement for the same reaction at 0° for the neutron group going to the ground state of ^{22}Na. This is further discussed in the last section.

2. Experimental procedure and results

Targets of thickness about 3·5 keV for 3 MeV alphas, were fabricated by evaporating calcium fluoride (CaF_2) on to ten mil thick tantalum backing. This compound was chosen for its substantially high melting point (1360°C) and high stability to alpha

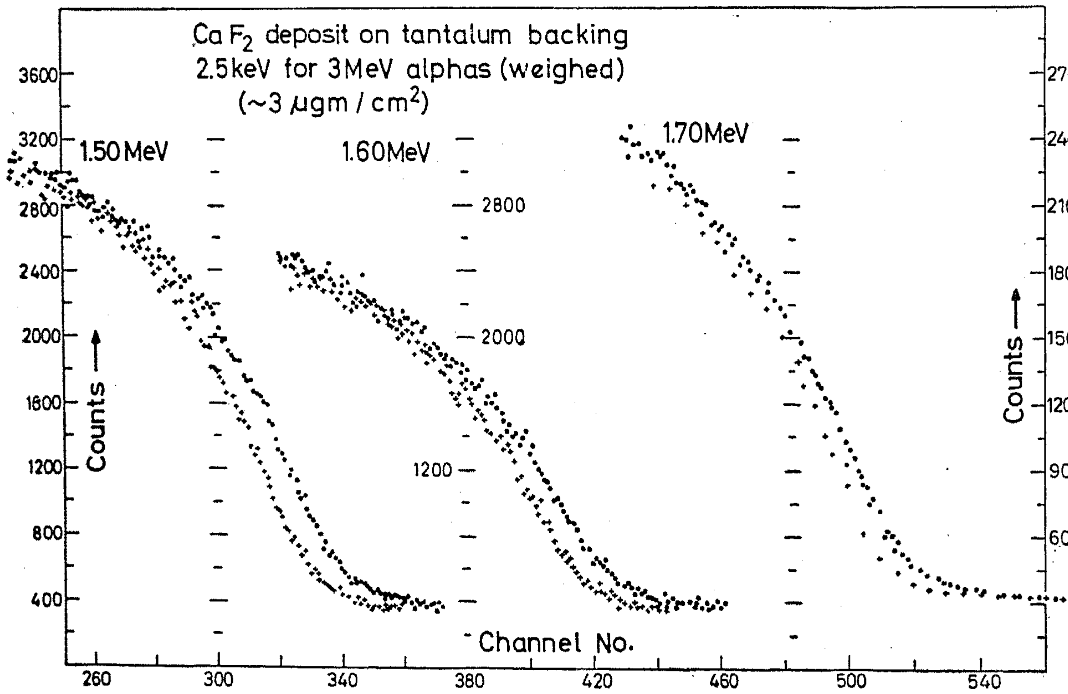

Figure 1. Typical alpha back scattered spectra indicating the decrease in energy loss as the incident alpha energy increases.

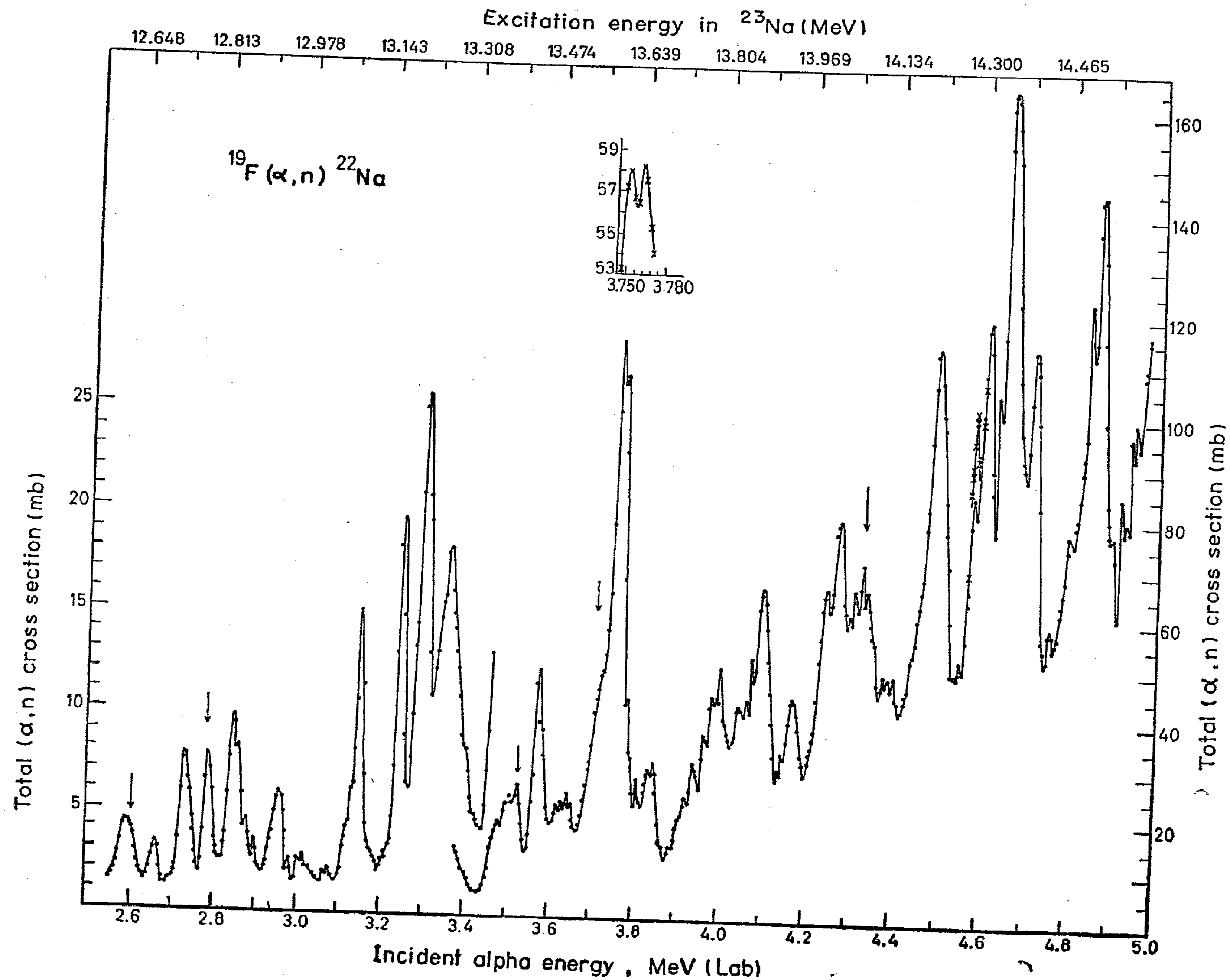

Figure 2. The excitation function for $^{19}F(\alpha, n)\,^{22}Na$ reaction from $E_\alpha = 2{\cdot}6$ to $5{\cdot}1$ MeV. For E_α from $2{\cdot}6$ to $\sim 3{\cdot}4$ MeV the ordinate on the left hand side gives the $\sigma_{\alpha,n}$ values. The ordinate on the right hand side gives the $\sigma_{\alpha,n}$ values, for E_α above $\sim 3{\cdot}4$ MeV up to $\sim 5{\cdot}1$ MeV.

bombardment. Only 100 nanoamperes of analyzed, singly ionized ^4He beam from the Van de Graaff accelerator at our laboratory were used to bombard the targets. Repeated measurements of the neutron yield at a few energies were carried out at intervals of a few hours to check for the presence of any target deterioration. No decrease in yield was observed even after 48 hr of bombardment. The target was situated at the centre of a 4π geometry neutron counter, which consisted of BF_3 counters embedded in a large cubic block of paraffin (Sekharan *et al* 1967). The target thickness was determined by measuring the shift in the edge of the back scattered alpha particle spectrum from the tantalum side of the target and from the side with CaF_2 deposit respectively. The details of this measurement are described elsewhere (Balakrishnan *et al* 1974). The method is illustrated in figure 1 which shows typical scattered spectra and the shift in the edge for three incident alpha energies 1·50, 1·60 and 1·70 MeV at a backward angle of 165° for CaF_2 targets.

The neutron yield was measured as a function of bombarding energy from 2·6 to 5·1 MeV in steps of 5 keV. The beam dependent background due to non target materials was measured at an interval of $\sim$ 200 keV by rotating the target holder through 180° so that the back of the tantalum backing faced the beam. The neutron yield, after subtraction of this background, was converted into absolute cross section. The resulting excitation function is shown in figure 2. The absolute error was estimated to be $\pm 15\%$, comprising of the independent individual errors in target thickness measurement ($\pm 10\%$), efficiency of the 4π counter ($\pm 7\%$) (Gupta and Kerekatte 1971), current integration ($\pm 1\%$) (Gupta 1968) and counting statistics (negligible).

Due to the 1% abundance of ^{13}C in the carbon contamination present in the target and because of the positive Q value (2·214 MeV) for the $^{13}C(\alpha, n)^{16}O$ reaction, a significant contribution to the neutron yield could come from this reaction especially up to about 3·4 MeV where the $^{13}C(\alpha, n)^{16}O$ reaction exhibits strong resonances (Bair and Haas 1973). The resonances due to this reaction are expected to contribute at bombarding energies marked by arrows in figure 2. The resonances which could be identified as wholly due to ^{13}C were not analysed. It was assumed that the error

Table 1. Excitation energies, peak total cross-sections, maximum neutron energy and total level width for the resonances analysed in this study. ($^{19}F(\alpha, n)\,^{22}Na$).

Resonance energy E_α (MeV)	Exciation energy in ^{23}Na E_x(MeV)	Peak total cross section $^{19}F(\alpha, n)^{22}Na$ (mb)	Maximum neutron energy E_n (MeV)	Total level width Γ_{cm} (keV)
2·730	12·722	7·4	0·367	35
3·150	13.069	14·6	0·727	25
3·250	13·151	18·5	0·808	25
3·300	13·193	24·3	0·850	25
4·095	13·850	50·0	1·526	45
4·170	13·912	38·0	1·589	45
4·490	14·176	82·0	1·861	65
4·605	14·271	83·0	1·958	45

due to contribution from this reaction at energies other than these resonances up to about 3·4 MeV would be small. This error was estimated in the following manner: The strongest resonance in the $^{13}C(\alpha, n)^{16}O$ reaction, in the range of alpha energy covered in our work, is at $E_\alpha \sim 2{\cdot}8$ MeV; The amount of ^{13}C contaminent could be estimated from the strength of this resonance seen in figure 2, by assuming that it is entirely due to ^{13}C and there is no contribution from the $^{19}F(\alpha, n)$ reaction at this energy. The major error due to ^{13}C contribution is in the resonance at 3·3 MeV (table 1) in the present work, as the second strongest resonance in the $^{13}C(\alpha, n)$ reaction is also at 3·318 MeV. It was found that the correction due to the ^{13}C contaminent could be up to 20% for this resonance. In all other cases this error would be very much less than the absolute error assigned to the cross section values ($\pm 15\%$). Due to the rapidly rising nature of the $^{13}C(\alpha, n)^{16}O$ excitation function beyond 5 MeV, the measurement above 5·1 MeV bombarding energy would have very large errors due to the ^{13}C contaminent. Because of this trouble the measurements were terminated at 5·1 MeV. Similarly, large errors due to ^{13}C contaminent made it meaningless to extend the measurement below 2·6 MeV.

The excitation function in figure 2 shows a large number of resonances. Considering that the resolution is $\sim$ 5 keV (for 3·5 MeV alphas) and that most of the observed resonances exhibit widths few times the resolution, the chance that any finer resonances are unresolved is very small. In order to confirm this inference, as well as to check the reproducibility of data, the excitation function was measured with 2·5 keV energy increment over small regions around 3·77 and 3·80 MeV. These data are shown as an insert in figure 2. It can be seen that the double peaks of the strong structure seen just below 3·8 MeV on the main curve are better resolved but no new peaks have shown up. The data around 4·6 MeV are plotted as crosses above the main curve and indicate the well resolved narrow resonances ($\Gamma \sim 10$ keV) just below 4·6 MeV which show up as a one point shoulder in the main curve. This check confirms that narrow resonances with widths of about 10 keV can still be identified in the main curve and any finer resolution measurements are not likely to reveal significantly more resonances. On the other hand the number of resonances seen in the present work is much more than that observed in the work done at this laboratory with coarser resolution (Sekharan *et al* 1965).

3. Analysis

3.1. *Individual resonance analysis*

Although a large number of overlapping resonances are seen in figure 2, there are a few resonances which can be considered as well as resolved and isolated. These resonances would be amenable to the Breit-Wigner single level analysis for extraction of the pertinent partial and reduced widths. However, this analysis requires the knowledge of spin and parity for the corresponding levels of the compound nucleus. Recently Schier and coworkers (1976) have studied the $^{19}F(\alpha, p)\,^{22}Ne$ reaction and assigned spin and parity to a number of levels in the same excitation region of the compound nucleus ^{23}Na. Considering that the only difference between that work and the present work is in the outgoing channel, it is very likely that the resonance seen in the two excitation function can be correlated, although the resolution in the

Table 2. Partial widths and reduced widths and other resonance parameters for the resonances analysed in the study of ^{19}F (α, n) ^{22}Na reaction. (For explanation of parameters ω_γ, etc. see Gove 1959.)

Resonance energy (MeV)	ω_γ (keV)	J^π (Schier)	l_α	Γ_α (keV)	Γ_n (keV)	$P_{\alpha l}$ Penetrability	γ_α^2 reduced width (keV)	θ_α Percentage Wigner limit
2·730	0·488	5/2+	2	0·17	34·83	$1{\cdot}87\times10^{-2}$	4·54	0·848
		7/2−	3	0·13	34·87	$4{\cdot}76\times10^{-3}$	13·65	2·55
3·150	0·793	1/2+	0	0·82	24·18	$2{\cdot}10\times10^{-1}$	1·95	0·364
		7/2−	3	0·20	24·80	$1{\cdot}81\times10^{-2}$	5·52	1·03
3·250	1·036	5/2+	2	0·35	24·65	$7{\cdot}95\times10^{-2}$	2·20	0·411
		7/2−	3	0·27	24·73	$2{\cdot}37\times10^{-2}$	5·70	1·06
3·300	1·379	7/2−	3	0·35	24·65	$2{\cdot}70\times10^{-2}$	6·48	1·21
		9/2+	4	0·28	24·72	$5{\cdot}48\times10^{-3}$	25·55	4·71
4·095	6·323	1/2−	1	7·61	37·39	$6{\cdot}35\times10^{-1}$	5·99	1·11
		7/2−	3	1·64	43·36	$1{\cdot}40\times10^{-1}$	5.87	1·09
4·170	4·893	3/2−	1	2·6	42·4	$6{\cdot}88\times10^{-1}$	1·89	0·35
		5/2+	2	1·79	43·21	$3{\cdot}97\times10^{-1}$	2·25	0·42
4·490	1·639	3/2−	1	0·83	64·17	$9{\cdot}49\times10^{-1}$	0·437	0·08
		3/2+	2	0·83	64·17	$5{\cdot}61\times10^{-1}$	0·739	0·138
4·605	1·176	3/2−	1	0·6	44·4	1·02	0·294	0·055
		3/2+	2	0·6	44·4	$6{\cdot}47\times10^{-1}$	0·46	0·086

(α, p) work is four times poorer than the present work. A careful comparison between these two excitation functions has enabled us to identify 12 of the resonances seen in the present work with the corresponding resonances of the (α, p) study. Eight of these resonances for which spin and parity are determined by Schier *et al* (1976), are listed in table 1 along with the total width and the peak cross sections as measured in the present work. For these resonances, the Breit-Wigner analysis was carried out following the procedure described by Gove (1959). The results are shown in table 2 which lists the resonance energies, the possible J^π values assigned in the (α, p) work, corresponding orbital angular momentum of the alpha particle exciting the resonance, the extracted partial widths Γ_α and Γ_n from the data given in table 1 (assuming that the smaller of the two values is Γ_α), the reduced widths γ_α^2 and ratios of these reduced widths to corresponding Wigner limits as percentages. It can be seen from the last column of table 2 that none of the 8 resonances analysed seems to have a strong alpha particle nature, except for the resonance at 3·3 MeV, which would have a reduced width equivalent to 4% of the Wigner limit if the spin parity is $(9/2)^+$ (Resonance No. 4, table 2).

3.2. *Statistical analysis*

About 57 resonances could be identified in the excitation function which would correspond to the levels in the compound nucleus ^{23}Na in the range of excitation from 12·6 to 14·5 MeV. Apart from the individual resonance analysis described in the previous section the total number of resonances is large enough to subject it to statistical analysis. The average spacing between resonances is about 35 keV, while the average width is around 25 keV. These agree well with similar values observed by Freeman and Mani (1964). Just as an individual resonance can be analysed in terms of the rele-

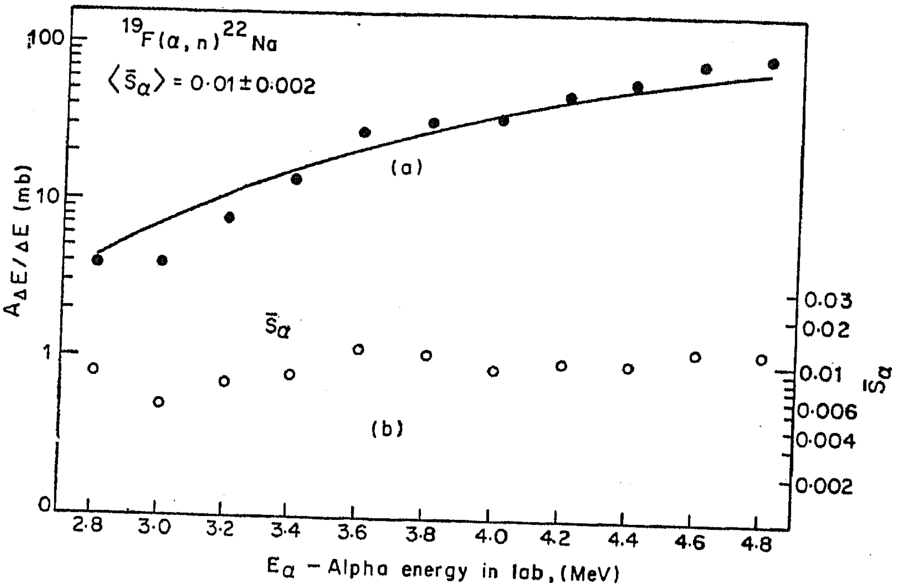

Figure 3. (a) Plot of $A_{\triangle E}/\triangle E$ against the bombarding energy in MeV. (b) Plot of strength function $\bar{S}_\alpha$ as a function of E_α.

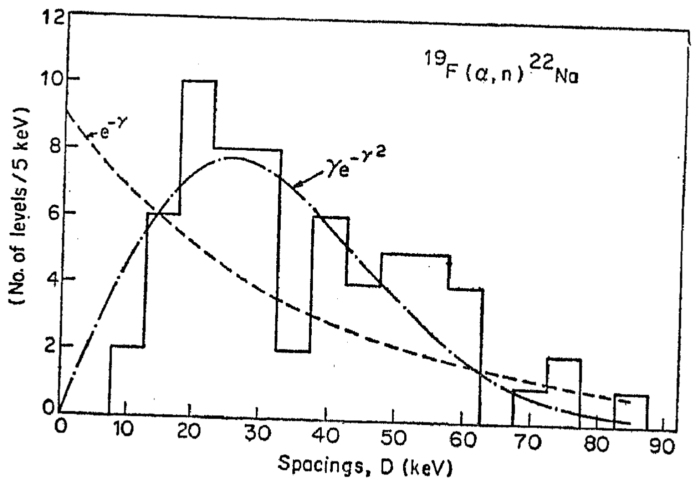

Figure 4. Experimentally observed distribution of level spacing, along with the exponential and Wigner distributions.

vant reduced widths, an excitation function containing a large number of resonances can be analysed in terms of the 'strength function' which can be considered as an average over reduced widths contributions for all the compound nuclear levels concerned. Following the procedure used by Hass and Bair (1973) for similar analysis, the cross section data of figure 1 were averaged over an energy interval $\triangle E$ and the area under this averaged curve per unit energy interval was plotted as a function of the incident alpha particle energy as shown in figure 3. Under the assumption that $\Gamma_\alpha \ll \Gamma_n$, a value of alpha particle strength function $\bar{S}_\alpha$ can be obtained for each data point shown in figure 3, from the expression,

$$\frac{A_{\triangle E}}{\triangle E} = \frac{2\pi^2 \lambda\!\!\!^{-2}}{(2I+1)} \left[\sum_J (2J+1) \sum_{l=|J-I|}^{J+I} \frac{2kR}{A_l^2} \right] \bar{S}\alpha.$$

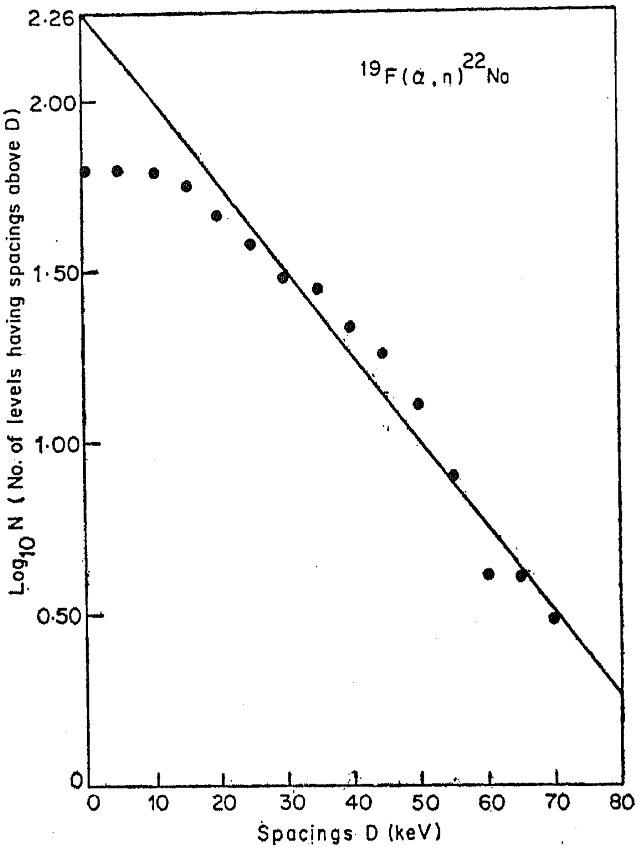

Figure 5. The level distributions, plotted as the log of the number of levels in ^{23}Na having a spacing greater than some spacing D, against D.

Here $A_{\triangle E}/\triangle E$ is the area per unit energy interval and other symbols have their usual meaning. The bar over $\bar{S}_\alpha$ indicates the averaging over J. As can be seen, the value of $\bar{S}_\alpha$ remains almost constant with respect to the bombarding energy and has an average value of $\langle \bar{S}_\alpha \rangle = 0{\cdot}010 \pm 0{\cdot}002$, where $\pm 0{\cdot}002$ represents the maximum deviation. With this value substituted for $\bar{S}_\alpha$ in the above expression, a fit to the points in figure 3 can be calculated which is shown as the continuous line in that figure. This result can be interpreted as an indication of the constancy of alpha parentage of the levels in the compound nucleus ^{23}Na in the excitation range 12·6 to 14·5 MeV. Such a behaviour would be expected on the basis of general statistical model when there are no special levels or intermediate structures present.

Wigner (1957) has shown that spacings between levels for a given spin may not follow a random distribution. However, if levels with various spin values are being observed, their distribution of spacings is probably not far from random i.e. the level spacings will exhibit an exponential distribution. Figure 4 shows the experimentally observed distribution of level spacing along with the exponential and the Wigner distributions. The Wigner distribution seems to fit the data a little better at the lower spacing values. In the case of an exponential distribution, a plot of log N vs D, where N is the number of levels having a level spacing greater than a given spacing D, should be a straight line, with a slope inversely proportional to the average level spacing (Bair and Haas 1973). Figure 5 shows the plot of the common log of the number of levels in ^{23}Na obtained from the present study having a spacing greater than spacing D against D. Again the deviation from the exponential distribution for the spacing below 25 keV can be noted. This is discussed in the next section.

4. Discussion and conclusions

At the outset before discussing the results of the experiment, it should be noted that ^{13}C contamination has seriously limited the usefulness of the range over which the excitation function is measured. Apart from the build up on the target during the run, carbon contents of the substrate (Ta in the present case) also could be a contributing factor to the yield of neutrons due to ^{13}C (Balakrishnan *et al* 1975).

In the present work, the cross section for the $^{19}F(\alpha, n)\,^{22}Na$ reaction has been measured for incident alpha particle energy range from 2·6 to 5·1 MeV. This covers the excitation energy range from 12·6 to 14·5 MeV in the compound nucleus ^{23}Na. Out of the 57 resonances observed, the spin and the parity are known for 8 resonances through earlier work (Schier *et al* 1976). For these 8 resonances, the total partial and reduced widths are determined from the present work. Out of the two values obtained for the partial widths through the Breit-Wigner analysis of the individual resonances, the larger value is identified as the neutron width Γ_n and the smaller one as the alpha particle width Γ_α. In view of the fact that all the resonances analysed here are below the Coulomb barrier, which is about 5 MeV in the present case, the penetrability factor for alpha particles will be much smaller than those for the neutrons and even if the reduced alpha particle width γ_α^2 and the reduced neutron width γ_n^2 for a resonance are equal, the corresponding partial width Γ_n will be much larger than Γ_α because of the difference in penetrabilities. Thus the assumption $\Gamma_\alpha \ll \Gamma_n$ is justified in general at these bombarding energies. It should be noted that the partial width Γ_n consists of a sum of neutron partial widths corresponding to different neutron groups leaving the residual nucleus ^{22}Na in a number of excited states including the ground state, as the 4π neutron counter being a flat response counter measures the total yield of neutrons irrespective of their energies. Because of Γ_n being a composite of Γ_{n0}, Γ_{n1}, Γ_{n2}, etc., it is not meaningful to extract the neutron reduced width γ_n^2 which require the knowledge of the orbital angular momentum of the outgoing neutron groups. It is likely that, depending on the spin and parity of the state of the ^{22}Na which is being excited and the constraint due to the angular momentum available through the entrance channel, all subpartial widths Γ_{n1}, Γ_{n2}, etc. are not equal and that Γ_n is mostly composed of only one subpartial neutron width. However, this cannot be confirmed in the present experiment. Further, as the (α, p) channel seems to be competing favourably (see below) with the (α, n) channel, the Γ_n values extracted in the present work will be actually a combination of Γ_n and Γ_p. This will still leave our Γ_α estimation unaltered in the present analysis.

In identifying the eight resonances which are analysed here with the corresponding ones in the (α, p) work of Schier *et al* (1976), we have assumed that for all the resonances in this region the γ_n^2 will be comparable to γ_p^2 and hence the same resonances will appear in the excitation functions for the proton as well as for the neutron exit channel. In general even when $\gamma_p^2 \sim \gamma_n^2$, the cross sections in the two channels will not be comparable because of the Coulomb barrier for the protons and the absence of this barrier for the neutrons. However, as the Q value of the (α, n) channel is

$-1\cdot9505$ MeV and the (α, p) channel is $+1\cdot6747$ MeV, the energy of the outgoing protons would be about 4 MeV higher than that of the neutrons. This higher energy would result in high penetrability for the protons through the Coulomb barrier and thus the cross sections for the proton and neutron channels are comparable as can be seen by comparing the present work with that of Schier *et al* (1976). Earlier work done at this laboratory involving measurement of excitation function for seven gamma rays emitted from alpha bombardment of ^{19}F (Balakrishnan *et al* 1972) showed that the yield for gamma rays resulting from $(\alpha, p\gamma)$ and $(\alpha, n\gamma)$ reactions was comparable. After this paper was prepared for publication, the work of Van der Zwan and Geiger (1977) has recently been published where they have measured the differential cross section for the ground neutron group at 0° from the ^{19}F (α, n) ^{22}Na reaction. From a comparison of our data with their work, it was found that the prominent resonance positions in the two works agree to within ± 3 keV. This has further justified our original identification of the major resonances through a comparison with the (α, p) work.

The eight resonances analysed in this experiment scan a region of about two MeV of excitation energy in the compound nucleus. They can be considered as 'samples' indicating the strength of the alpha particle parentage of the levels in their neighbourhood. It can be seen from table 2 that the alpha particle reduced widths γ_α^2 do not vary widely, indicating a general, almost constant, low alpha particle strength. The same inference is further strengthened through the 'strength function' analysis where again one single value of $\langle \bar{S}_\alpha \rangle$ fits the averaged cross section as discussed in section 3·2 above.

The deviation of the log N vs D plot from a straight line at low values of D could arise from two factors. It can be due to the presence of narrower levels which are not resolved in the experiment and thus would be missed. However, considering the fact that very few resonances are observed having widths lower than 15-20 keV (as discussed in section 2) while the resolution of the experiment is about 5 keV, it is not likely that many narrow resonances are missed. The other factor causing the deviation could be due to the fact that the level spacing distribution is a Wigner distribution and not an exponential one. The comparison shown in figure 4 also supports this conclusion.

The results on level spacing distribution studies of this work are very different from those of an earlier study carried out at this laboratory of the reaction ^{29}Si (α, n) ^{32}S (Balakrishnan *et al* 1975) where the log N vs D plot deviated from a straight line only for values of D equal to or less than the resolution of the experiment (~ 5 keV).

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