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POSITIVE PARITY LEVELS POPULATED IN THE $^{17}O(^{3}He,p)^{19}F$ REACTION *

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ABSTRACT

Positive parity levels in ^{19}F populated in the $^{17}O(^{3}He,p)$ reaction are studied upto $E_x \sim 7$ MeV. The angular distributions of the levels are studied in terms of the DWBA method of single-step process using two-particle spectroscopic amplitudes derived from (sd) shell model calculations. The difference in shape presented by different levels of the same J^{π}-value is well given by the shell model amplitudes.

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I. INTRODUCTION

The ^{19}F is an odd mass nucleus situated near the beginning of the (sd) shell and some of the early shell model and rotational model calculations[1),2)] in the fifties were carried out on the level spectrum of ^{19}F. Information then available was rather meagre and ^{19}F has since been the subject of a number of experimental and theoretical investigations with vastly improved techniques and properties of most of the low lying levels are now known, as summarized by Azenberg-Selove [3)]. The present work on the $^{17}O(^{3}He,p)^{19}F$ reaction is a part of the $(^{3}He,p)$ reactions initiated at Oxford on the oxygen-isotopes and given here are the results on the positive parity levels in ^{19}F.

At energies well above the Coulomb barrier, the $(^{3}He,p)$ reaction is expected to proceed mostly through a single step process in populating the levels with a dominant $(sd)^3$ configuration outside the ^{16}O core. As the target nucleus is of spin $5/2^+$ and since the reaction can transfer both spin singlet and spin triplet np pair, several sets of (LJ) transfers will be involved. A study of the $(^{3}He,p)$ reaction should offer a test of the details of the wave functions and give considerable information on the structure of the levels concerned. However, compared to the varieties of particle transfer reactions and several capture reactions leading to ^{19}F, information from $^{17}O(^{3}He,p)^{19}F$ reaction is rather meagre. The only previous $(^{3}He,p)$ reaction is due to Bishop et al. [4)] covering an excitation energy of ~ 5.6 MeV. An (α,d) reaction on ^{17}O was concerned with the first two $7/2^+$ and two $11/2^+$ levels [5)]. There are several levels of either parity including those immediately above $E_x \sim 5.6$ MeV that are of special interest to the $(^{3}He,p)$ reaction because of selective population of these levels in different reactions, namely $^{16}O(\alpha,p)$, $^{18}O(^{3}He,d)$, $^{20}Ne(t,\alpha)$, $^{20}Ne(d,^{3}He)$, $^{16}O(^{6}Li,^{3}He)$, $^{16}O(^{7}Li,\alpha)$ [Refs.6-13] as discussed in Sec.III. The present work was therefore undertaken and levels upto $E_x \sim 7$ MeV are studied and measurements of angular distributions over a narrow range by Bishop et al. [4)] for some of the levels have been carried over to larger angles.

II. DWBA ANALYSIS

The local zero range DWBA analyses were carried out using the code DWUCK4 due to Kunz. The optical model potential was of the standard Woods-Saxon form for ^{3}He particles and the real part of the deuteron, while a

Woods-Saxon derivative was employed for the imaginary part of the deuteron potential. A real spin-orbit term of the usual Woods-Saxon derivative form was added to both the ^{3}He and d-potentials. Several sets of potential parameters were used as shown in Table I.

The potential parameter H1 is the average of two ^{3}He potentials used by Hiebert et al. [14] in the study of the reaction $^{16}O(d,{}^3He)^{15}N$ and later used by Mangelson et al. [15] and Sen Gupta et al. [16] in the analyses of the $^{16}O({}^3He,p)$ reaction at 18-20 MeV. The parameter set H2 is the average of two sets given by the elastic scattering of 17 MeV ^{3}He particles from ^{16}O (Mangelson et al. [15]). The set H3 is from Polsky et al. [17] used for the ^{3}He-^{16,17}O scattering at 15 MeV. The set H4 is from Fortune et al. [18] and the last set H5 is from Kattenborn et al. [19] as given by the elastic scattering of 18-20 MeV ^{3}He particles from several light nuclei.

The proton potential P1 is the standard Perey potential [20], while the set P2 has its geometrical parameters arbitrarily reduced by ~10% to fit some of the levels in the $^{16}O({}^3He,p)$ reactions [15]. The parameter set P3 is from Watson et al. [21] as given by the elastic scattering of 10-50 MeV protons from different light nuclei and the set P4 is from Perey [20]. The main characteristics of the last two sets is that they contain a spin-orbit term, which the first two sets do not.

There is no unique choice for the bound state wave functions, less so in a two-nucleon transfer reaction [22]. The wave function for each of the transferred nucleons was calculated by assuming a (real) Woods-Saxon potential well with geometrical parameters specified by r_0 = 1.25 fm and a = 0.65 fm including a Thomas-Fermi spin-orbit term of strength λ = 25. The well depths are adjusted by the programme so as to reproduce the appropriate separation energy given as follows for each of the transferred particles

$$\frac{1}{2}\,(E_B(\text{final}) - E_B(\text{initial}) - E_x)\ \text{MeV, for singlet spin}$$

and

$$\frac{1}{2}\,(E_B(\text{final}) - E_B(\text{initial}) - E_x - 2.23)\ \text{MeV for triplet spin.}$$

The DWBA programme requires as input the two-particle spectroscopic amplitudes for calculating the cross sections. These were obtained from the three single particle energies and sixty three two-body matrix elements given by the shell model calculations of Halbert et al. [23] In the notation of Halbert et al. these are labelled as K + SPE, KB + SPE, K + 12FP, RIP and MSDI, defining the different Hamiltonians used; they differ from one another in the number of free parameters and the details of the fitting procedure. The shell model assumes an inert ^{16}O-core with the extra-core nucleon (nucleous) in $^{19}F({}^{17}O)$ distributed in the unrestricted $1d_{5/2}$- 2s - $1d_{3/2}$ model space. The shell model programme of Rochester- Oak Ridge (MULTISHELL) was new followed by the programme TENSOR to obtain the two-particle spectroscopic amplitudes for the $^{17}O({}^3He,p)^{19}F$ reaction.*

III. RESULTS AND DISCUSSION

To begin with a detailed DWBA analysis was carried out for the levels E_x = 0.0, 0.193 and 4.647 MeV, with respective $J^{\pi} = 1/2^+, 5/2^+$ and $13/2^+$. Consistently better fits to the measured angular distributions were obtained by the parameter sets containing a spin-orbit potential in both the entrance and exit channels, in particular the combinations H4P3 and H5P4. These combinations were also used by Crozier and Fortune [24] in the analysis of the $^{18}O({}^3He,p)^{20}F$ reaction. It also turned out that the DWBA angular distribution shapes were vastly independent of the spectroscopic amplitudes given by the different Hamiltonians, as illustrated in fig.1, but the magnitude was.

As well as depending on the structure of the stipping interaction, the absolute magnitude of the predicted cross section depends on the internal ^{3}He wave function, the optical model parameters and the details of the bound state wave function (like geometrical parameters, spin-orbit term, prescription on separation energy, etc.). Some of these are reflected in the normalization constant N used for a comparison of the DWBA cross section to experiment, namely through the relation [22] with obvious notations

$$\sigma_{Exp}(\Theta) = N\left(\frac{2J_f+1}{2J_i+1}\right)\sum_{LJST} b^2_{ST}\left|D_{ST}\right|^2 (T_i T_{iz} T\alpha | T_f T_{fz})^2 \frac{\sigma_{DW}(\Theta)}{2J+1}$$

* These are not shown, but may be obtained from the author.

The (LJST) refer is the transferred particles and $(T_i T_{iz} T \otimes T_f T_{fz})$ is an iso-spin Clebsch-Gordan coefficient. The quantity b^2_{ST} is essentially a spectroscopic factor for light particles, being 1/2 for both spin states and $|D_{ST}|^2$ is the weighting factor, which following Nann et al.[22] were taken as 0.72 and 0.30 respectively for S=0 and S=1 transfers.

As discussed above, unlike one-nucleon transfer reactions, the absolute value of N is not correctly given by the DWBA method for two-nucleon transfer reactions. It is expected that the relative value of N should nonetheless be fairly independent of the transition, provided of course the nuclear structure information has been properly included in the DWBA calculations. Results on the relative values of N for the three levels mentioned above, namely E_x = 0.0, 0.193 and 4.647 MeV, are summarized in Table 2 for the potential parameters H4P3 and H5P4. They agree with one another to within a factor of about 2. As for the potential parameters, the overall fit is somewhat better for the combination H4P3, but the forward angle data in some cases are better given by the other set H5P4. The remaining angular distributions are therefore analyzed with these two parameter sets using the spectroscopic amplitudes derived from the Hamiltonians labelled K + 12FP (level spectrum of ^{19}F is somewhat better described by this than the others).

The levels most strongly populated in the ^{17}O(^{3}He,p) reaction include all known positive parity levels in ^{19}F with dominant $(sd)^3$ character lying upto $E_x \sim 7$ MeV. The DWBA results are compared to the measured angular distributions for these levels in figs. 1-5. Fits in most cases are satisfactory.

Selection rules from a pure (sd) basis allow, except for the $13/2^+$ level, more than one L-transfers in populating the levels. Dominant L-values are shown underlined in Table 3, including cases where both the L's have comparable contributions; also included in the table for a comparison are the L-transfers given by the previous (^{3}He,p) reaction upto $E_x \sim 5.6$ MeV [4]. The shell model amplitudes correctly give the dominance of L=2 transition for the $5/2^+_2$ level and comparable contributions from both L=0 and L=2 for the $5/2^+_1$ and $5/2^+_3$ levels (fig.2); further discussions on the $5/2^+_3$ level

will follow. The angular distributions for the two $7/2^+$ levels (E_x=4.378 and 5.465 MeV) have been measured covering larger angles than in ref. 4) and the difference in shape between them is again given by the calculations (fig.3). Similarly the angular distributions leading to the two $9/2^+$ levels are reasonably well reproduced as dominant L=2 and L=4 respectively for the 2.777 and 6.592 MeV levels (fig.4).

As well as being described within the framework of the $(sd)^3$ shell model, the positive parity levels in ^{19}F have often been accounted for by the rotational model including mixing between the $K^{\pi}=1/2^+$ and $3/2^+$ bands. There have been several discussions on the level spectra and possible classification on the band structure of ^{19}F(refs. 25)-30) and many others). We only make a passing remark on the matter with relevance to the (^{3}He,p) reaction.

The identification of the levels at E_x=0.0, 1.559, 0.193, 5.465, 2.777 and 4.647 MeV, with respective $J^{\pi} = 1/2^+, 3/2^+, 5/2^+, 7/2^+, 9/2^+$ and $13/2^+$, as members of the $K^{\pi}=1/2^+$ g.s. rotational band is probably firmly established anf they are characterized by their dominant $(sd)^3$ configuration. Characteristic γ-decay (large in-band E2 transition) and relatively strong excitation of the levels in various reaction (^{16}O(α,p), ^{17}O(^{3}He,p), ^{16}O(^{6}Li,^{3}He), ^{16}O(^{7}Li,α), ^{18}O(^{3}He,d)) are the basis of this identification. There are of course understandable exceptions. The low-lying $7/2^+$, $9/2^+$ and $13/2^+$ levels should not be accessible to a single-step ^{18}O(^{3}He,d)stripping reaction[8),9)], hence must be weak. Similarly, an almost non-observation of the low-spin states in the ^{16}O(α,p) reaction [7)] is a consequence of momentum mismatch. The $11/2^+$ member poses difficulty. The lowest known $11/2^+$ level at 6.50 MeV [3)] is not populated in the present work, nor in any three-nucleon stripping reaction on ^{16}O (the weak excitation in ^{16}O(α,p) reaction at 20 MeV [6)] is probably through a non-single step process, compound nuclear mechanism for example at such a low energy [7)]) and is not to be identified with the g.s. band. This is further evidenced by theoretical calculation[29),31)] which predict a poor overlap of this level with the band. Neither should

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* The J^{π}_i indicates the i th shell model state of this spin

the other $11/2^+$ level E_x = 7.937 MeV observed in the $^{17}O(\alpha,d)^{19}F$ reaction[12] be identified as a member of the g.s. band. There is in fact more than one candidate above $E_x \sim 9$ MeV for this [30].

The other positive parity $K^{\pi}=3/2^+$ band with 3.901 MeV as the band head does not appear to be well defined. Based mainly on the linearity of excitation energy against J(J + 1) and small value of moment of inertia parameter ($\hbar^2/2\mathcal{J}$) similar to the g.s. rotational band of ^{21}Ne and ^{23}Na, the levels E_x = 3.901, 4.555, 5.465, 6.592 and 7.937 MeV, with respective $J^{\pi}=3/2^+$, $5/2^+$, $7/2^+$, $9/2^+$ and $11/2^+$, have been proposed as members of this rotational band [26]. That 3.901 and 4.555 MeV levels are not of $(sd)^3$ character is well established from varieties of particle transfer reactions and characteristic γ - decay. The 3.901 MeV level is not given by any (sd) shell model calculation, but can be built upon the basis ^{12}C-core plus particles outside (refs.[31],[33], for example). On the other hand, the 5.465 MeV level is of dominant $(sd)^3$ character and is a member of the g.s. band [27], while the 6.592 MeV level with characteristic γ-decay appears at the right energy predicted for the $9/2^+$ shell model state [29]. Their angular distributions have already been presented (figs. 3 and 4).

We end with a discussion on other positive parity levels populated in the (^{3}He,p) reaction but not hitherto mentioned.

Below E ~7 MeV, the 5.337, 5.939 and 6.252 MeV are the known $1/2^+$ levels other than the g.s. (ref. 3)), the first two of which are weakly populated in the present work as also in the $^{18}O(^3He,d)$ reaction [8],[9]. They should not therefore be associated with the $(sd)^3$ shell model state. This is in keeping with the γ-decay properties of these levels and the shell model calculation [29] finds it extremely difficult to assign either of these to the $1/2^+$ level. The third level is described as the $1/2^+_3$ level [29] and is also fairly strongly excited in the $^{18}O(^3He,d)$ reaction [8],[9]. It is not clear whether or not the level is excited in the present work, since it will not be resolved from the neighbouring level at E_x = 6.277 MeV ($J^{\pi}=5/2^+$). The excitation energy of the group is found to be consistently closer to the known $5/2^+$ level at 6.282 MeV [3]. The angular distribution is of little help, since it is found to have comparable contributions from L=0 and 2

transfers (fig.2) and the latter L-value is compatible for the $5/2^+$ - $1/2^+$ transition also.

The known $3/2^+$ levels upto $E_x \sim 7$ MeV other than the 1.559 and 3.901 MeV levels already mentioned are 5.50, 6.498 and 6.526 MeV [3]. Only the 5.50 MeV level is populated in the (^{3}He,p) reaction but it is so weak that no reliable measurement of angular distributions is possible.

All the known $5/2^+$ levels upto $E_x \sim 7$ MeV are populated in the (^{3}He,p) reaction. The ones not already mentioned are the 5.542 and 6.836 MeV levels. They are weakly excited, as also in (^{7}Li,α) reaction. The measured angular distributions could be rasonably well fitted with L=2+4 transfers assuming pure configuration.

Other than the two levels mentioned earlier the known $7/2^+$ levels upto $E_x \sim 7$ MeV are 6.070, 6.330 and 6.554 MeV. The first of these were not resolved from the 6.090 MeV level, while the 6.33 MeV level was unfortunately under contaminant at most of the forward angles. Angular distribution could be measured over the lab angles 48.75° - 86.25° so that no meaningful comparison with DWBA is possible. It is fairly strongly populated in the (^{3}He,p) reaction and one or the other of 6.07 and 6.33 MeV levels may be a candidate for the $(sd)^3$ $7/2^+_3$ shell model state predicted to be at about this energy.

IV. CONCLUSION

The (^{3}He,p) reaction is known to selectively populate levels with dominant two-nucleon correlations and in the present context it is the $(sd)^3$ shell model levels that are preferentially excited over other positive parity levels that may appear through core excitation. Thus in conjunction with three-nucleon stripping reactions on ^{16}O and characteristic γ -decays the (^{3}He,p) reaction helps in identifying such types of levels. Properties are presented for some levels not studied in the previous (^{3}He,p) reaction. The DWBA method using two-nucleon spectroscopic amplitudes from $(sd)^3$ shell model calculations successfully give the difference in angular distribution shapes displayed by levels of same J^{π} values; one has of course to be careful in choosing the right optical model parameters so that a meaningful comparison with experiment is possible. But unlike one-nucleon transfer reactions, the normalization constant is not probably properly given; it is found to a vary over a factor of about 2.

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TABLE 1

Optical model parameters (depths in MeV and lengths in fm)

Particle		V	r_0	a	W	$4W_D$	r_I	a_I	V_s	r_s	a_s	r_C	Ref.
^{3}He	H1	180	1.08	0.784	15.6		2.12	0.468				1.40	15)
	H2	220	1.11	0.653	7.1		2.11	0.815				1.40	15)
	H3	156	1.05	0.829	6.0		2.40	0.592				1.40	17)
	H4	177	1.138	0.724	18.0		1.602	0.769	5.0	1.138	0.724	1.40	18)
	H5	130	1.31	0.724	18.0		1.602	0.769	5.0	1.31	0.724	1.40	19)
p	P1	42.5	1.25	0.65		33.6	1.25	0.47				1.25	15)
	P2	42.6	1.11	0.58		33.6	1.11	0.42				1.11	15)
	P3	V'	r'	0.57		4W'	r'	0.50	5.5	r'	0.57	r'	21)
	P4	V''	1.25	0.65		54	1.25	0.47	7.5	1.25	0.65	1.25	20)
n,p bound state		a)	1.25	0.65					λ =25			1.25	

a) Adjusted

$V' = 60.0 - 0.3E + 0.4(Z/A^{1/3}) + 27(N - Z)/A$

$r' = 1.15 - 0.001\ E$

$W' = 9.6 + 10(N - Z)/A - 0.06\ E$

$V'' = 53.3 - 0.55\ E + 0.4\ (Z/A^{1/3}) + 27(N - Z)/A$

TABLE 2

The normalization constant N (relative values)

E_x(MeV)	Potential	K+12FP	KB+SPE	K+SPE	RIP	MSDI
0.0	H4P3	160	130	150	120	160
0.193	H4P3	250	255	240	320	190
4.647	H4P3	100	100	90	100	100
0.0	H5P4	150	130	150	120	150
0.193	H5P4	240	240	220	280	190
4.647	H5P4	140	140	120	150	140

TABLE 3

L - transfer for levels with dominant $(sd)^3$ character

E_x(MeV)	J^π	L - transfers*	
		a)	b)
0.0	$1/2^+$	$\underline{2}$	$\underline{2}$(+4)
0.193	$5/2^+$	$\underline{0}+\underline{2}$	$\underline{0}$
1.559	$3/2^+$	$\underline{0}+2$	$\underline{0}$
2.777	$9/2^+$	$\underline{2}$	$\underline{2}$
4.378	$7/2^+$	$\underline{0}+\underline{2}$	$\underline{0}+2$
4.647	$13/2^+$	$\underline{4}$	$\underline{4}$
5.100	$5/2^+$	$0+\underline{2}$	$0+\underline{2}$
5.465	$7/2^+$	$\underline{2}$	$\underline{2}$
6.277	$5/2^+$	$\underline{0}+\underline{2}$	
6.592	$9/2^+$	$\underline{4}$	

* Dominant L-transfer is underlined

a) Present work

b) Bishop et al. [4)]

FIGURE CAPTIONS

Fig. 1 DWBA fit to the g.s. and 4.647 MeV levels. Solid line and broken line in this and the following figures are respectively for the parameter sets H4P3 and H5P4

Fig. 2 DWBA fit to the $5/2^+$ levels

Fig. 3 DWBA fit to the $7/2^+$ levels

Fig. 4 DWBA fit to the $9/2^+$ levels

Fig. 5 DWBA fit to the $3/2^+$ levels

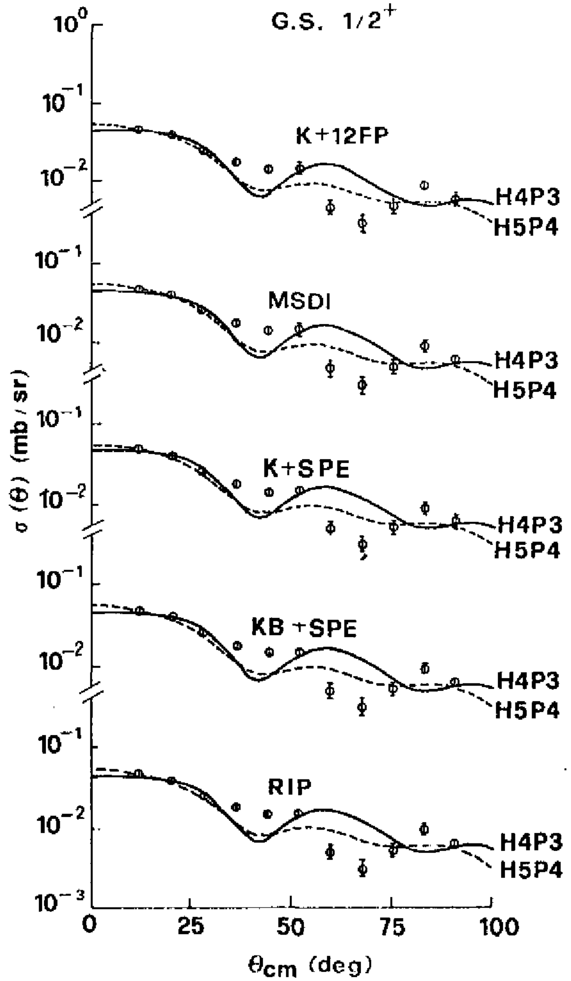
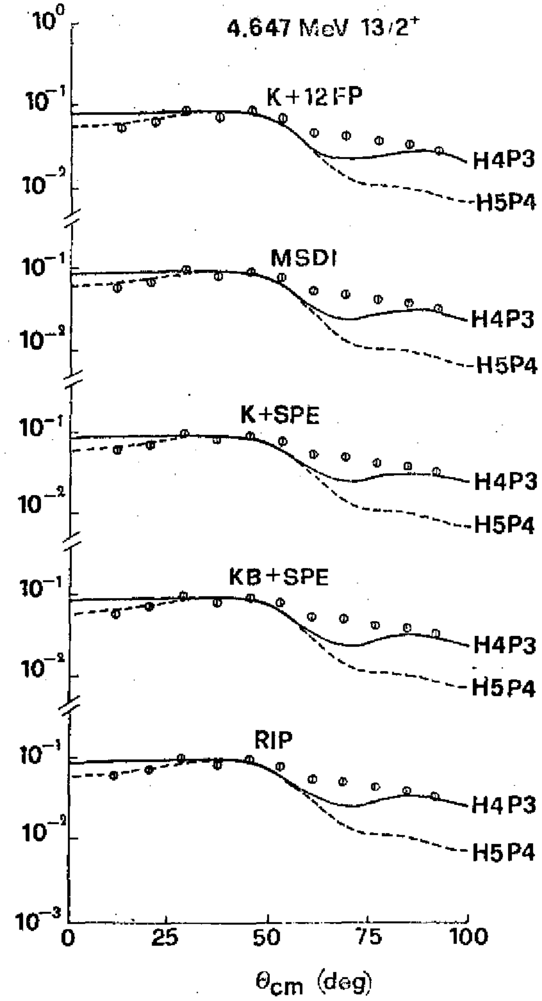
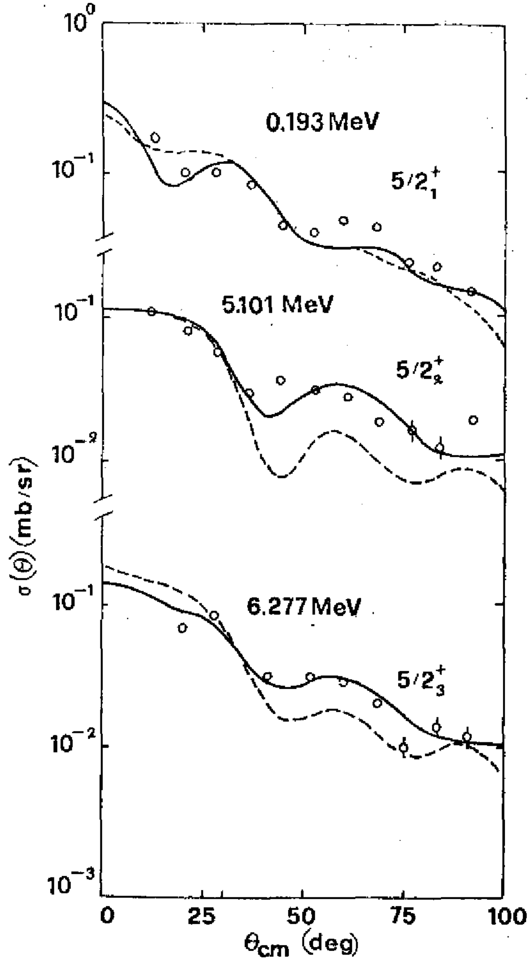


Fig. 1a



4.647 MeV 13/2+
K+12FP
MSDI
K+SPE
KB+SPE
RIP
H4P3
H5P4
θcm (deg)

Fig.1b



0.193 MeV
5/2+1
5.101 MeV
5/2+2
6.277 MeV
5/2+3
σ(θ)(mb/sr)
θcm (deg)

Fig.2

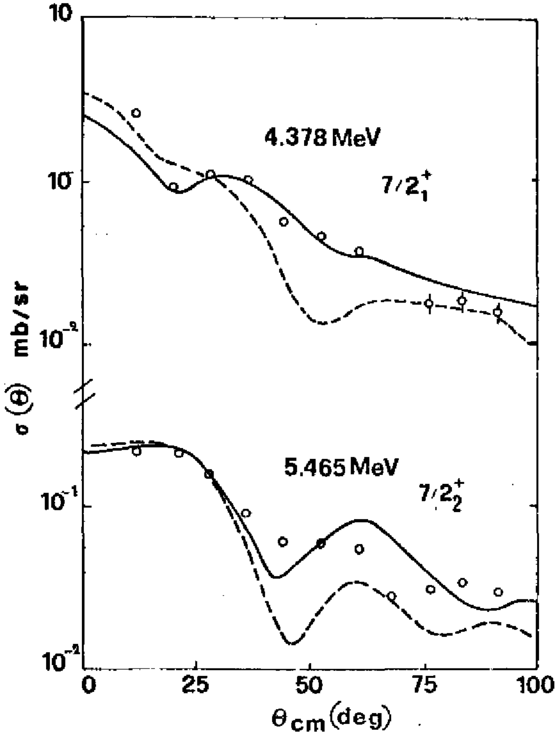

10
10
10^{-2}
$\sigma(\theta)$ mb/sr
4.378 MeV
$7/2_1^+$
5.465 MeV
$7/2_2^+$
10^{-1}
10^{-2}
0
25
50
75
100
θ_{cm}(deg)

Fig.3

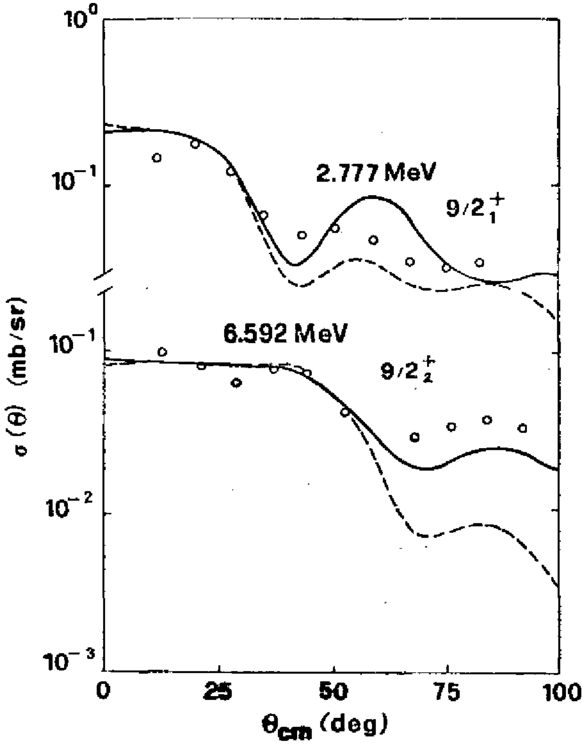

10^0
10^{-1}
2.777 MeV
$9/2_1^+$
10^{-1}
6.592 MeV
$9/2_2^+$
$\sigma(\theta)$ (mb/sr)
10^{-2}
10^{-3}
0
25
50
75
100
θ_{cm} (deg)

Fig.4

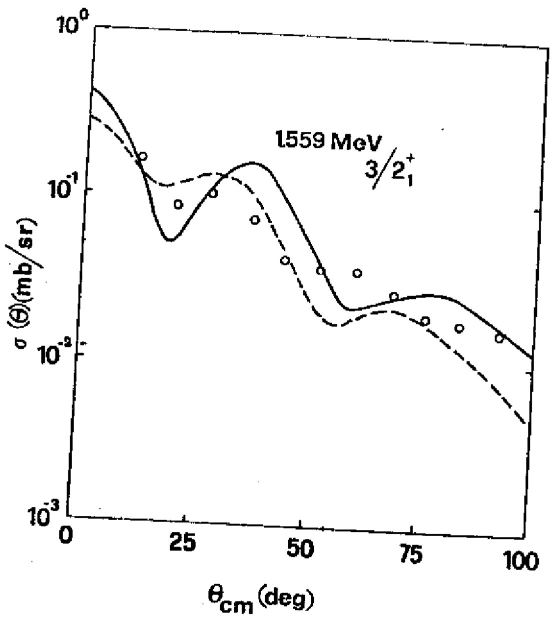


Fig.5