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MEASUREMENT OF (p, p) AND (p, α) CROSS SECTIONS FOR LITHIUM AND FLUORINE*

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Simultaneous measurements have been made of the differential cross sections (E_p = 1.36 MeV, θ_L = 90°) for the ^{6}Li(p,p)^{6}Li, ^{7}Li(p,p)^{7}Li, ^{19}F(p,p)^{19}F, ^{6}Li(p,α)^{3}He, ^{7}Li(p,α)^{4}He and ^{19}F(p,α_0)^{16}O reactions using LiF targets. The measurements provide a consistent set of cross sections for calibration purposes. The results are generally in agreement with previous cross section determinations except for the case of the ^{19}F(p,α_0)^{16}O reaction which is discussed in detail.

1. Introduction

Although measurements of absolute cross sections of nuclear reactions involve relatively simple apparatus and trivial calculations, actual experiments involve the determination of many elusive quantities. A precision of better than 10% for an absolute cross section is generally difficult to attain. As an example, published results for the ^{19}F(p, α_0)^{16}O total cross section at the resonant proton energy of 1.36 MeV are given in table 1. Obviously, the quoted errors do not give a true picture of the imprecision in the various experiments. Similar discrepancies in the published absolute cross sections for the ^{6}Li(p, p)^{6}Li, ^{7}Li(p, α)^{4}He and ^{6}Li (p, α) ^{3}He reactions emphasize the need for new measurements of these cross sections. An accurate simultaneous determination of all of these cross sections by using LiF targets would provide standards for relative cross section measurements and would resolve problems caused by reliance on previous ambiguous values. Internal consistency in the results can be checked by comparison with the precise ^{7}Li(p, p)^{7}Li data[7-9].

TABLE 1
Cross section for the ^{19}F(p,α_0)^{16}O reaction at E_p = 1.36 MeV, θ_L = 90°.

σ(mb)	dσ/dΩ (mb/sr)	ref.
3.1	0.25	1,2)
46 ±5	2.14±0.30	3)
	2.71±0.27	4)
40 ±4	1.8 ± 0.2	5)
81	1.8	6)

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The experiment reported here consists of: 1. The simultaneous determination of the ^{7}Li(p, p)^{7}Li, ^{19}F(p, p)^{19}F, ^{7}Li(p, α)^{4}He and ^{19}F(p, α_0)O^{16} cross sections using a natural LiF target; 2. The simultaneous determination of the ^{6}Li (p, p) ^{6}Li, ^{19}F (p, p) ^{19}F, ^{6}Li(p, α)^{3}He and ^{19}F(p, α_0)^{16}O cross sections using an isotopically enriched LiF target (95% ^{6}Li).

2. Apparatus and procedure

2.1. General

Data were taken using the 3 MV Van de Graaff accelerator at the University of Maryland Nuclear Research Laboratory. The proton beam from the accelerator was analyzed by a 90° deflecting magnet and regulated to an energy spread of less than 1 keV.

The beam was focussed by a quadrupole magnet to a spot about 2 mm in diameter on a LiF target in a scattering chamber. A Faraday cup and current integrator monitored the proton beam.

In order to facilitate the comparison of the cross section for the ^{19}F(p, α_0)^{16}O reaction with previous results, an energy of 1.36 MeV and an observation angle of 90° were chosen. All of the other cross sections were then measured under the same conditions of bombardment and detection.

Particles emitted at 90° to the beam were detected by a surface barrier detector, the pulses from which were amplified by conventional electronics and fed into a multichannel analyzer.

In a second part of the experiment, particles emitted at 90° to the beam entered a double-focussing 180° magnetic spectrometer through an ⅛″ aperture about 3″ from the target. The exit slits of the spectrometer were opened to ¾″ to allow total peak collection by a surface barrier detector. The magnetic field was monitored by a Hall probe. Pulses from the detector were analyzed in the same way as when the scattering chamber was used.

2.2. Targets

Thin carbon foils were prepared by first coating microscope slides with barium chloride in an evaporator and then placing them about 20 cm above two carbon rods. An arc was struck several times for 2 – 3 sec intervals until a layer of carbon appeared on the slides. The extremely soluble barium chloride made it easy to float the carbon films onto small target holders. A carbon foil and a tantalum disc were then placed in the evaporator about 30 cm from the filament. Each target was mounted on an aluminium slab and masked with a $\frac{1}{2}''$ hole. A piece of thin aluminum foil was weighed on an electro-balance and then placed over a $\frac{3}{4}''$ hole on the slab in close proximity to the foil and disc. The Al foil weighed about 0.3 mg/cm^2. Natural lithium fluoride was evaporated for the LiF runs and lithium fluoride enriched to 95% ^{6}Li was evaporated for the ^{6}LiF runs. The targets weighed from 0.03 to 0.1 mg/cm^2.

Target thicknesses were also determined by placing each target at $45 \pm 1°$ to the proton beam and scanning the ^{19}F(p, $\alpha\gamma$)^{16}O resonance at 872.5 keV. A NaI crystal was used to detect the γ rays. The resonance has a known width of 4.7 ± 0.2 keV[10]) from which the target thickness can be obtained using previous values for the stopping cross section of LiF for 872 keV protons[8,11-12]). Targets were typically 6-25 keV thick for 872 keV protons.

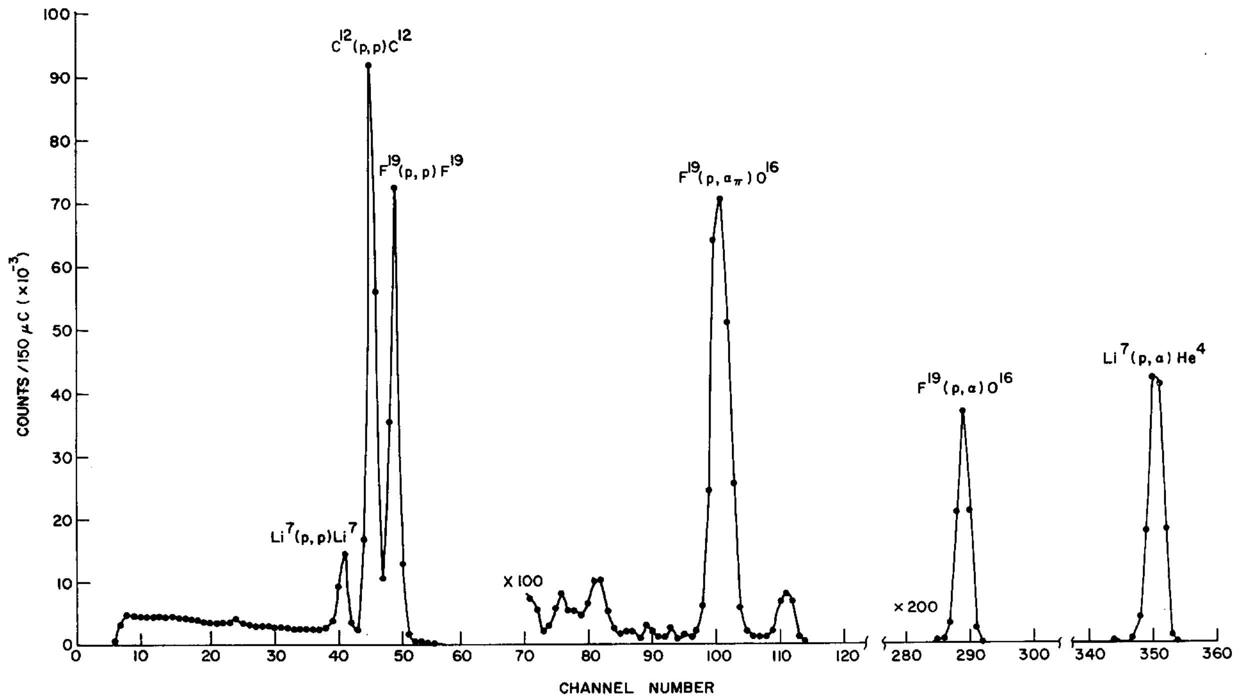
Target deterioration was checked by making a series of measurements of the yield from the ^{19}F (p, α_0)^{16}O reaction at E_p = 1.36 MeV. The yield decreased by about 10% during a 4-h period. Beam intensity was 0.3 μA and the target was 10 keV thick for 872 keV protons. A typical run in the scattering chamber was 2 h at 0.06 – 0.2 μA so that target deterioration effects were judged to be less than 2%.

2.3. Current integration

The current integrator was calibrated by using a 1.355 V mercury battery and various precision resistor chains. The possibility of leakage current or spurious current readings was investigated by alternating accumulating charge with and without the target. There was no discernible difference.

2.4. Solid angles

The solid angles for both parts of the experiment was measured directly from the geometry. For most of the scattering chamber measurements an aperture of diameter $0.0995 \pm 0.0010''$ was placed in front of the



Fig, 1. Spectrum for LiF+p reaction at E_p = 1.36 MeV and θ_L = 90°, measured in the scattering chamber.

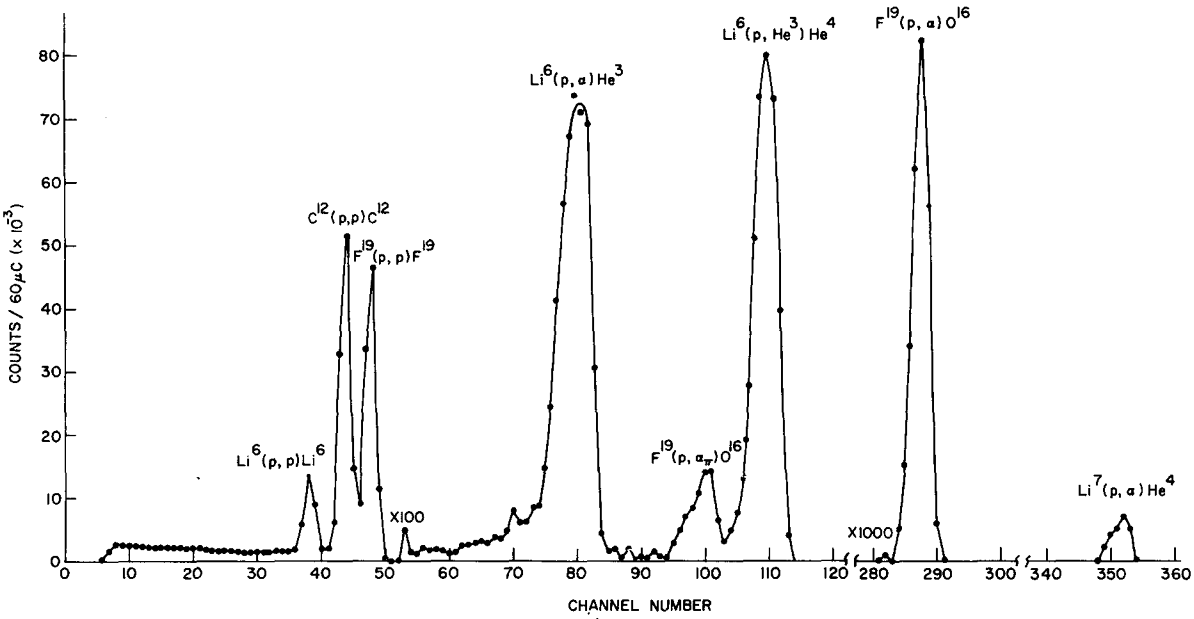


Fig. 2. Spectrum for ^{6}LiF+p reaction at E_p = 1.36 MeV and θ_L = 90°, measured in the scattering chamber.

detector at 4.16±0.05″ from the target:

$$\Omega_{\mathrm{Lab}} = (4.93 \pm 0.11) \times 10^{-4} \text{ sr}.$$

For the spectrometer experiment the aperture was 0.125±0.001″ in diameter and was placed 2.94±0.03″ from the target:

$$\Omega_{\mathrm{Lab}} = (1.43 \pm 0.04) \times 10^{-3} \text{ sr}.$$

A 90 μg/cm^2 copper target (thickness determined by weighing) was evaporated onto a carbon foil and the solid angles were confirmed to within 10% by measuring the yield of elastically scattered protons and comparing with the Rutherford formula.

2.5. Particle spectra

After locating the peak of the 1.36 MeV resonance in the ^{19}F(p, α_0)^{16}O reaction, particle spectra were measured. Typical results obtained in the scattering chamber for LiF and ^{6}LiF targets are shown in figs. 1 and 2.

A momentum profile obtained with the magnetic spectrometer for the two α particle groups from a typical tantalum-backed LiF target is shown in fig. 3. Similar flat-topped profiles, indicating total peak collection, were not obtained for the groups from the ^{6}Li(p, α)^{3}He reaction. Therefore, the cross section results for this reaction using the spectrometer are considerably less reliable and are not reported. Only one measurement of elastic scattering was attempted with the spectrometer because target deterioration problems required lengthy runs at low beam currents.

3. Results

3.1. Calculations

Cross sections were determined using the relation

$$\mathrm{d}\sigma/\mathrm{d}\Omega = \{(\text{Yield/C})/(\text{no. protons/C})\} \cdot (N\Omega n f)^{-1}, \quad (1)$$

where N is the number of target atoms per cm^2, Ω is the detector solid angle, n is the number of identical particles emitted per reaction, and f is the fractional abundance of the desired isotope. The determination of the number of target atoms/cm^2 was accomplished by weighing and by using the observed width of the ^{19}F(p, αγ)^{16}O resonance. For the latter determination, a stopping cross section of

$$\varepsilon = (9.6 \pm 0.4) \times 10^{-8} \text{ keV} \cdot \text{cm}^2/\text{molecule}[8,11,12]),$$

was used.

3.2. Errors

Statistical errors and errors introduced by background subtraction and peak unfolding were generally a few percent but reached about 10% for some weak groups.

Target thicknesses were obtained by averaging values from weighing and from resonance width measurements. The latter were weighted three times the former in the averaging. The net uncertainties, including the

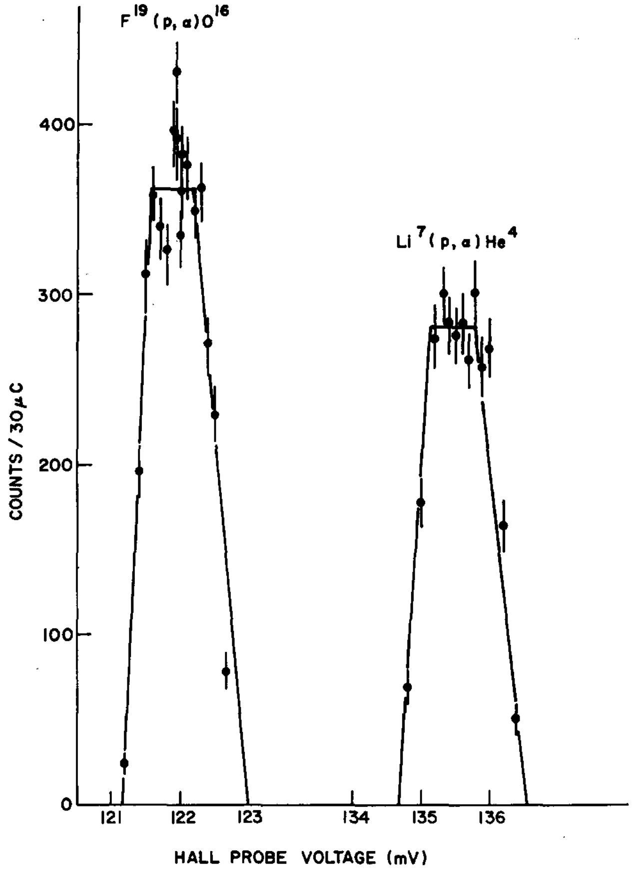


Fig. 3. Spectrometer profile for LiF+p reaction at $E_p = 1.36$ MeV and $\theta_L = 90°$.

uncertainty in the stopping cross section for LiF, were about 8%.

The errors in current integrator calibration and in solid angle measurements were both about 2%.

An uncertainty of about 2% is introduced because of errors in setting the bombarding energy exactly on the resonance peak.

3.3. Cross sections

The cross sections obtained according to the method described are shown in table 2. Values are given for runs with particular targets; the uncertainties listed for these values are statistical only. The uncertainties given for the weighted-mean cross sections include statistical as well as systematic errors.

4. Previous work

Unless otherwise specified all cross sections are at $E_p = 1.36$ MeV and all differential cross sections are at $\theta_L = 90°$.

4.1. $^6Li(p, p)^6Li$

There appears to be no data available at $\theta_L = 90°$ ($\theta_{cm} = 99.65°$) although McCray[13]) has made measurements at $\theta_{cm} = 90.7$ and 126°. An extrapolation of McCray's data gives a value of about 64 ± 10 mb/sr at $\theta_L = 90°$. A comparison with the data of Bashkin and Richards[14]) at $\theta_L = 164°$ indicates that their data is about $\frac{1}{3}$ lower, or about 42 ± 10 mb/sr. Fasoli et al.[15]) obtained values about 17% higher than those of McCray; this corresponds to about 75 ± 12 mb/sr. The present value (61 ± 9 mb/sr) confirms McCray's intermediate result.

4.2. $^7Li(p, p)^7Li$

Many differential cross section measurements are available for the $^7Li(p, p)^7Li$ reaction. Malmberg[7]) measured 40 ± 4 mb/sr and Warters[8]) obtained 40 ± 2 mb/sr; Liberman[9]) made the most recent determination of 37 mb/sr. No uncertainty is given for the last measurement but it must be at least 4% because of the uncertainty in the stopping cross section of LiF. Our result (34 ± 4 mb/sr) is slightly smaller than these previous values.

4.3. $^{19}F(p, p)^{19}F$

Webb et al.[16]) measured $(d\sigma/d\Omega)/(d\sigma/d\Omega)_{\mathrm{Rutherford}}$ and obtained 1.08 at $\theta_L = 90°$; this ratio corresponds to 246 ± 15 mb/sr for the differential cross section and is in good agreement with the present result of 233 ± 21 mb/sr.

4.4. $^6Li(p, \alpha)^3He$

Using the angular distribution coefficients obtained by Marion et al.[17]) for the $^6Li(p, \alpha)^3He$ reaction at $E_p = 1.36$ MeV, the differential cross section at $\theta_L = 90°$ from this experiment is 14.8 mb/sr. McCray[13]) obtained a cross section of about 55% of this result, or 8.2 mb/sr. Again, the present result (10.9 ± 1.4 mb/sr) is intermediate.

4.5. $^7Li(p, \alpha)^4He$

Freeman et al.[4]) made measurements similar to those presented here. Thin LiF targets were evaporated and weighed; thicknesses were about 20 $\mu g/cm^2$ or 2–3 keV for 1.5 MeV protons. Simultaneous measurements were made of the α-particle yields from the $^7Li(p, \alpha)^4He$ and $^{19}F(p, \alpha_0)^{16}O$ reactions at $E_p = 1.36$ MeV and $\theta_L = 90°$. The $^{19}F(p, \alpha_0)^{16}O$ cross section was found to be 2.71 ± 0.27 mb/sr. This value was then

TABLE 2

Results of cross section measurements*.

	Target designation	Effective target thickness (keV, 45° to beam)			Cross section (mb/sr), E_p = 1.36 MeV, θ_L = 90°					
						(p, p)			(p, α)	
		Weighing	Resonance	Ave.	^{6}Li	^{7}Li	^{19}F	^{6}Li	^{7}Li	^{19}F
	Scattering chamber									
1.	LiF on C	13.4	15.4	14.9	—	33±3	234±24	—	0.45±0.04	0.99±0.08
2.	^{6}LiF on C	27.7	23.0	24.2	60±8	—	218±27	11.6±1.3	—	0.98±0.11
3.	LiF on C	13.4	15.8	15.2	—	34±3	208±24	—	0.46±0.09	0.99±0.09
4.	^{6}LiF on C	6.8	9.7	9.0	58±17	—	270±90	11.8±1.9	—	1.07±0.17
5.	^{6}LiF on C	8.2	7.3	7.5	66±17	—	211±22	9.7±1.2	—	1.17±0.12
	Spectrometer									
6.	LiF on Ta	12.7	12.4	12.5	—	—	—	—	0.40±0.03	1.02±0.07
7.	LiF on Ta	14.8	16.1	15.8	—	—	—	—	0.35±0.04	0.90±0.09
8.	^{6}LiF on Ta	17.5	19.5	19.0	—	—	— —	—	—	0.91±0.08
9.	^{7}LiF on Ta	14.3	13.3	13.6	—	—	—	—	—	1.02±0.08
10.	LiF on C	—	14.1	14.1	—	36±4	239±30	—	0.46±0.04	1.05±0.15
	Average				61±9	34±4	223±21	10.9±1.4	0.42±0.06	1.02±0.10

* Uncertainties of individual values are statistical only; uncertainties of the average values contain the statistical and systematic errors.

TABLE 3

Differential cross sections (E_p = 1.36 MeV, θ_L = 90°) for the (p, p) and (p, α) reactions on lithium and fluorine.

(p, p)			(p, α)		
^{6}Li	^{7}Li	^{19}F	^{6}Li	^{7}Li	^{19}F
64±10[a]	40±4[b]	246±15[c]	14.8±2.2[d]	1.04±0.12[i]	2.71±0.27[e]
42±10[f]	40±2[g]		8.2±0.5e[a]	0.68±0.17[h]	0.25[l]
75±10[g]	37[j]			0.56±0.04[k]	2.14±0.20[l]
				0.63±0.13[m]	1.8 ±0.2[n]
					0.95±0.10[p]
Present results					
61± 9	34±4	223±21	10.9±1.4	0.42±0.06	1.02±0.10

* Relative error only.
[a] ref. 13, 26
[b] ref. 7
[c] ref. 16
[d] ref. 17
[e] ref. 4, but see section 4.5 and 4.6
[f] ref. 14
[g] ref. 8
[h] ref. 18
[i] ref. 1, 2
[j] ref. 9
[k] ref. 23
[l] ref. 3
[m] ref. 24
[n] ref. 5
[p] ref. 6, corrected according to the prescription given in section 4.6
[q] ref. 15

averaged with a value,* 2.16 ± 0.32 mb/sr, obtained from the results of Clarke and Paul[3]) and the $^7Li(p, \alpha)^4He$ cross section was determined relative to this average; the value obtained was 0.94 ± 0.08 mb/sr. If the cross section is referred only to the measured value of 2.71 ± 0.27 mb/sr, the result is 1.04 ± 0.12 mb/sr. The cross sections of Freeman et al. are therefore about a factor of 2 higher than those of the present experiment, although the ratio of their cross sections, 2.60 ± 0.15, is in good agreement with the present value, 2.35 ± 0.12. The reason for this discrepancy of the factor of 2 is not known, but it should be remarked that the two cross sections reported by Freeman et al. are the highest that appear in the literature (table 3).

Cassagnou et al.[18]) measured the angular distributions and the total cross sections for the $^7Li(p, \alpha)^4He$ reaction over the range of bombarding energies from 1 to 5 MeV and has analyzed similar data from various other experiments[19-22]). Using average values of the angular distribution coefficients given by Cassagnou et al., we find the cross section at $E_p = 1.36$ MeV and $\theta_L = 90°$ to be 0.68 ± 0.17 mb/sr.

Sweeney[23]), using the same technique described above for the spectrometer results, measured the $^7Li(p, \alpha)^4He$ differential cross section at $\theta_L = 90°$ for energies from 1.4 to 1.95 MeV. The value for $E_p = 1.36$ MeV extrapolated from this data is 0.56 ± 0.04 mb/sr.

Wilson[24]), using both the scattering chamber and spectrometer methods, measured the differential cross section at $\theta_L = 120°$ and obtained 0.90 ± 0.08 mb/sr. Using the angular distributions of Cassagnou et al.[18]), Wilson's value corresponds to 0.63 ± 0.13 mb/sr at $\theta_L = 90°$. The present result for the $^7Li(p, \alpha)^4He$ cross section (0.42 ± 0.06 mb/sr) is slightly lower than the previous values but is in fair agreement with the most recent measurements.

4.6. $^{19}F(p, \alpha_0)^{16}O$

Streib et al.[1]) measured the α-particle yields at $\theta_L = 90°$ for the $^{19}F(p, \alpha\gamma)^{16}O$, $^{19}F(p, \alpha\pi)^{16}O$ and $^{19}F(p, \alpha_0)^{16}O$ reactions using TaF_5 targets. No absolute cross sections were given, but using their yield curves Chao[2]) obtained a total cross section of 3.1 mb. Using Streib's assumption of isotropy†, the differential cross section is 0.25 mb/sr.

* Our evaluation of the Clarke and Paul data gives 2.14 ± 0.30 mb/sr for $E_p = 1.36$ MeV and $\theta_L = 90°$; section 4.6.

† A poor assumption [3,6]). However, Streib apparently measured the differential cross section at $\theta_L = 90°$ and then used the assumption of isotropy to obtain a value for the total yield, so that the value 0.25 mb/sr is independent of any assumption about the angular distribution.

Clarke and Paul[3]) irradiated CaF_2 targets evaporated onto copper discs. Target thicknesses were obtained by comparing thin- and thick-target α-particle yield curves at the 1.372 MeV $^{19}F(p, \alpha\gamma)^{16}O$ resonance. The targets used were found to be about 1.7 keV thick for 1 MeV protons. At $E_p = 1.358$ MeV and $\theta_L = 90°$, their values for the differential and total cross sections are 2.14 ± 0.30 mb/sr and 46 ± 5 mb, respectively.

The experiment of Freeman et al.[4]) has been discussed previously; their value for the differential cross section is 2.71 ± 0.27 mb/sr.

Ranken et al.[5]) used CaF_2 targets (24 keV thick for 2 MeV protons) evaporated onto silver discs. Their cross section scale for the $^{19}F(p, \alpha_0)^{16}O$ experiment was obtained by normalizing to the values obtained by Chao et al.[2]) for the $^{19}F(p, \alpha\pi)^{16}O$ resonance at 1.236 MeV. Using their data for $\theta_L = 160°$ and the angular distributions of Clarke and Paul, they obtain a differential cross section of 1.8 mb/sr at $\theta_L = 90°$ and a total cross section of 40 ± 4 mb. However, the data of Clarke and Paul give a value of 7/26 for the ratio of the $^{19}F(p, \alpha_0)^{16}O$ cross section at 1.36 MeV to that at 1.75 MeV ($\theta_L = 90°$). Using Ranken's value for the $^{19}F(p, \alpha_0)^{16}O$ differential cross section at 1.75 MeV and $\theta_L = 90°$, 4.0 mb/sr, this implies that the $^{19}F(p, \alpha_0)^{16}O$ differential cross section at 1.36 MeV is 1.1 mb/sr. This value is in excellent agreement with the present results. One can only conclude that either the angular distributions of Clarke and Paul or the absolute cross section scale of Chao is incorrect.

Isoya et al.[6]) used 8 keV CaF_2 targets to measure angular distributions and total cross sections for the $^{19}F(p, \alpha_0)^{16}O$ reaction. Target thicknesses were determined by weighing the material before evaporation and assuming an isotropic or cosine distribution of evolved material on the hemisphere. They obtain 1.8 mb/sr and 81 mb for the differential and total cross sections, respectively. The angular distribution is qualitatively in agreement with Clarke and Paul but has a much sharper minimum at $\theta_L = 90°$. If one uses the angular distribution of Isoya et al. and normalizes the total cross section to 43 ± 6 mb [the average of refs.[3]) and[5]) which appear to be correct; section 5], the differential cross section at $\theta_L = 90°$ is 0.95 ± 0.10 mb/sr, a value that agrees well with the present result (1.02 ± 0.10 mb/sr).

5. Conclusions

The cross sections of Streib et al.[1]), Clarke and Paul[3]), and Ranken et al.[5]) for the $^{19}F(p, \alpha_0)^{16}O$

reaction are interrelated as described previously. The inconsistency between the results of Ranken et al. and those of Clarke and Paul indicates that the latter's angular distribution may be in error. In fact, the results of Isoya et al.[6]) confirms this and lends credance to the smaller value for the differential cross section. In order to check on this point, we have also measured the angular distribution at $E_p = 1.36$ MeV. The results are in reasonable agreement with those of Isoya et al. and definitely show that the angular distribution of Clarke and Paul does not have a sufficiently deep minimum at 90°. The error in the work of Clarke and Paul may be due to having set the bombarding energy slightly too low since at $E_p = 1.32$ MeV it is known[25]) that the angular distribution is not as anisotropic as at 1.36 MeV.

The cross sections of Isoya et al. are independent of the previous measurements but the method of determining target thickness is open to challenge and the total cross sections are high by about a factor of two. The following set of self-consistent assumptions will resolve all of the ambiguities concerning the $^{19}F(p, \alpha_0)^{16}O$ data:

1. Streib et al., did not intend to measure absolute cross sections and any attempt to extract a value from their data is dangerous. In any event, the value obtained, 0.25 mb/sr, is a factor of four lower than any other measurement;

2. Clarke and Paul's angular distribution for the $^{19}F(p, \alpha_0)^{16}O$ reaction at 1.36 MeV does not have a sufficiently sharp minimum at $\theta_L = 90°$; the angular distributions of Isoya et al. appear to be correct;

3. The absolute cross section data of Freeman et al. and of Isoya et al. are both high by about a factor of 2, possibly due to poor target thickness determinations;

4. The total cross sections of Clarke and Paul and of Ranken et al. are correct.

The present results are compared with previously published data in table 3. Except for the disagreement with Freeman et al. and for the erratic results for the $^{19}F(p, \alpha_0)^{16}O$ cross section, the results of the present experiment are in generally good agreement with all previous data.

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