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Resonant Capture of Protons by Fluorine in the Energy Range 0.5 to 2.2 Mev

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The energy of a proton beam from a pressurized electrostatic generator was measured absolutely by means of an electrostatic analyzer, and used to irradiate thin targets containing fluorine. The γ-ray yield was observed as a function of proton energy and the energies for resonant proton capture were determined to an accuracy of one part in a thousand in most cases. The width of each resonance at half-maximum yield was also measured.

1. INTRODUCTION

THE γ-ray yield from a F^{19} target irradiated by protons has been observed by several workers previously, using nonabsolute methods of beam energy measurement. An absolute determination of the lowest very strong resonance was made by Herb, Snowden, and Sala,[1] using an electrostatic analyzer, and Ajzenberg and Lauritsen[2] have corrected the values obtained by earlier workers, using this determination as a calibration point. Their values were drawn from several sources, and it seemed possible that experimental errors involved were to some extent cumulative when intermediate standards were used. The values also depend on the linearity of the energy measurements.

It was therefore decided to make a survey of the γ-ray yield in the energy range 0.5 to 2.2 Mev by using an absolute electrostatic analyzer. It was also hoped that the high-energy resolution would enable more accurate determinations to be made of the half-width of the resonance, and that the high target currents available would enable a search to be made for previously undetected weak resonances.

2. BEAM ENERGY MEASUREMENT

The energy of the proton beam from a pressurized electrostatic generator[3] was determined by an absolute electrostatic analyzer of deflecting angle 63.2° which has been described in detail elsewhere.[4] The energy resolution of the instrument was one part in 1200, and the uncertainty in the estimation of the mean proton beam energy is estimated to be about $5/10^4$. The linearity of the voltage scale determined by this instrument has been checked by observing the 874.5-kev resonance using mass 1, mass 2, and mass 3 components of the beam. The signals from the exit-slit jaws of the analyzer were used to stabilize the voltage of the electrostatic generator by controlling the magnitude of an electron beam up the accelerator tube.[5]

The electrostatic analyzer was followed by a magnetic deflector of angle 26.8°, which separated out ions of unwanted mass. The distance between the exit-slit jaws of the electrostatic analyzer and the deflecting magnet was equal to the focal length of the magnet so that a parallel horizontal beam was obtained at the exit of the magnet. This beam was used to irradiate the target.

Currents of up to 25 μa were obtained immediately after the electrostatic analyzer, and proton currents of up to 10 μa were recorded on the target after the magnet. These currents proved to be excessive for much of the present experiment and were reduced by the deliberate misalignment of the analyzer and magnetic deflector.

These high target currents (with high-energy resolution) were due in part to the angle of deflection of the analyzer which focused a parallel incident beam in the plane of the exit slits, and in part to the high speed of the machine voltage stabilizing circuits.

3. EXPERIMENTAL PROCEDURE

The targets were evaporated "*in vacuo*" on to carefully cleaned and polished copper backings. Those most used had a thickness in energy units of 1 kev for a 1-Mev incident proton beam. Some determinations were also made by using targets of thickness 2 and 3 kev. The targets were heated to 200°C during irradiation and a liquid nitrogen trap was installed immediately in front of them to prevent the deposition of carbon. By repeated determinations of one of the strongest and narrowest resonances, it was shown that less than 1 kev of carbon had been deposited on the target surface after twenty hours of irradiation.

The γ-rays were detected by means of a Geiger-Müller counter with a lead radiator placed immediately behind the flange supporting the target. The current falling on the target was fed into a beam current integrator[6] which, in conjunction with a standard timer, was arranged to switch off the scaler recording γ-ray counts when a charge of 10 μcoul had fallen on the targets. Over regions of special interest and for weak resonance observations higher target charges were used (Figs. 2 and 3). For most of the irradiations

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[1] Herb, Snowden, and Sala, Phys. Rev. **75**, 246 (1949).

[2] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).

[3] D. R. Chick and D. P. R. Petrie, Proc. Inst. Elec. Engrs. (to be published).

[4] Hunt, Petrie, Firth, and Trott, Proc. Inst. Elec. Engrs. (to be published).

[5] B. Millar and R. Bailey (to be published).

[6] J. L. W. Churchill and W. W. Evans, Electronic Eng. (to be published, 1955).

target currents of between 1 and 5 μa were adequate. Higher currents produced overheating of the target and very high counting rates at the peak of the stronger resonances. The consequent counting losses would have led to errors in the estimation of the half-widths of the resonances.

In general, the beam energy was varied in steps of 2 kev, but in order to estimate the peak and half-widths of narrow resonances, these steps were reduced to 200 ev. Each of the resonances was determined several times, and the determinations quoted are the mean values after correction for target thickness, relativity effects and the small angle of inclination of the incident beam to the normal to the entrance plane of the analyzer. This latter correction was determined by rotating the analyzer through an angle of 180° about a vertical axis and redetermining several of the stronger resonances throughout the energy range.[4]

In order to check that the resonances were due to fluorine they were observed on both calcium fluoride and lithium fluoride targets, and an additional irradiation was made of a clean copper backing. Radiation from the copper backing became detectable at about 1 Mev and increased to 5000 counts/10 μcoul at 2.2 Mev. This background is shown in Fig. 1 and has been subtracted from the resonance curves.

The background of the Geiger-Müller counter due to cosmic radiation and x-radiation from the machine was determined by intercepting the beam some distance from the target. This proved to be negligible compared with the true counting rate for all machine energies up to 2.2 Mev.

4. RESULTS

The resonances observed are shown in Fig. 1. To show the weaker resonances clearly, additional plots have been made on which the vertical scale is divided by the factor indicated, and to accommodate four of the stronger resonances the vertical scale has been multiplied by a factor of two.

The mean resonance determination and half-width measurements are shown in Table I; the values of Ajzenberg and Lauritsen are also shown for comparison. For completeness, three resonances in the lower-energy scale measured at this laboratory using a smaller generator and absolute analyzer are included. Resonances observed at 780.3 kev and 1.607 Mev are shown separately on Fig. 2. The yield in the energy range 1 Mev to 1.35 Mev appeared to be of particular interest and has been shown separately in Fig. 3.

The standard deviations of several determinations of each of the resonances were less than five parts in 10^4 of the mean values, except for the very broad peaks. These variations are produced by random errors, one of which is the uncertainty in determining the peak from an observed resonance curve. This uncertainty is proportional to the half-widths of the resonances and inversely proportional to the yield, and becomes the

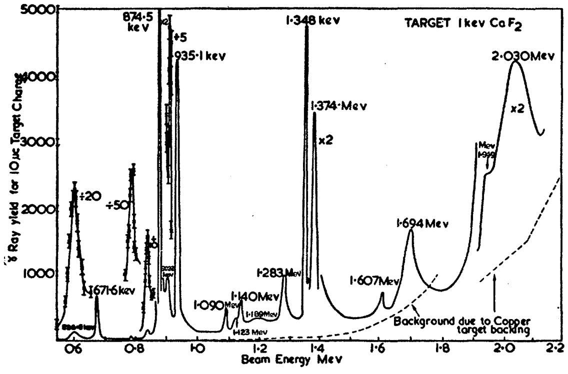

FIG. 1. γ-ray yield curve for the $F^{19}+p$ reaction (10-μcoul target charge).

TABLE I. Resonant energies and half-widths.

Values listed by Ajzenberg and Lauritsen				Values in present work	
Resonant energy kev	Half-width kev	Observer	Method of energy measurement	Resonant energy kev	Half-width kev
224.2	1.0	Hunt and Jones	Absolute electrostatic analyzer		
340.4	2.8	Hunt	Absolute electrostatic analyzer		
483.1	2.2	Hunt	Absolute electrostatic analyzer		
598	37	Bonner and Evans[a]	Magnetic analyzer	596.8 ±1.0	30.0± 3
669	7.5	Bonner and Evans[a]	Magnetic analyzer	671.6 ±0.7	6.0± 0.7
				780.3 ±0.8	7.6± 1.0
831	8.3	Bonner and Evans	Magnetic analyzer	834.8 ±0.9	6.5± 1.0
873.5	5.2	Herb *et al.*	Absolute electrostatic analyzer	874.5 ±0.9	5.4± 0.3
900	4.8	Chao *et al.*	Electrostatic analyzer	902.3 ±0.9	5.1± 1.0
935.3	8.0	Chao *et al.*	Electrostatic analyzer	935.1 ±0.9	8.6± 0.5
1092	<1.2	Bonner and Evans	Magnetic analyzer	1090 ±1.0	0.7± 0.3
				1123 ±2.0	22 ± 5
1137	4.1	Bonner and Evans	Magnetic analyzer	1140 ±1.0	2.5± 5
1176	~130	Bonner and Evans	Magnetic analyzer	1189 ±7.0	110±20
1290	19.2	Chao *et al.*	Electrostatic analyzer	1283 ±1.4	18.6± 1.0
1355	8.6	Chao *et al.*	Electrostatic analyzer	1348 ±1.3	5.6± 0.5
1381	15.0	Chao *et al.*	Electrostatic analyzer	1375 ±1.4	11.0± 1.0
				1607 ±1.6	6.0± 1.0
1690	30.0	Willard *et al.*	Magnetic analyzer	1694 ±1.7	35.0± 3.0
1940	15	Willard *et al.*	Magnetic analyzer	1949 ±2.5	40 ±10
2030	60	Willard *et al.*	Magnetic analyzer	2030 ±3.0	120±20

[a] All values obtained by Bonner and Evans were multiplied by 873.5/862 in order to agree with Herb's absolute determination.

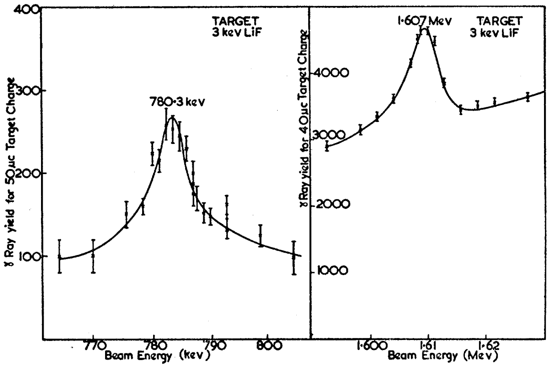

FIG. 2. The 780.3-kev and 1.607-Mev resonances.

main source of error for extremely broad resonances such as that at 1.189 Mev.

The errors quoted in Table I were obtained by adding the standard deviation of the results obtained to the estimated systematic errors in the measurements of the beam energy.[4]

5. DISCUSSION OF RESULTS

On irradiating fluorine with protons, γ rays are produced by three processes, $F^{19}(p,\alpha\gamma)O^{16}$, $F^{19}(p,p'\gamma)F^{19}$ and $F^{19}(p,\gamma)Ne^{20}$. No attempt was made in this work to distinguish between the γ rays from each of these reactions.

The present absolute determination of the lowest strong resonance at 874.5±0.9 kev is in good agreement with Herb's value of 873.5±0.9 kev. Except for the 1.189-Mev resonance, for which uncertainties are large because of the large half-width, the agreement with values based on the determinations of Bonner and Evans is in general better than three parts in a thousand.

Our determinations are about five parts in a thousand lower than those obtained by Chao *et al.* for the higher resonances, but the agreement is better in the lower voltage range.

Comparison with the results of Willard *et al.* is only possible over a limited energy range, but the discrepancy is not greater than the limits of accuracy to which Willard quotes his results. Our estimates of the half-width of the two higher resonances, however, are appreciably greater than those of Willard. They were made by fitting two Breit-Wigner curves to the observed yield curve, the errors are comparatively large because of uncertainty in estimating the contribution from higher resonances.

Resonances at 780.3 and 1607 kev were not observed by earlier workers, but were observed independently by Barnes[7] in the $F^{19}(p,p'\gamma)F^{19}$ reaction while the present work was in progress.

A resonance at about 1120 kev has previously been observed by Devons *et al.*[8] for the emission of electron-positron pairs from the 6.06-Mev excited state of O^{16} formed by the $F^{19}(p,\alpha)O^{16*}$ reaction. Annihilation radiation from these pairs may account for the resonance peak in the present measurements, Devons also observed a slight pair peak at about 780 kev.

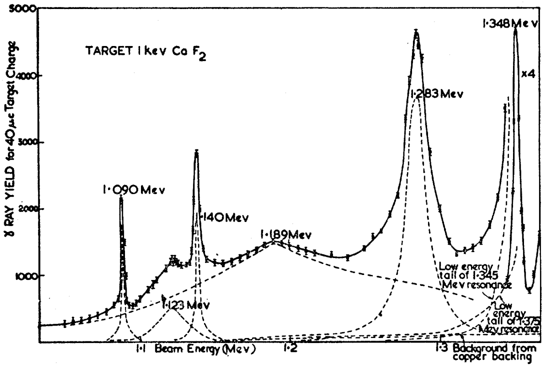

FIG. 3. γ-ray yield curve between 1 Mev and 1.3 Mev (40-μcoul target charge).

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[7] T. Lauritsen (private communication).

[8] Devons, Goldring, and Lindsey, Proc. Phys. Soc. (London) **67**, 134 (1954).