used to compute the cross section for a disintegration process leading to emission of a muon having θ' within any particular angular range.

A numerical example will now be given. The cross section for obtaining muons with angles $\theta' \geq 30°$ is found to be

$$\sigma_{\rm diss}(\theta' \geq 30°) \cong 2.0 \times 10^{-30} Z^2 \text{ cm}^2,$$

assuming that one starts with 250-Mev pions. The kinetic energy of these muons will be $\lesssim 150$ Mev. On the other hand one may compare this with the cross section for scattering of the pions into an angle $\theta' \geq 30°$, which is found to be

$$\sigma_{\rm scat}(\theta' \geq 30°) = 7.7 \times 10^{-30} Z^2 \text{ cm}^2.$$

These scattered pions would have an energy of 250 Mev, of course, and since the two cross sections are at least of the same order of magnitude, it should not be difficult to detect the muons, if they are actually emitted. Unfortunately, however, the cross section in both cases is quite small.

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The Yield of Gamma-Rays and Neutrons from the Proton Bombardment of Fluorine*

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The excitation function of gamma-rays produced by the proton bombardment of fluorine has been extended from 2.1 to 5.4 Mev with a resolution of 0.1 percent. 17 new resonances were observed with maxima at 2.32, 2.51, 2.63, 2.80, 3.02, 3.19, 3.49, 3.92, 4.00, 4.29, 4.49, 4.57, 4.71, 4.78, 4.99, 5.07, and 5.20 Mev. The $F^{19}(p,n)Ne^{19}$ threshold was determined to be 4.253 ± 0.005 Mev, and the neutron yield in the forward direction was extended to 5.3 Mev. Maxima occur at 4.29, 4.46, 4.49, 4.57, 4.62, 4.71, 4.78, 4.99, 5.07, and 5.20 Mev. The $Ne^{19} - F^{19}$ mass difference was calculated from the threshold measurement to be 0.00349_9 amu.

I. INTRODUCTION

THE excitation function of gamma-rays produced by the proton bombardment of fluorine has been previously measured with good resolution in the region from 0 to 1.5 Mev.[1,2] The 15 resonances observed have natural widths which vary from less than 1.2 to 37 kev. Three additional resonances have been reported between 1.5 and 2.1 Mev.[3] It has been shown[4] that these gamma-rays arise from the following reaction:

$$\begin{aligned} F^{19} + H^1 &\rightarrow (Ne^{20})^* \rightarrow {}^*O^{16} + He^4 + Q_1, \\ {}^*O^{16} &\rightarrow O^{16} + h\nu + Q_2. \end{aligned} \tag{1}$$

An analysis of the energy spectra of these gamma-rays[5] resolves them into two lines at 6.1 and 7.0 Mev. No lines between 8 and 18 Mev exist having an intensity of greater than one percent of the 6.1-Mev line. The resonances in this reaction are of sufficient sharpness and intensity to serve as useful calibration points on an absolute voltage scale.[2,6,7]

The $F^{19}(p,n)Ne^{19}$ reaction is endothermic with a measured threshold of 4.18 ± 0.25 Mev.[8] The excitation function has not been reported previously with good resolution.

The new Van de Graaff accelerator at Oak Ridge[9] is capable of producing magnetically analyzed protons up to 5.5 Mev. In order to determine the energy resolution and calibrate the absolute voltage scale of this machine, the known gamma-ray resonances in fluorine were measured. The excitation function was then extended to 5.4 Mev. The $F^{19}(p,n)Ne^{19}$ threshold was determined and the excitation function was measured up to 5.3 Mev.

II. EXPERIMENTAL PROCEDURE

Ordinary 15-mil tantalum sheet was found to have a very thin surface layer of TaF_5 (the average stopping power was about 100 ev for 1-Mev protons), and was used for targets in the calibration experiments. For measurements above 2 Mev, thin layers of CaF_2 were evaporated on 15-mil tantalum (the stopping power was 5 kev for 2-Mev protons). The gamma-ray and neutron backgrounds were determined from an evapo-

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rated calcium metal target of proper thickness. The evaporations were carried out by Dr. H. E. Banta of the High Voltage Group.

The gamma-rays were detected with a single crystal NaI scintillation counter biased to count only gamma-rays above approximately 3 Mev. The crystal was positioned one cm from the target along the beam axis. The neutron yield, in the forward direction, was obtained with a long counter[10] spaced 50 cm from the target. For the determination of the $F^{19}(p,n)Ne^{19}$ threshold a counter sensitive to low energy neutrons (about 10 kev for this particular reaction) similar to that described by Bonner and Butler[11] was employed. Electronic circuits were conventional. The yield was monitored by a beam current integrator of the Watt type.[12]

Protons accelerated by the 5.5-Mev electrostatic generator at Oak Ridge enter the analyzing magnet through two adjustable pairs of perpendicular entrance slits, are bent through 105° (in the vertical plane) with a radius of 37.7 cm, and leave through two similar pairs of exit slits. The entrance slits for the present work were set 4 mm apart, while the exit slits were limited to 1.5 mm, thus permitting a resolution of better than 0.2 percent. The beam voltage is stabilized by corona current using an error signal taken at the mass-one exit slits. This maintains the focused beam sufficiently well-centered to permit the somewhat better resolution of 0.1 percent as determined experimentally from the known gamma-ray resonances in fluorine. These were observed with their natural widths as reported elsewhere.[3] By making use of the monatomic, diatomic, and triatomic hydrogen beams (ranging from 1 to 3μa) the proton energy may be varied continuously from 0.15 to 5.5 Mev.

The absolute proton energy scale was determined by calibrating the current supplied to the magnet with known resonances in fluorine. The three hydrogen beams available give 31 calibration points ranging from 0.3404 Mev (mass-one) to 5.524 Mev (the 1.381-Mev resonance on mass-two). The magnet was carefully recycled between runs. The 0.222-Mev resonance was too weak to be observed with the present beam intensities at low voltages. The TaF_5 target was found, by comparison of its yield with the somewhat thicker CaF_2 targets, to have a thickness much less than the natural width of any of these resonances. Deposits of carbon were noted after many hours of operation, but were not thick enough to shift the resonances by more than 0.05 percent. The 31 points are fitted with an accuracy of 0.1 percent by an equation of the form

$$E_p = aI^2 - bI^3 \qquad (2)$$

where E_p is the proton energy in Mev and I is the magnet current in amperes. However, shifts in the magnet current amounting to 0.2 percent have occurred over a three-month interval, and all energies except the

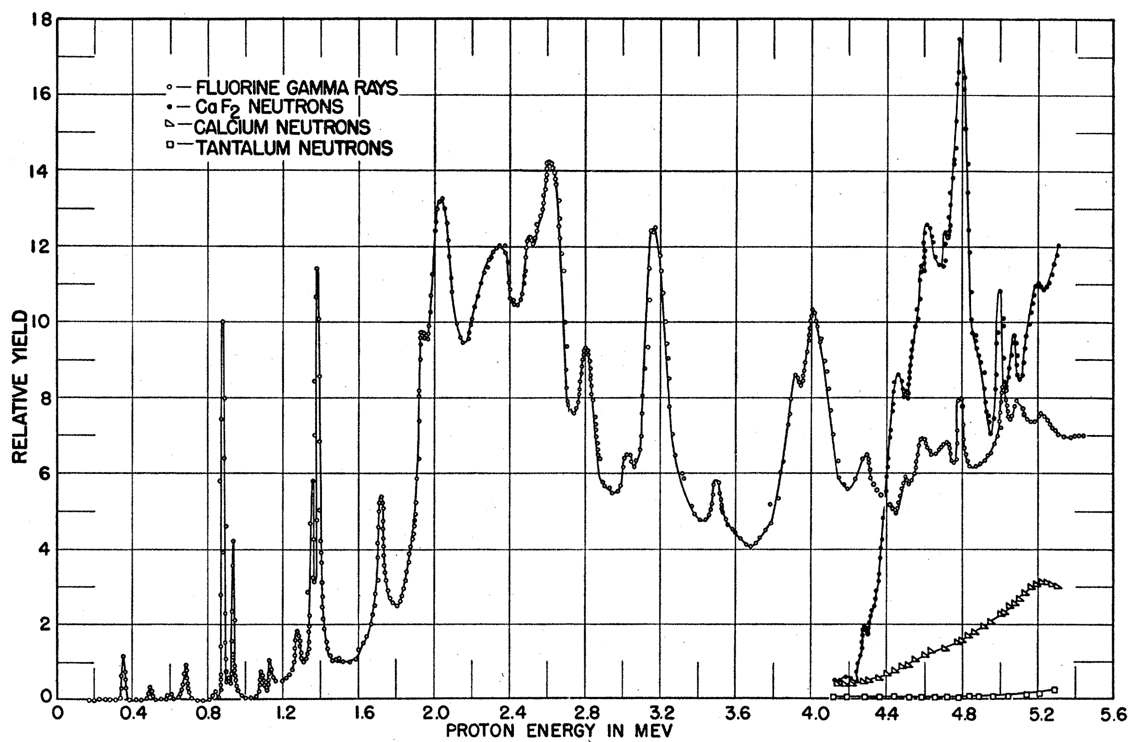

FIG. 1. Resonances in the yield of gamma-rays and neutrons (in the forward direction) from the proton bombardment of fluorine. The relative neutron background yields of calcium and tantalum are included.

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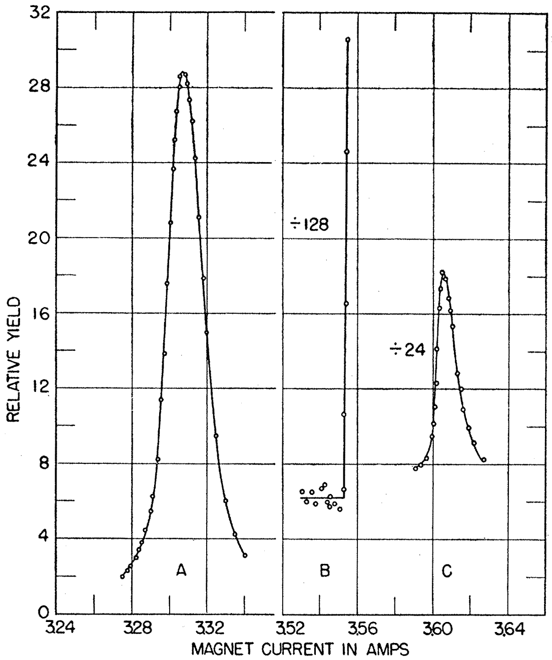

FIG. 2. Typical run for the $F^{19}(p,n)Ne^{19}$ threshold determination. A is the 0.9353-Mev fluorine gamma-ray resonance observed with the mass-two beam at the mass-one equivalent magnet current setting of 3.741 Mev. B is the mass-one beam neutron threshold. C is the 0.486-Mev fluorine gamma-ray resonance observed with the mass-three beam at the mass-one equivalent magnet setting of 4.374 Mev.

(p,n) threshold are reported with this accuracy relative to the resonance energies of the fluorine gamma-ray calibration points. The $F^{19}(p,n)Ne^{19}$ threshold was obtained with 0.1 percent accuracy by measurement of the 0.9353-Mev gamma-ray resonance on mass-two just below, and the 0.486-Mev resonance on mass-three just above threshold in a single magnet cycling (repeated numerous times).

III. RESULTS

Figure 1 shows the yield of gamma-rays produced by the proton bombardment of fluorine from 0.15 to 5.4 Mev, the yield of neutrons, in the forward direction, from threshold to 5.3 Mev, and the neutron backgrounds from calcium and tantalum (thick target yield). The gamma-ray background from these elements was negligible.

The gamma-ray yield below 2.1 Mev contains the known resonances with the exception of the one at 0.222 Mev which was not observed because of insufficient intensity. Above 2.1 Mev, 17 new maxima are observed at 2.32, 2.51, 2.63, 2.80, 3.02, 3.19, 3.49, 3.92, 4.00, 4.29, 4.49, 4.57, 4.71, 4.78, 4.99, 5.07, and 5.20 Mev. The experimental resolution is 0.1 percent, but the levels are so closely spaced that the resonances are not isolated, and hence an accurate assignment of their energy cannot be made. A rough analysis with a scintillation spectrometer indicates that up to 5.3 Mev most of the gamma-rays arise from reaction (1).

The neutron yield exhibits the same maxima above threshold at 4.29, 4.49, 4.57, 4.71, 4.78, 4.99, 5.07, and 5.20 Mev, and two additional ones at 4.46 and 4.62 Mev. To check that the neutron and gamma-ray maxima coincided, the yields were re-run simultaneously with the long counter at 0° and the scintillation counter at 90° with respect to the proton beam. The (p,n) threshold was determined, with an accuracy of 0.1 percent relative to the 0.9353-Mev mass-two and 0.486-Mev mass-three gamma-ray resonances, to be 4.253 Mev. A typical run is shown in Fig. 2. The $Ne^{19}-F^{19}$ mass difference obtained from this threshold is 0.00349_9 amu, taking the mass difference $(n-H^1)$ from Li, Whaling, Fowler, and Lauritsen.[13] The positron from Ne^{19} has been observed to have an end point of 2.20 Mev.[14] The maximum energy for this disintegration is calculated from the present threshold to be 2.24 Mev.

TABLE I. Resonances in the gamma-ray and neutron yields from the proton bombardment of fluorine. $E_{m\gamma}$ is the measured maximum in the gamma-ray yield. E_{mn} is the measured maximum in the neutron yield (at 0°). Γ_A and Γ_B are rough estimates of the full level widths at half-maximum in gamma-ray and neutron yields, respectively. $E_{exc}(Ne^{20})$ is the calculated excitation energy for the level in the compound nucleus (Ne^{20}).

Number	$E_{m\gamma}$ (Mev)	E_{mn} (Mev)	Γ_A (kev)	Γ_B (kev)	E_{exc} (Mev)
1	1.69	...	30	...	14.26
2	1.94	...	15	...	14.49
3	2.03	...	60	...	14.58
4	2.32	...	85	...	14.85
5	2.51	...	30	...	15.04
6	2.63	...	90	...	15.15
7	2.80	...	60	...	15.31
8	3.02	...	30	...	15.53
9	3.19	...	80	...	15.68
10	3.49	...	40	...	15.97
11	3.92	...	30	...	16.38
12	4.00	...	110	...	16.45
13	4.29	4.29	50	45	16.73
14	...	4.46	...	80	16.89
15	4.49	4.49	30	20	16.92
16	4.57	4.57	30	20	16.99
17	...	4.62	...	60	17.04
18	4.71	4.71	30	25	17.13
19	4.78	4.78	35	45	17.19
20	4.99	4.99	20	20	17.39
21	5.07	5.07	35	30	17.47
22	5.20	5.20	70	70	17.59

Table I summarizes the resonances observed in the gamma-ray and neutron yields, their estimated level widths, and the excitation energies in the compound nucleus Ne^{20}, calculated from

$$E_{exc}=[12.646+(19.0044/20.0126)E_m] \text{ Mev}. \quad (3)$$

The proton binding energy 12.646 Mev was obtained from the mass values of Mattauch and Flammersfeld.[15]

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