suggests allowed beta transitions to the 535- and 650-kev levels as observed. However, with the invocation of conventional selection rules, it is not possible to explain the large value of log *ft* of the transition to the 57-minute metastable level ($\Delta I=1$, no, allowed). Recently, De-Shalit and Goldhaber[15] have discussed the problem of anomalous values of log *ft* for allowed and first forbidden beta transitions. They have emphasized the possible influence of the nuclear core. Their explanation can be applied if the ground state of Ru^{103} is assumed to have orbital $g_{7/2}$. In that event, one or more pairs of neutrons of orbital $d_{5/2}$ will be present in the ground state configuration of Ru^{103}. The most probable configuration would be $g_{7/2}{}^7\ d_{5/2}{}^2$. On the other hand, the effect of the $g_{9/2}$ protons of Rh^{103} on the isomeric and 95-kev levels would be such as to make the neutron configuration of those levels $g_{7/2}{}^8\ d_{5/2}{}^0$. According to De-Shalit and Goldhaber,[15] the beta transitions would be further slowed by the change of orbitals ($d_{5/2}\rightarrow g_{7/2}$) experienced by one pair of neutrons. From these considerations, it can be said that the neutron configuration of the 535- and 650-kev levels of Rh^{103} is probably $g_{7/2}{}^6\ d_{5/2}{}^2$, very similar to the arrangement of the neutron pairs of the ground state of Ru^{103}.

Since the value of log *ft* for the electron capture decay of Pd^{103} to the isomeric level of Rh^{103} corresponds to an allowed transition, the ground state configuration of Pd^{103} is probably $g_{7/2}{}^7$.

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High-Energy Gamma Rays from the Proton Bombardment of Fluorine*

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Resonances for emission of gamma rays of energy greater than 8 Mev in the reaction $F^{19}(p,\gamma)Ne^{20}$ have been measured for proton energies from 550 to 1450 kev using a thin target. Resonances were seen at 669, 874, 935, 980, 1090, 1280, 1320, 1355, 1380, and 1430 kev. The effect of false high-energy gamma-ray counts resulting from the nearly simultaneous detection of two 6–7 Mev gamma rays in the reaction $F^{19}(p,\alpha\gamma)O^{16}$ was noted and a method for correcting for this effect was devised. The intensities of gamma rays for the two reactions were compared at each resonance. Also, the angular distribution of the 12-Mev gamma rays emitted at the 669-kev (p,γ) resonance was measured and found to be isotropic to within two percent probable error.

INTRODUCTION

RESONANCES for the emission of 6.1-, 6.9-, and 7.1-Mev gamma rays from the proton bombardment of fluorine in the reaction $F^{19}(p,\alpha\gamma)O^{16}$ are well known.[1] It is also known that at 669-kev proton bombarding energy the compound nucleus Ne^{20*} can decay by alpha-particle emission to O^{16*} and also by gamma-ray emission to the 1.63-Mev level in Ne^{20}. The energy of this gamma ray has been measured to be about 12 Mev.[2,3] It was the purpose of this experiment to look for other resonances for emission of gamma rays of energy greater than 8 Mev, indicating a transition to some lower energy state of Ne^{20}.

The angular distribution with respect to the proton beam of the 12-Mev gamma rays emitted at the 669-kev (p,γ) resonance in fluorine has been measured by using two Geiger counters in an absorption-coincidence measurement.[4] The distribution was found to be isotropic within ten percent. In the present work,

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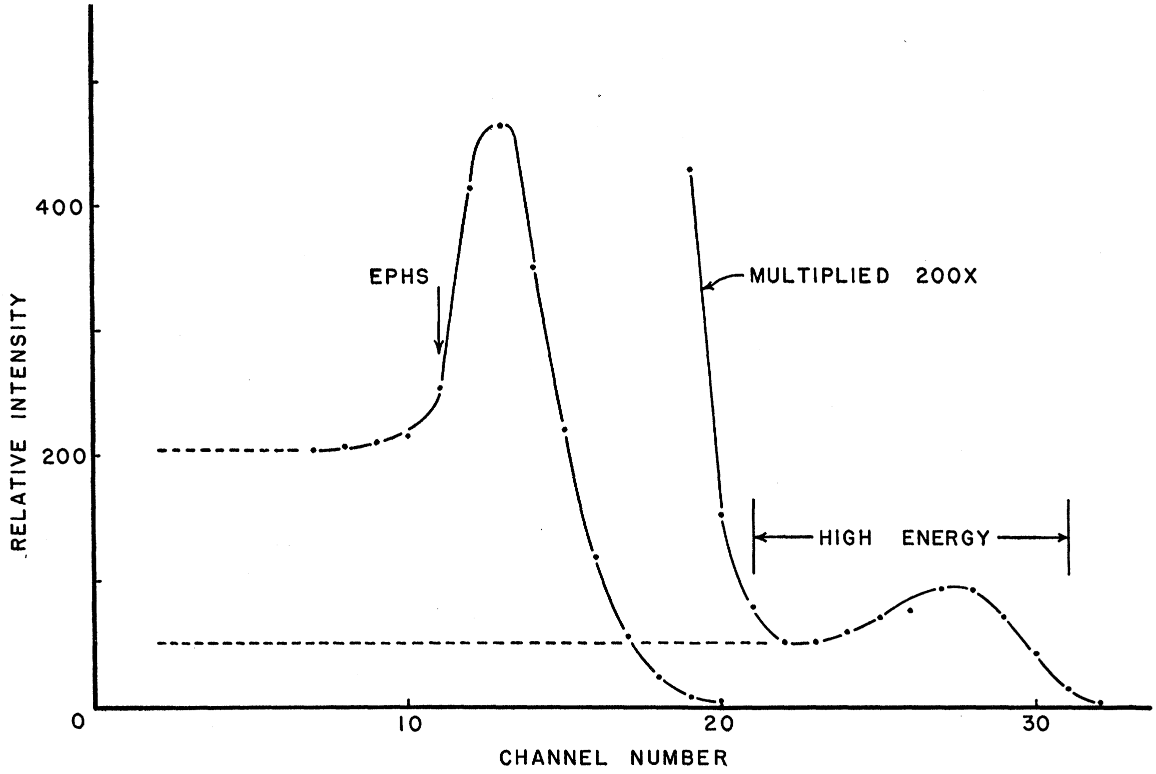

FIG. 1. Spectrum of the gamma rays from proton bombardment of fluorine at the proton energy of 669 kev.

measurements have been made to reduce the uncertainty in the isotropy.

EXPERIMENTAL PROCEDURE

Yield Curves

Protons were accelerated from 550 to 1450 kev using the University of Kentucky electrostatic accelerator. The energy resolution was adjusted to ±0.25 percent for this experiment, and beam currents from 0.5 to 5.0 microamperes were used.

The gamma-ray detector was a scintillation counter composed of a Du Mont 6292 photomultiplier tube and a 1 in.$\times 1\frac{1}{2}$ in. NaI(Tl) crystal enclosed in a thin aluminum casing and surrounded by magnesium oxide. The pulse-height spectrum from the detector was analyzed by a twenty-channel pulse-height analyzer.[5]

When obtaining the yield curves for gamma rays, the voltage on the photomultiplier tube and the gain of the amplifier in the pulse-height analyzer were adjusted so that pulses resulting from the 6–7 Mev gamma rays and from gamma rays of higher energy were simultaneously observed. In this work, 6–7 Mev gamma rays are referred to as low-energy gamma rays, and gamma rays of energy greater than 8 Mev are referred to as high-energy gamma rays. Figure 1 shows a typical pulse-height spectrum obtained with proton bombarding energy of 669 kev. The shape of this spectrum is in agreement with other high-energy gamma-ray measurements and with theoretical predictions.[6] The twenty channels were positioned so that the peak of the pulse-height spectrum from the low-energy gamma rays appeared in the first five channels and the peak from the high-energy gamma rays appeared in the last ten channels. The arrow designated EPHS in Fig. 1 marks the position of channel one.

The ordinate used for plotting the high-energy yield curve was obtained by adding all counts that appeared in the last ten channels; the ordinate used for plotting the low-energy yield curve was obtained from the total count scaler. This included the yield of high-energy gamma rays; but, at most, this never exceeded a two percent addition and in no way appreciably effected the results. It was necessary to do this because the high yield of 6–7-Mev gamma rays caused the mechanical registers in some of the individual-channel "scale of sixteen" scalers to lose counts. The total count scaler is a "scale of 256" circuit and was able to record all pulses.

Figure 2 shows the yield curve obtained for the low- and high-energy gamma rays obtained from a target made by evaporating sodium fluoride upon tantalum backing. The target was twenty kilovolts thick at the 874-kev $(p\alpha\gamma)$ resonance in fluorine. The presence of the sodium made the analysis of the fluorine yield

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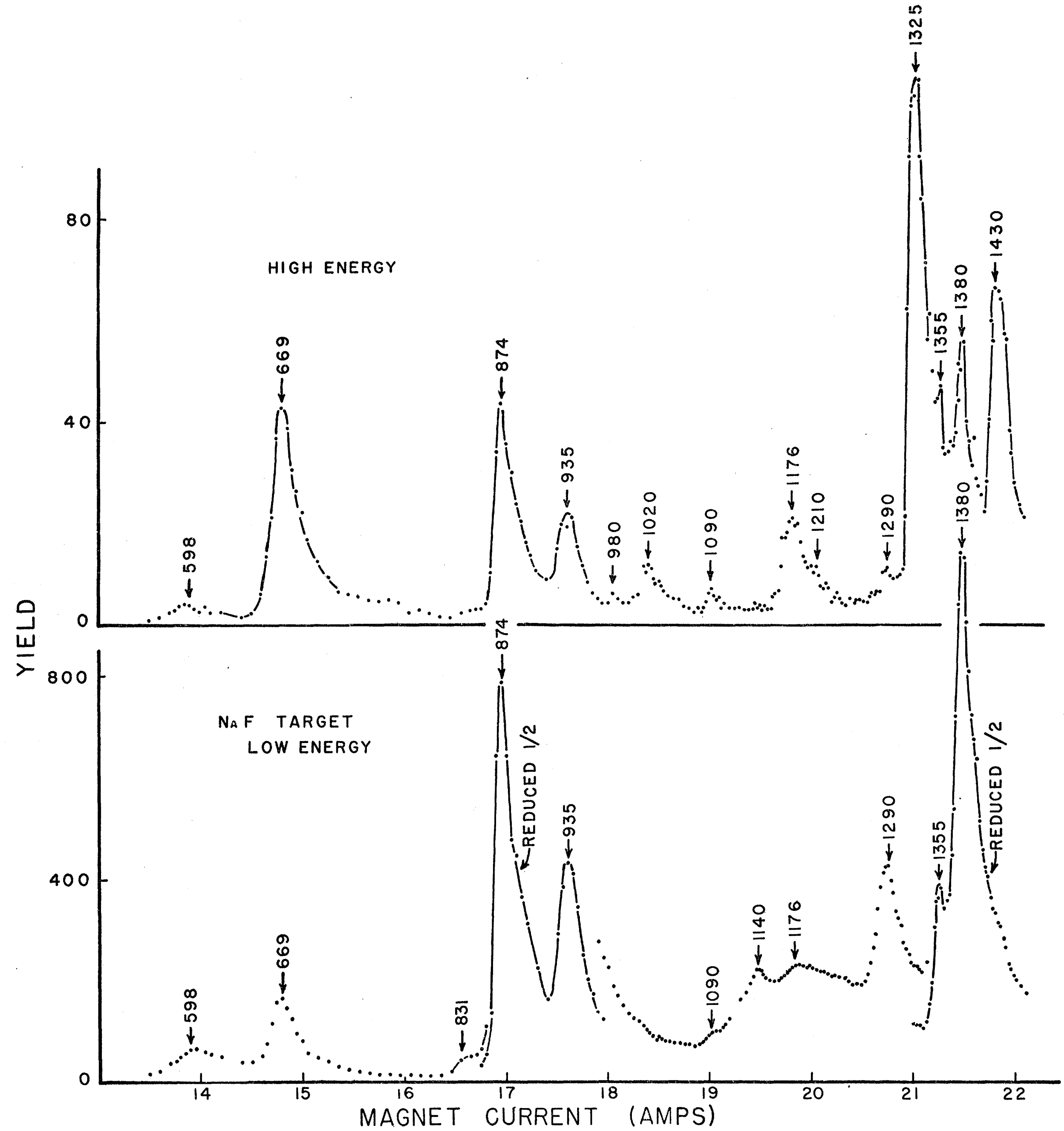

FIG. 2. Gamma-ray yield from proton bombardment of a sodium fluoride target. The high-energy yield has not been corrected for the effect of pile-up. The high-energy ordinate is in units of 16 counts and the low-energy ordinate in units of 256 counts.

difficult, but made possible qualitative confirmation of some of the recently reported work on (p,γ) resonances in sodium.[7]

A second target free of sodium was prepared by etching the surface of a piece of tantalum with hydrofluoric acid. Figure 3 shows the yield curve obtained using this target which was about fifteen kilovolts thick at the 874-kev $(p,\alpha\gamma)$ resonance in fluorine.

While obtaining these yield curves for low- and high-energy gamma rays, it was noted that the number of counts that appeared in the high-energy channels varied with the beam current even though the proton energy remained constant. Closer inspection of this phenomenon showed that the effect was caused by two 6–7 Mev gamma rays causing scintillations in the sodium iodide crystal so close together in time that the two individual output pulses partly overlapped. The resultant output pulse appeared as the sum or

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[7] Teener, Seagondollar, and Krone, Phys. Rev. **93**, 1035 (1954).

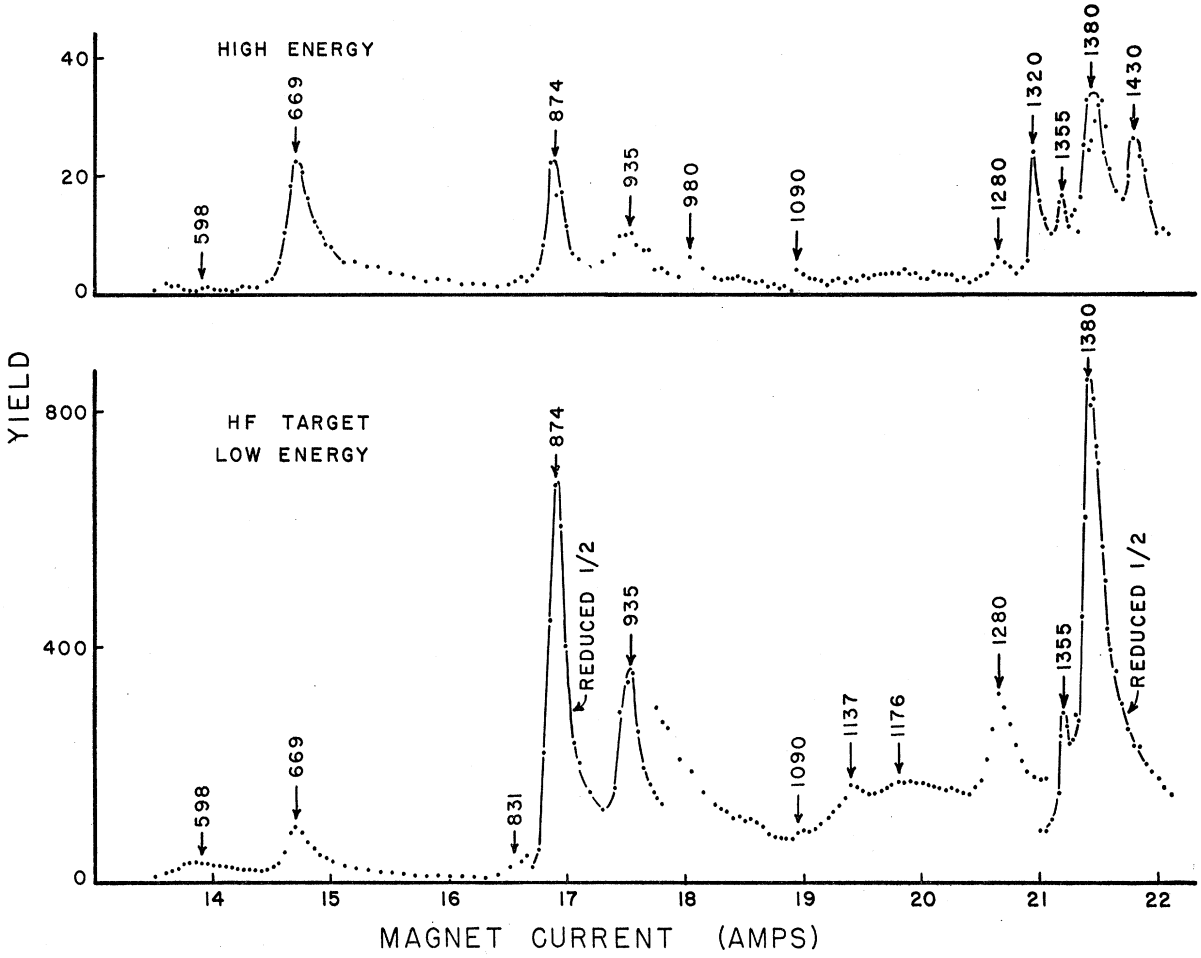

FIG. 3. Gamma-ray yield from proton bombardment of a tantalum fluoride target. The high-energy yield has not yet been corrected for the effect of pile-up. The high-energy ordinate is in units of 16 counts and the low-energy ordinate in units of 256 counts.

partial sum of the two pulses. The analyzer recorded the peak of the resultant pulse and hence a false high-energy count was recorded. This effect is called *pile-up*. A method of correcting for this effect has been devised.

Angular Distribution

The angular distribution of high-energy gamma rays at the 669-kev resonance was obtained by using the previously described scintillation counter, a linear amplifier, and a scaler. The discriminator on the scaler was adjusted to count only pulses from the high-energy gamma rays. No difficulty was experienced here from pile-up.

The detector was placed with the crystal face 7 cm from the target and was rotated in a horizontal plane about an axis through the target and perpendicular to the beam. The yield of gamma rays was measured with the plane of the target making angles of both +45° and −45° with respect to the proton beam. The yield was observed at angles of 0° and 45°, 90° and 135° on either side of the proton beam. This permitted experimental correction for absorption of gamma rays in the 5-mil tantalum target-backing. The angular distribution was found to be isotropic within two percent, after correction for finite solid angle.[8]

PILE-UP CORRECTION

Bateman[9] has shown that for radioactive decay processes the probability that n events will occur in any given time interval t is given by $x^n e^{-x}/n!$. Here x is the average number of events occurring in the time interval considered and is given by at, where a is the average counting rate. From this, then, the probability that no events will occur in a time interval t is e^{-at}. However the probability that an event will occur in a time interval δt is given by $a\delta t$. The probability that an event will not occur for some time interval t but will occur in a time δt immediately following t is given by $e^{-at}a\delta t$. If a total of n_t events are observed, then the

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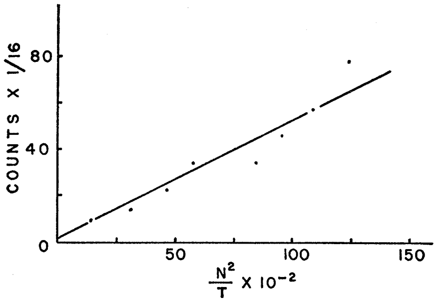

FIG. 4. Pile-up counts *vs* N^2/T for the proton bombardment of fluorine at the proton energy of 874 kev. N is the total yield in units of 256 counts and T is the counting time. The experimental arrangement is the same as that used when obtaining the yield curves of Fig. 2 and Fig. 3.

expected number that will fall within a time between t and $t+\delta t$ after a previous event is $n_t e^{-at} a \delta t$.

This result predicts that small intervals between events are more likely regardless of the counting rate a. This result has been checked experimentally by several authors,[10,11] and it is for this reason that reduction of the beam current did not completely eliminate pile-up in this experiment.

This expression, however, can be used to calculate the number of gamma-ray counts that will occur close enough together in time to cause pile-up. Suppose that scintillations must occur separated by a time t' or less for the leading edges to overlap sufficiently to cause pile-up. The total number of counts that meet this requirement is

$$N_p = \int_0^{t'} n_t e^{-at} a dt = n_t (1 - e^{-at'}).$$

The design of the pulse-height analyzer requires that t' be something less than a microsecond. Also the experiment was performed holding a to some value less than 500 counts per second. Hence the above expression may be approximated by

$$N_p = n_t a t'.$$

The value of a will be given very nearly by n_t/T, where n_t is the total number of scintillations occurring in the sodium iodide crystal during the time of observation T. However in this experiment the total number of scintillations n_t was not detected but only some fraction of that total. Since the pulse spectrum has a definite shape, then the total number of scintillations n_t can be obtained from the observed total count N by multiplying by some constant s, or $n_t = sN$. Substituting for a and n_t we have $N_p = s^2 N^2 t'/T$.

The total number of counts k that appear in the high-energy channels will be composed of the true high-energy counts N_t, background counts N_b, and pile-up counts N_p, or

$$k = N_t + N_b + N_p = N_t + N_b + s^2 t' N^2 / T.$$

The equation for k-N_b is linear in N^2/T and the slope contains all the unknown factors. The slope can be determined experimentally. For this experiment it was determined by bombarding the target at the strong 874-kev $(p,\alpha\gamma)$ fluorine resonance for 6–7-Mev gamma rays. k and N were recorded for a specified number of protons incident on the target for several values of constant beam current. The resultant high-energy counts were then plotted as ordinates against values of N^2/T. Figure 4 shows the result. The number of background counts in the high-energy channels was so small that no correction was necessary. The value of the slope obtained was 1.24×10^{-6} second. The validity of this method of correcting for the presence of pile-up counts has been satisfactorily established by use of the 0.61-Mev gamma rays from a Cs^{137} source.

RESULTS

The tantalum fluoride target shows evidence of high-energy gamma-ray resonances at 669, 874, 935, 980, 1090, 1280, 1320, 1355, 1380, and 1430 kev. Figure 5 shows these resonances after corrections for pile-up. At the strong resonances for low-energy gamma rays, the effect of pile-up is very pronounced.

A measure of the intensity of the high-energy gamma rays was obtained by comparing the ratio of the peak number of high-energy gamma rays emitted to the number of low-energy gamma rays emitted at the same proton energy. This was done by taking into account the predicted shape of the spectra[6] and the fact that only a portion of it was observed. The results are shown in Table I. At the 874-kev resonance, the value of 0.03±0.01 percent given in the table is in good agreement with an earlier determination[12] of the ratio as having an upper limit of 0.05 percent. The resonances at 1090, 1320, and 1430 kev are in agreement with results published during the course of this experiment.[13]

TABLE I. Intensity ratios. The intensity of the high-energy gamma rays from $F^{19}(p,\gamma)Ne^{20}$ is compared to the intensity of the low-energy gamma rays from $F^{19}(p,\alpha\gamma)O^{16}$ at the corresponding energy.

E_p(kev)	Intensity ratio (percent)
669	1.80±0.36
874	0.03±0.01
935	0.03±0.01
980	0.22±0.04
1090	0.34±0.07
1280	0.06±0.01
1320	0.90±0.18
1355	0.12±0.02
1380	0.08±0.02
1430	0.35±0.07

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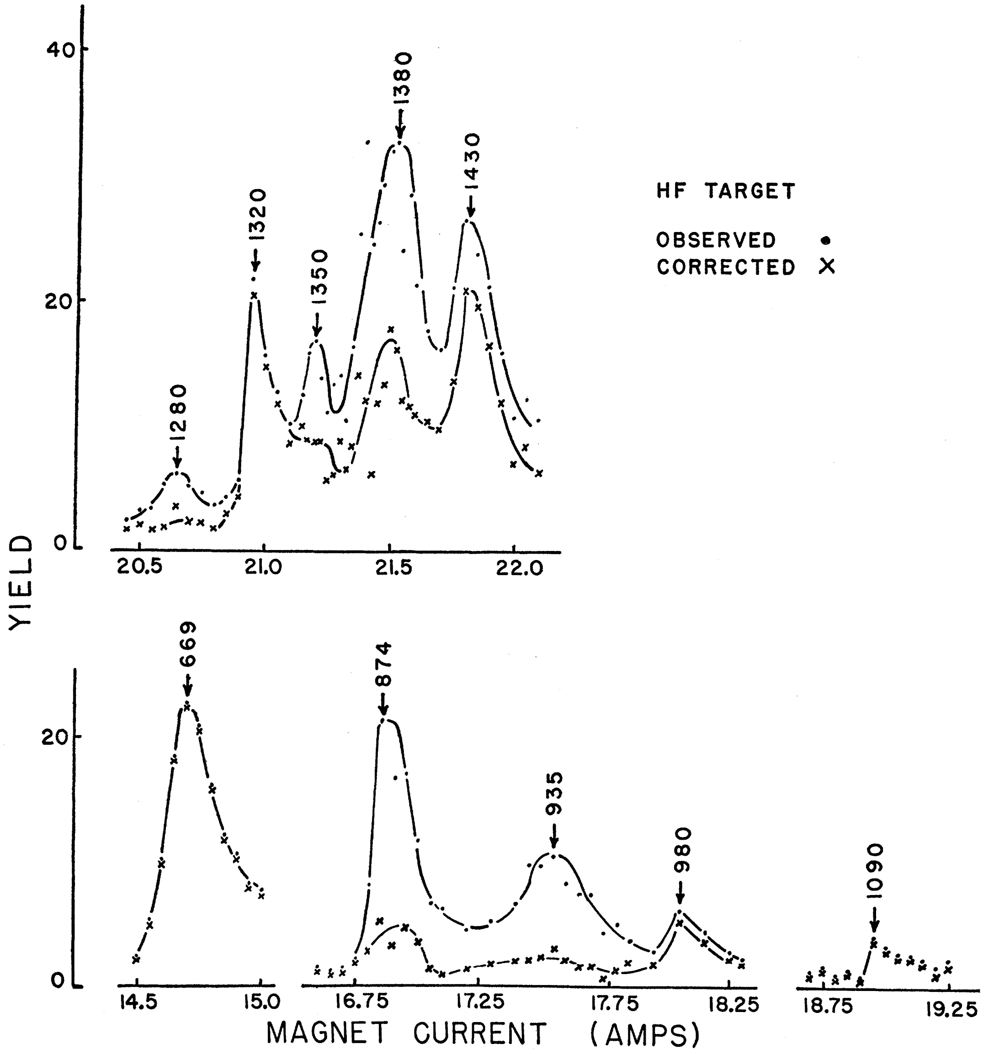

FIG. 5. Yield of high-energy gamma rays from proton bombardment of fluorine, corrected for the effect of pile-up.

The sodium fluoride target shows evidence of high-energy resonances at 598, 669, 874, 935, 980, 1020, 1090, 1176, 1210, 1290, 1325, 1355, 1380, and 1430 kev. The additional resonances may be attributed to (p,γ) resonances in sodium. Other work[7] has shown the existence of resonances in sodium for gamma-ray energies lying between 1.6 and 12 Mev; the present work shows the resonances for gamma-ray energies greater than 8 Mev.

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Note added in proof.—It has been reported that in some scintillation counting arrangements there arise spurious high-energy pulses due to the presence of 5- to 7-Mev gamma rays, in addition to those high-energy pulses due to pile-up. To investigate this effect in the equipment described above, a thick Be^9 target was bombarded at various currents at a fixed proton beam energy. N was maintained constant, on the assumption that the number of spurious counts would be proportional to the number of gamma rays. The curve obtained upon plotting $k-N_b$ *vs* N^2/T is a straight line which extrapolates to the origin. A reasonable upper limit on the number of spurious counts gives an intensity ratio, as defined above, of slightly less than 0.01 percent. It is concluded that the intensity ratios given above are not altered by this effect.