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Absolute Magnetic Analysis of $F^{19}(p,p')F^{19*}$ Reaction*

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An annular magnet spectrometer has been used to study groups of protons scattered inelastically from the two lowest excited states of F^{19}. The results of six experiments at bombarding energies between 2.1 and 4.5 Mev indicate an assignment of 110.4±0.6 and 197.8±1.2 kev, respectively, for these levels. No other groups ascribable to F^{19} were observed in the region of excitation up to 730 kev, and no multiplet structure was observed for either of the F^{19} groups. The experiments were capable of detecting proton groups with an intensity with respect to the ground state group of 2 percent. Doublet separations of 3 kev would have been detected.

INTRODUCTION

The Rice Institute annular magnet has previously been utilized in the study of certain exoergic reactions yielding information on the excited state[1] and the ground state[2] Q values of light elements. The addition of a 6-Mev Van de Graaff accelerator to the facilities available at The Rice Institute has made practical the use of the spectrometer to study inelastic proton scattering. For the first application of the spectrometer to this type of experiment, the inelastic scattering of protons from F^{19} was chosen because of interest in the number and in the spacing of the low lying energy levels of this nucleus.[3] The Rice Institute spectrometer is particularly suited to a reaction of this type where a high degree of accuracy and resolution are desirable.

APPARATUS

Application of the annular magnet to the study of spectra of inelastic proton groups, in which the momenta of the observed particles are less than those of the incident particles, provided a situation somewhat different from that previously encountered in using the instrument, and necessitated a number of changes in the apparatus. However, much of the equipment, particularly the magnet pole pieces and field regulation system, have been maintained as previously described.[1,2] Extensive changes in the slit systems were necessary in order to reduce the background of multiply scattered and energy degraded particles. A number of such improvements, indicated in Fig. 1, were made during the course of the experiments which extended over a period of several months. Consequently, the background in the later experiments was considerably lower than in the earlier ones.

To facilitate taking data on extended spectra, the proportional counter detector previously used has been replaced with the camera shown in the upper part of Fig. 1. This device is capable of successively rotating up to eight nuclear track plates into position to accept, at an incident angle of 12.5°, particles which have traversed semicircular orbits from the target. The plates are held on a roughly octagonal table which is rotated on precision bearings and can be locked to hold a plate accurately in position, K. The camera is also equipped with a shutter at L, which, like the mechanism for rotation of the table, is operated without disrupting the vacuum in the system. An optical indexing system at M, which projects the image of a fine straight wire filament onto one edge of the plate, has been provided for the measurement of the radius of curvature.

PROCEDURE

The experimental arrangement is shown in Fig. 1, which is a cross-sectional view in the mean plane of the annular gap of the magnet. A beam of protons from the accelerator enters the tube from the lower left hand corner on the figure, after having passed through a 90° analyzing magnet and a set of collimating slits. Upon entering the tube the beam passes through an externally adjustable set of slits, A, which serve to collimate the beam further. A viewing quartz, B (shown withdrawn), may be inserted to facilitate the adjustment of the slits.

Passing into the uniform portion of the field between the annular pole pieces, the beam goes successively through the traveling slit, C, between the target slits, D, through the target foil, E, and finally is collected in the Faraday cup, F. For each different magnetic field setting, the position of the magnet is adjusted (with the traveling slit withdrawn) such that at the target slit the edges of the beam slightly overlap the edges of the slits. The traveling slit, which has a width less than half that of the target slit, is then inserted and adjusted to allow the beam to pass through the middle of the target slit. This is accomplished by viewing, through a port at G, the beam spot which is visible on the fluorescent coating of the target slits.

The reading of the micrometer of the traveling slit determines[2] the angle θ, which the incident particles make at the target with a mean acceptance orbit of the spectrometer. The magnet may be so positioned

* Supported by the U. S. Atomic Energy Commission.
† Now at the Bell Telephone Laboratories, Murray Hill, New Jersey.
[1] E. Klema and G. C. Phillips, Phys. Rev. 86, 951 (1952).
[2] K. Famularo and G. C. Phillips, Phys. Rev. 91, 1195 (1953).
[3] C. Mileikowsky and W. Whaling, Phys. Rev. 92, 528(A) (1953).

that this angle is very close to 180°. A partition, *H*, prevents the acceptance by the spectrometer of particles scattered from the traveling slit.

Protons scattered from the target pass around the tube to the detector, *K*. The slit, *J*, at 90° serves to define both the solid angle, 1.8×10^{-4} steradian, and acceptance angle, $\pm2°$, of the spectrometer, as the widths of other slits have been set slightly larger than required to define the maximum and minimum rays accepted.

Coated Eastman NTA plates were used as detectors throughout the experiment. The plates were read with a microscope equipped with a traveling stage graduated to one micron. Tracks were counted in 137-micron intervals along the focal diameter as a function of their distance from the optically projected indexing line. It was possible to survey, on one plate at a specified magnetic field setting, about 15/700 of the momentum spectrum. Successive plates were exposed at different magnetic fields so as to give a slight overlap in the momentum intervals.

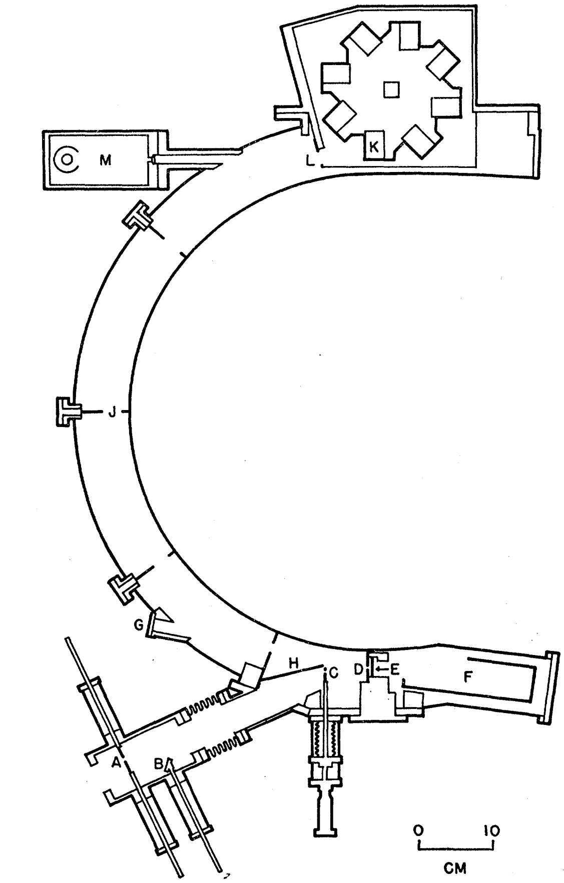

FIG. 1. Experimental arrangement. (*A*) collimating slits; (*B*) viewing quartz; (*C*) micrometer driven traveling slit; (D) target slit; (*E*) target; (*F*) Faraday cup; (*G*) viewing port; (*H*) anti-scattering partition; (*J*) defining slit; (*K*) nuclear track plate detector; (*L*) camera entrance slit and shutter; (*M*) optical indexing system.

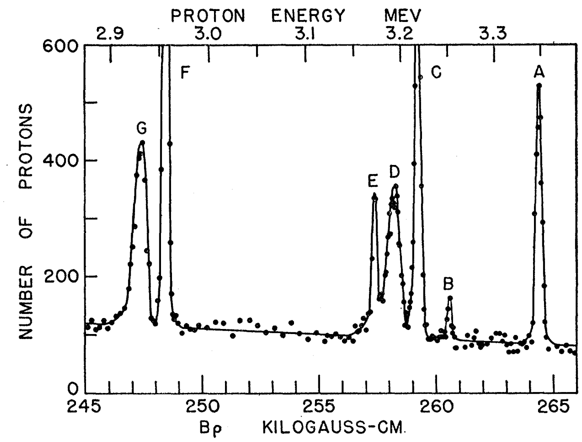

FIG. 2. Number of proton tracks *versus* $B\rho$ for scattering from F^{19}. Bombarding energy 4.140 Mev. Groups: (*A*) F^{19} (ground state); (*B*) F^{19} (110-kev state); (*C*) O^{16} (front surface); (*D*) O^{16} (back surface); (*E*) F^{19} (198-kev state); (*F*) C^{12} (front surface); (*G*) C^{12} (back surface).

The distribution of tracks on the plates may be described by the line shapes proposed by Famularo[2] with only slight modifications to allow for the changes in the detection system. This analysis predicts that the momentum assignment of a group of particles from a sharp state is given by the intercept of the extrapolated straight leading edge of the distribution with the background. No evidence has been found to suggest deviation from the perfect focusing properties of the magnet upon which this analysis is based.

The radius of curvature of an observed group of particles is found from the sum of three lengths along the focal diameter: the distance between the edge of the beam at the target and the inboard edge of the target slit, obtained from the micrometer readings of the traveling slit; the distance between the inboard edge of the target slit and the projected index line, determined by comparison with a standard meter bar; and the distance from the projected index line to the extrapolated end of the particle group, obtained from a plot of the distribution of tracks on the plate. The field at which a plate is exposed is determined by a proton moment magnetometer. Corrections for the regulation properties and slight inhomogeneities of the magnet are made as previously described.[2] The targets used throughout the experiment were thin layers of CaF_2 evaporated onto nickel foils 10 microinches thick.

INTERPRETATION

Figure 2 is a representative member of the series of six spectra taken at different bombarding energies. It shows the general characteristics observed in each case. O^{16} and C^{12}, appearing as surface contaminants, produce elastic groups both from the front and back surfaces of the foil, the latter groups showing a characteristic broadening due to straggling in the double traverse of the foil. In Fig. 2, where the bombarding energy was

TABLE I. Summary of the experimental results.

Bombarding energy mev	Half-width F^{19} groups kev	Percent intensity of ground state detectable[a]	Range of excitation kev	First excited state Q value kev	First excited state Percent intensity of ground state	Second excited state Q value kev	Second excited state Percent intensity of ground state
2.1534	13	2	440	109.7	~2	198.7	~6
2.8394	11	3	440	b	b	198.3	62
2.9566	11	c	360	110.0	c	195.7	c
3.1818	12	5	425	111.4	9	198.3	19
4.1398	6	7	680	110.9	14	198.9	43
4.5320	52	8	730	110.1	17	196.6	144

[a] Criterion for detectability: three times counting statistics of background.
[b] Obscured by O^{16} ground-state group.
[c] Spectrum did not include ground state.

4.140 Mev, the first excited state group of F^{19} lies above the elastic group from O^{16}. As the bombarding energy is lowered this group merges with the oxygen group, finally appearing resolved between the oxygen groups from the front and back surfaces at about 2 Mev. Similarly, the group corresponding to the second excited state of fluorine, which appears superimposed upon the oxygen group from the back of the foil in Fig. 1, moves farther toward the carbon as the bombarding energy is lowered. Such changes in the relative positions of the groups, which may be calculated from elementary considerations as expressed in Eqs. (1) and (3) below, make is possible by bombarding at two or more different energies to assign unambiguously the mass of the scattering nucleus to the groups from both elastic and inelastic scattering processes.

When the angle between the incident and emitted particles at the target is 180°, the relations between the energies are particularly simple,

$$E_2=\left(\frac{M-m}{M+m}\right)^2 E_1, \qquad (1)$$

for elastic groups, where m is the rest mass of the scattered particle, M the rest mass of the scattering nucleus, and E_1 and E_2 the energies of the incident and scattered particles, respectively.

A second-order correction term $(\delta E)_\alpha$, is applied to the relativistically corrected energy of each group to obtain the energy the particle would have had, had it been emitted at $\theta=180°$ rather than at $\theta=180°+\alpha$. This correction term is given by

$$(\delta E)_\alpha=-2E_1\alpha^2\Big/\left[1+\frac{M+m}{m}\left(\frac{E_2}{E_1}\right)^{\frac{1}{2}}\right], \qquad (2)$$

where α is determined from the micrometer reading of the traveling slit.

Using the corrected values of E_2, the bombarding energy, E_1, may be determined by Eq. (1) from the elastic groups from the target material and the various surface contaminants.

The Q values for excited states are calculated from the equation,

$$Q=\left(\frac{M+m}{M}\right)E_2-\left(\frac{M-m}{M}\right)E_1+\frac{2m}{M}(E_1E_2)^{\frac{1}{2}}, \qquad (3)$$

where the corrected values of the energy and the nuclear masses of Li and Whaling[4] are used.

EXPERIMENTAL RESULTS

The results of six determinations are listed in Table I. Also tabulated is information bearing on the possibility of the existence of other states of F^{19}. Upper limits may be set for the intensity of any possible undetected groups resolvable from the known groups, by using the criterion that a group of intensity three times the counting statistics of background would be detectable. The half-width of the fluorine groups and the range of excitation energy of F^{19} covered by each spectrum are also listed.

CONCLUSIONS

Table II contains a comparison of these Q values with other recently published determinations. The errors quoted for the present results are based solely on internal consistency. The estimation of the error in the energy assignment for an individual group based on a systematic analysis of the possible sources of error is of the order of 4 kev; however, small systematic errors constant throughout a spectrum make only very small contributions to the error of the Q value, since the Q value is essentially the difference between two measured energies. Thus, only errors which vary from group to group or plate to plate contribute significantly, and it is felt that the internal consistency provides an adequate representation of these errors.

On the basis of spectra obtained for cases where two known groups were superimposed but not resolved, it is estimated that if double structure with a separation of 3 kev or more existed it would have been possible to detect its presence, provided that one group had an intensity of at least 25 percent of the other. From the

TABLE II. Comparison of reported Q values.

Source	Experiment	First excited state kev	Second excited state kev
a	$F^{19}(p,p')F^{19*}$ mag. spec.	108.8±0.8	196.0±1.4
b	$F^{19}(\alpha,\alpha')F^{19*}$ γ-ray	113 ±2	196 ±2
c	$F^{19}(p,p')F^{19*}$ mag. spec.	110.4±0.6	197.8±1.2

[a] Peterson, Fowler, and Lauritsen, Phys. Rev. **96**, 1250 (1954).
[b] N. P. Heydenburg and G. M. Temmer, Phys. Rev. **94**, 1252 (1954).
[c] Present report.

[4] Li, Whaling, Fowler, and Lauritsen, Phys. Rev. **83**, 512 (1951).

data of Table I, it may be seen that groups of 6-kev separation or more could have been resolved. It may also be seen that any isolated group with an intensity of approximately 2 percent of the ground-state fluorine group would have been detected; and furthermore, with the range of bombarding energies used, there exist no gaps in the excitation of F^{19} in which a state could be hidden by a contaminant group.

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Yield of High-Energy Gamma Rays from Proton Capture in Be^9

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Two yield curves have been taken for gamma rays of energy above 2.5 Mev and 5.6 Mev respectively, with proton energies from 150 kev up to 518 kev. The curve for gamma rays above 2.5 Mev shows a single broad resonance around 330-kev proton energy. After correction for barrier penetration the curve can be fitted by a Breit-Wigner formula with resonance energy 307 kev (corresponding to a level in B^{10} at 6.86 Mev) and with half-width 160 kev. The curve for gamma rays above 5.6 Mev also shows a nonresonant radiation, which consists of more energetic components.

THE yield of gamma rays from proton capture in beryllium has been investigated by Curran *et al.*,[1] by Hole *et al.*,[2] and by Hunt.[3] They all found a broad resonance around 340-kev proton energy, but Hunt observed another broad resonance of even higher yield, around 489 kev, while Hole obtained constant yield between 430 and 500 kev.

Trying to find the reason for this discrepancy, we have measured the gamma-ray yield between 150 and 520 kev with protons from our 0.5-Mev Van de Graaff machine. The gamma-ray detector was a NaI-scintillation counter.

First the yield was measured with the discriminator bias set to count only gamma quanta of energy above 2.5 Mev. In this way gamma counts from carbon contamination of the target were eliminated. Our targets were contaminated with fluorine during evaporation, but the sharp resonance at 340 kev could easily be singled out. The result is given in Fig. 1, curve I. The curve agrees well with reference 2 and shows no indication of the 489-kev resonance reported by Hunt.

Curve II shows the experimental yield after correcting for finite target thickness (10 kev at 300-kev proton energy) and taking into account the barrier penetration factor for *s*-wave protons according to Christy and Latter.[4] Curve III is calculated from the Breit-Wigner formula, with resonance energy 307 kev and half-width 160 kev. There is little evidence here for a resonance below 150 kev, but the disagreement with the calculated curve of Tangen[2] is chiefly due to the use of a different penetration factor. In the region 450 to 500 kev, however, the corrected yield is about twice the calculated yield from a single resonance at 307 kev.

Curve IV is the yield curve with the discriminator set to accept only quanta above 5.6 Mev. In this curve

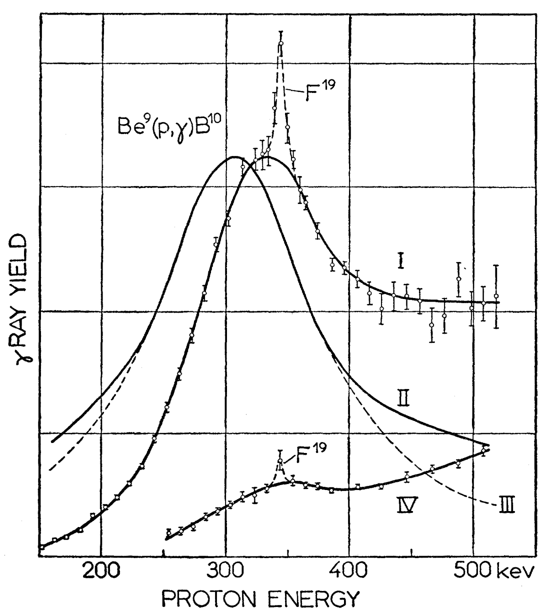

Fig. 1. Yield of gamma rays from proton capture in beryllium. Curve I: Experimental curve, gamma energy above 2.5 Mev. Curve II: Corrected for target thickness and barrier penetration. Curve III: Calculated from Breit-Wigner formula. $E_R=307$ kev, half-width 160 kev. Curve IV: Experimental curve, gamma energy above 5.6 Mev.

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1 Curran, Dee, and Petrzilka, Proc. Roy. Soc. (London) **169**, 269 (1939).
2 Hole, Holtsmark, and Tangen, Naturwiss. **28**, 335 (1940). R. Tangen, Kgl. Norske Videnskab. Selskabs Skrifter No. 1 (1946).
3 S. E. Hunt, Phys. Rev. **87**, 902 (1952).
4 R. F. Christy and R. Latter, Revs. Modern Phys. **20**, 185 (1948).