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Absolute Precision Determination of Several Resonance and Threshold Energies and the α-Particle Energy of Po^{210}

Part II

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Zusammenfassung. Es werden gegenüber früheren Versuchen verbesserte Präzisionsmessungen der Energie und der Halbwertsbreite von je einer $Al^{27}(p, \gamma)Si^{28}$ und $F^{19}(p; \alpha, \gamma)O^{16}$ Resonanz beschrieben. Das neue magnetische 180°-Spektrometer hatte 0,04 bzw. 0,11 mm weite Spaltblenden bei 1 m Bahndurchmesser. Die Messresultate stimmen mit der durch Ausgleichsrechnung ermittelten theoretischen Ausbeutekurve innerhalb von statistischen Schwankungen überein. Die an dicken Targets gemessenen Resonanz-Energien betragen (871,80 $\pm$ 0,25) keV für Fluor und (991,83 $\pm$ 0,10) keV für Aluminium. Die Halbwertsbreiten ergaben sich zu (4,8 $\pm$ 0,2) keV und (100 $\pm$ 20) eV.

Introduction

In Part I of this paper[1]), we described absolute measurements of the thresholds of the reactions $Li^7(p, n)Be^7$ and $T(p, n)He^3$ and of the α-particle energy of Po^{210} with a semicircular magnetic spectrometer. The same apparatus and method has been used for remeasuring absolute energy values of the reactions $Al^{27}(p, \gamma)Si^{28}$ at 992 keV and $F^{19}(p; \alpha, \gamma)O^{16}$ at 872 keV both of which are often used as calibration standards. In both measurements, the half-width of the proton energy distribution after passing the spectrometer was smaller than the natural half-width of the resonance. Thick targets were used only and the measured points were always fitted to the theoretically predicted curves. At the same time these adjustments gave new values for the resonance half-widths.

$Al^{27}(p, \gamma)Si^{28}$ at 992 keV

The half-width of this resonance is known[3])[8]) to be $\leqq$ 100 eV. Therefore, we chose the highest possible resolution of the spectrometer. The energy distribution of the protons behind the exit slit, which ideally

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would be an isosceles triangle, had a full half-width of 80 eV. The target received a mean current of about $3 \cdot 10^{-2}$ μA which was measured as described in Part I. Two of the three targets used were thin layers of aluminum evaporated in the vacuum of the target chamber on a copper backing. They were at least 3 keV thick, as proved by the γ-ray yield 3 keV above the resonance. The targets therefore were thick for the resonance under consideration. Targets made in the same way on a gold backing failed to give reproducible results, and the thick target yield above resonance was reduced to less than one half during a one hour's run. We do not know the reason for this behaviour. On the other hand, the targets on copper gave well reproducible results for at least three passages across the resonance, during a time of about two hours. The two targets mentioned above were heated to about 100°C. No systematic shift of the resonance value between the single passages has been observed. Therefore, no distinction between the three or four passages of one measurement has been made. A third measurement with 220 eV resolution was done on a target which consisted of a 0.2 mm thick aluminum band heated by a current to about 400°C. Both targets made by evaporation showed only very little background below the resonance. These measurements were also used for determining the half-width, whereas from the third target only the resonance value was taken, because of poorer statistics and resolution. Table 1 gives the data of the three measurements. The resonance energy was calculated from these measurements by assigning the weights 4, 4, and 1.

The γ-detector was a $2 \times 2''$ NaI(Tl) scintillation counter which was placed about 10 mm behind the target. The counter axis coincided with the proton beam at the target. All pulses corresponding to photo peaks from γ-quanta of energy between 1.6 and 13 MeV were counted. The time proportional background was smaller than 40% of the lowest counting rate observed. This background could be substracted, since the time used for each single point has been recorded. This time did not vary by more than 10%.

In order to calculate the resonance energy from the measured points, the following method was used: Assuming an idealized energy distribution of the protons behind the exit slit corresponding to an isosceles triangle and a Doppler broadening corresponding to the target temperature, a theoretical thick target yield curve was determined for a single level of Breit-Wigner shape. Four free parameters of this curve, i.e. the resonance energy, the half-width of the resonance, and the yields below and above resonance, were calculated by a least squares adjustment of the measured points. Because of the high resolution of the spectrometer, the yield curve of this sharp resonance rises very steeply. As expected,

the resonance value thus calculated differed by a few eV only from the value which was obtained by off-hand drawing a suitable curve into the measured points. Consequently, the error of the final result is practically not influenced by the uncertainty of the determination of ν_{uncorr}.

Table 1

Target	Aluminum evaporated in vacuo		Aluminum band	CaF_2
	Target I	Target II		
Target temperature (°C) . .	ca. 100	ca. 100	ca. 400	ca. 30
Temperature of molybdenum rod (°C)	22.0	22.0	22.5	21.0
Slit distance (mm)	1000.102	1000.102	1000.020	1000.013
Slit width (entrance and exit) (mm)	0.04	0.04	0.11	0.11
ν_{uncorr}(kcps)	12256.07	12256.00	12257.20	11490.75
Hartree correction (kcps) . .	− 0.35	− 0.35	− 0.46	− 0.10
Resonance energy (keV) . .	991.84	991.83	991.79	871.80

Figure 1 shows the results of the first two measurements and the curves calculated in the way indicated above. The deviations of the measured points from the curve are similar for the third measurement. We believe that absolute values of resonance energies, which finally have an error not much different from the resolution used, should be worked out only from theoretically determined yield curves with which in turn the measured points have to be statistically in agreement.

The resonance energies of the three measurements which had different Hartree corrections and different resolution coincide within 50 eV. Since the uncertainty in the determination of the magnetic field represents the main contribution to the final error of this resonance value, the shimming and measurement of the field was given special attention. An area of 10 mm width along the proton path did not contain any point where the field strength differed from the mean value by more than one part in 10^4. In the field measurements for obtaining the Hartree corrections the sweep used at the oscilloscope was 120 cps/mm. This gave a width of the nmr signal of about 8 mm. The position of this signal could be read on the screen with an estimated error of $\pm$ 1 mm. A Hartree correction consisted of field measurements at 45 points. The value at a single point was found to be reproducible within 200 cps or better. The two Hartree corrections

obtained before and after a run agree within 200 cps. Table 2 gives the errors of the first two measurements with targets on copper backings. Because the errors are strongly correlated, we take as the final error the error of a single measurement.

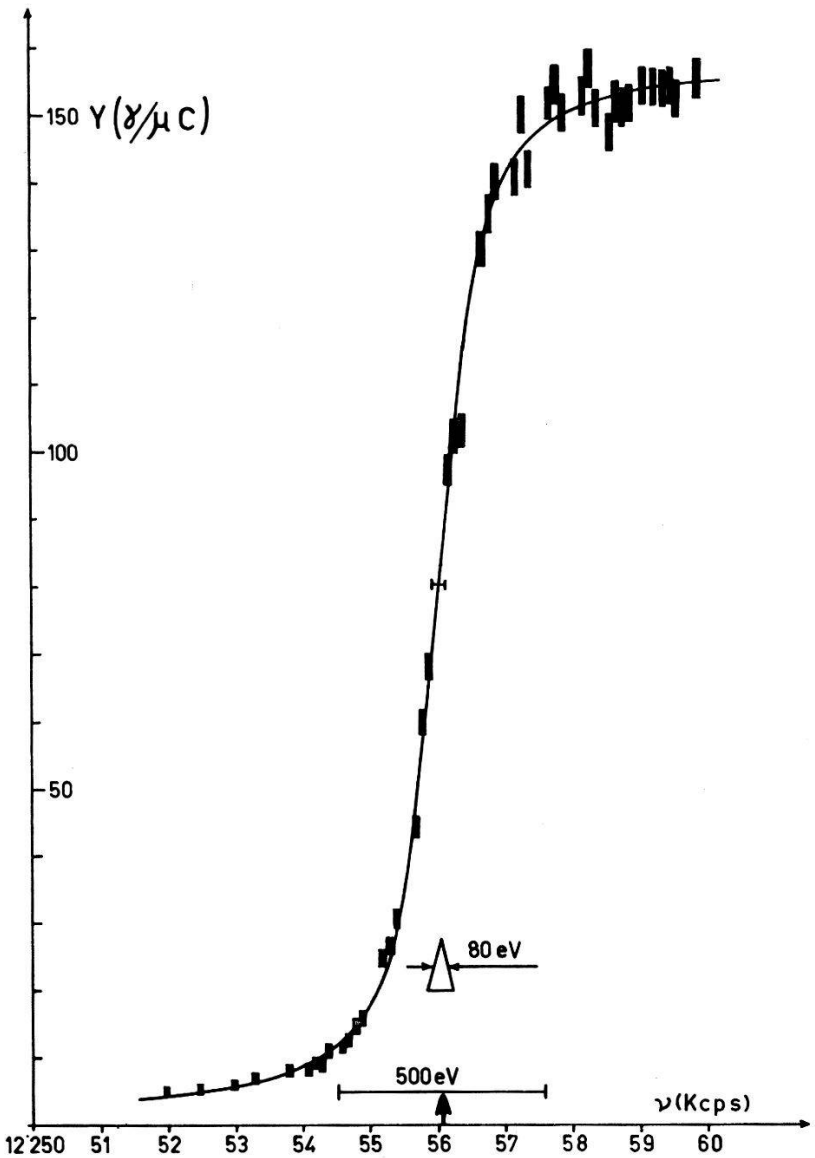

Fig. 1 a

Fig. 1 a and 1 b

γ-ray yield of the targets I and II from the $Al^{27}(p, \gamma)$ resonance versus spectrometer field (expressed in kcps). Counting and frequency errors are shown to scale. The triangle represents the probable energy distribution of the protons at the target. The curves were calculated as described in the text. The value of ν_{uncorr} is indicated by an arrow.

Recently, attention was called[2]) to the fact that the discrete energy losses which the incident protons suffer in passing through the target should produce wiggles on the high energy side of the thick target yield

curve together with a slight shift of the midpoint of the yield towards lower energy. We have been well aware of this effect which was already considered by J. W. MÜLLER in 1958[3]) and we have indeed occasionally observed an indication of such wiggles on freshly evaporated targets. However the effect was never reproducible and always disappeared after about 10 minutes of irradiation. An accompanying shift of the yield curve midpoint during this period did not exceed 40 eV. The subsequent stability of the midpoint for hours was always excellent. A shift of the

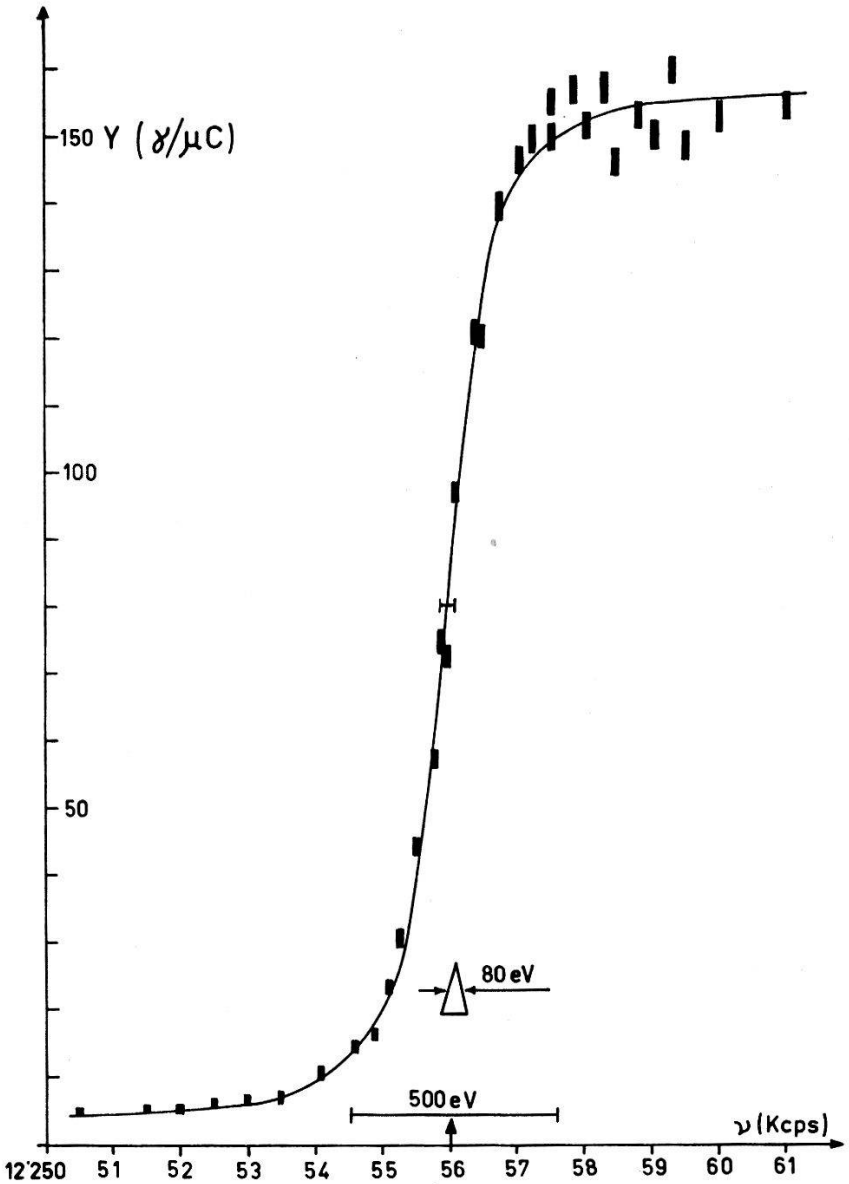

Fig. 1 b

midpoint by as little as 25 eV between the three or four passages belonging to a single measurement would in no case have escaped detection. Consequently, we do not believe that the disappearance of the wiggles was caused by continuous deposition of contaminating material. Furthermore,

a theoretical estimate shows that with our resolution and Doppler broadening and the Breit-Wigner width of this resonance the shift of the midpoint is certainly less than 60 eV. A detailed discussion if this effect and a different explanation of its origin will be the subject of a forthcoming paper.

Table 2

Absolute standard errors, expressed in frequency (kcps)

Source of error	$Al^{27}(p,\gamma)Si^{28}$ Target I	$F^{19}(p;\alpha,\gamma)O^{16}$ CaF_2 Target
1. ν_{uncorr}:	± 0,1	± 1.4
2. Asymmetrical energy distribution of protons behind the exit slit as a result of asymmetrical stabilization of the Van de Graaff voltage:	± 0.3	± 0.7
3. Hartree correction, including reading error of nmr signal on oscilloscope:	± 0.4	± 0.5
4. Measurement and stability of frequency (field) during runs:	± 0.05	± 0.05
5. Distance between slits, including uncertainty of temperature of the molybdenum rod: . .	± 0.3	± 0.3
6. Constants used for calculation of resonance energy:	± 0.2	± 0.2
Combined error:	$\sqrt{0.39}$	$\sqrt{2.83}$
Absolute energy value:	± 100 eV	± 250 eV

$F^{19}(p;\, a,\, \gamma)O^{16}$

This resonance was measured with a half-width of the energy distribution of 190 eV and a mean target current of $5 \cdot 10^{-2}\ \mu A$. Two measurements were made, one with a LiF target and the other with CaF_2. Both these targets have been prepared by vacuum deposition outside the target chamber and had a thickness of at least 50 keV. They were not heated. Instead, the beam was swept electrostatically across the target, as described in Part I[1]). Below the resonance, CaF_2 yielded a much lower counting rate than LiF. Furthermore, the reproducibility of the CaF_2 measurement was quite good, whereas LiF was less satisfactory in this respect, so as to make a determination of the resonance half-width doubtful. Although the resonance value obtained by the latter target differed by 40 eV only from the CaF_2 result, we did not consider it in calculating the final result, but think of it as a check of the other measurment.

The resonance value and the half-width from the CaF_2 target were determined in the same way as for $Al^{27}(p, \gamma)Si^{28}$, but without taking into account the Doppler broadening and the finite resolution of the spectrometer, since their contributions to the actual width are negligible. Figure 2 shows the yield curve from this target.

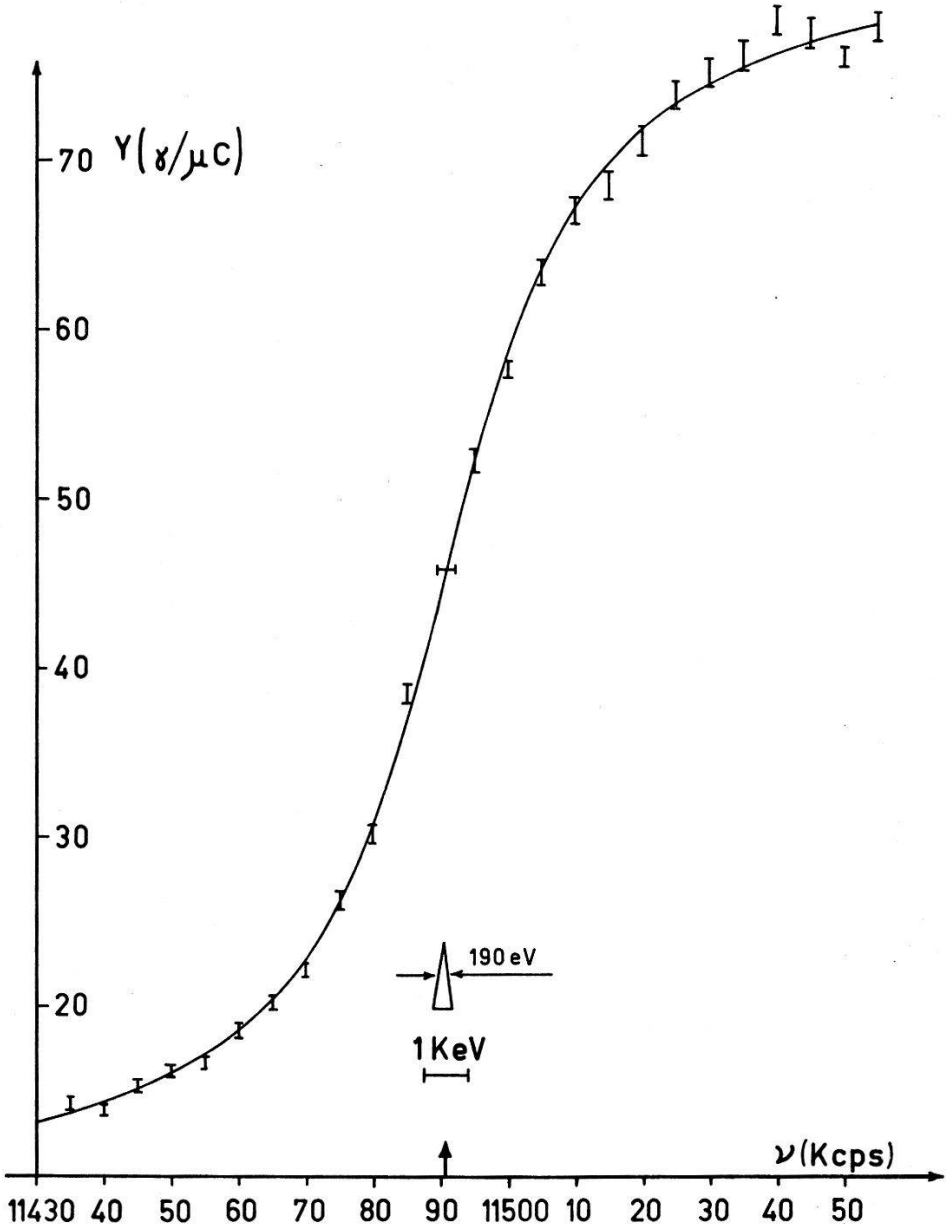

Fig. 2

γ-ray yield of the $F^{19}(p; \alpha, \gamma)$ resonance versus spectrometer field. The frequency error of a single point is too small to be shown, but the counting errors are shown to scale. No background has been subtracted. The curve was calculated as described in the text.

The same γ-ray detector was used as in the Al measurements. Only γ-quanta with energy above 3 MeV were counted. The time proportional

background amounted to less than 3% of the lowest counting rate and therefore has not been subtracted. Tables 1 and 2 show the data and errors of the CaF_2 measurement.

Results

Table 3 compares our results to some other more recent measurements. Our resonance energies and half-widths agree with the values obtained by electrostatic deflection by BONDELID[4]), especially if we take his most recent resonance value of $Al^{27}(p, \gamma)$[5]). Agreement exists also, within the error limits, with the resonance values of BECKNER *et al.*[6]). However, a comparison to the values of HUNT *et al.*[7]) shows a discrepancy larger than the errors indicated.

Table 3

Results and comparison to earlier values (keV)

	$F^{19}(p; \alpha, \gamma)O^{16}$		$Al^{27}(p, \gamma)Si^{28}$	
	E_{res}	Γ	E_{res}	Γ
BUMILLER *et al.*[10]) . . . (as corrected in [11]))	871.5 ± 0.4	4.5 ± 0.2	991.1 ± 0.2	< 0.5
BUMILLER *et al.*[3])[9]) . . .				0.06 ± 0.03
BONDELID and KENNEDY[4]) . . . . . (as corrected in [5]))	872.4 ± 0.4	4.5 ± 0.3	992.0 ± 0.5	0.10 ± 0.05
HUNT *et al.*[7])	873.5 ± 0.7	4.2	993.5 ± 0.8	< 0.4
BECKNER *et al.*[6])	872.3 ± 0.5		992.2 ± 0.5	
present work	871.80 ± 0.25	4.8 ± 0.2	991.83 ± 0.10	0.10 ± 0.02

The half-width of the Al resonance as measured in the present work and the value given by BUMILLER *et al.*[3])[8])[9]), (60 ± 30) eV, are compatible within the errors of both measurements. The error of the new half-width determination is smaller than in BUMILLER's paper. Owing to the high stability of the magnetic field, the fluctuations of the field did not broaden the yield curve. In addition, the relatively high intensity of the proton beam passing the spectrometer enabled us to use a higher resolution. The short measuring time, the absence of oil pumps, and the good vacuum in the target chamber allowed the target to be used at a temperature as low as 100°C. This however does not increase the precision considerably, because the Doppler broadening is reduced only very little. The precision with which the magnetic field could be reproduced or set to a predetermined value was very high, about ± 4 parts in 10^6 (corresponding to

$\pm$ 8 eV). Thus we did not make use of the possiblity of changing the target potential for the measurement of the half-width, as it was done in the previous experiment.

Our value of the Al resonance energy differs from the result obtained by BUMILLER *et al.*[10]) by three times the error quoted, even after correction for the permeability of the vacuum chamber, as mentioned by these authors and measured later on by STAUB and WINKLER[11]). Since BUMILLER, MÜLLER and STAUB[8]) obtained somewhat later, but with the same apparatus, nearly the same value as BUMILLER *et al.*[10]), this difference may be taken as an indication of one or several of the following systematic errors:

1. BUMILLER *et al.*[10]) used a middle slit aperture of 8 mm or 20 times more than in the present experiment. The actual orbit of the proton beam in the magnetic field was therefore only known within this limit and, since the magnet has a relatively high field gradient ($1/B \cdot dB/dr$ about 3×10^{-5} per mm, to be compared to the maximum value of 1×10^{-5} per mm in the new spectrometer), there was the possibility that the protons moved in a region where the average field was higher. About one third of the deviation (250 eV) could be accounted for in this manner. **2.** BUMILLER *et al.* used a geometric resolution which was more than ten times lower than in the present experiment. Although the method of stabilization of the van de Graaff accelerator used in the previous experiment reduced greatly the probability of getting an asymmetrical energy distribution of the protons upon emerging from the exit slit, an asymmetry small compared to the resolution would have caused a seizable error. BUMILLER *et al.* did not consider an error for asymmetrical stabilization. **3.** The nmr probe used by BUMILLER *et al.* for measuring the field was not only bigger than the one used in our experiment, but its axis was perpendicular to the particle orbit. Thus it gave a mean value of a rather inhomogeneous field because of the gradient mentioned above. In addition, the geometrical position of the probe and of the slits defining the particle orbits relative to the magnet were less well known than here. The effects mentioned under 3. may account for another quarter of the deviation. **4.** In the apparatus of BUMILLER *et al.*, the nmr probe for stabilizing and measuring the field during the runs was placed near to one end of the magnet, about 15° behind the entrance slit. Since the magnet was mechanically much less stable, the field distribution was also considerably less stable than in the present experiment. The deflection of the protons is mainly caused by the field in the middle region of the magnet as shown by the factor '$\sin \vartheta$' in the Hartree correction. Therefore, the field value measured during a run entered with comparatively little weight into the determination of the proton energy. The field distribution towards the ends

of this magnet was found to fluctuate somewhat in time. These fluctuations enter strongly into the field measurement but only little into the deflection. We have examined this effect and found that it could explain up to one third of the deviation. In the previous experiment, no error was considered for this effect. **5**. The magnet used by BUMILLER *et al.* had always a slight periodical variation of field strength along the particle orbit, which was due to the threaded holes used for fixing the pole pieces. This period coincided with the distance between the successive points in which the field was measured for obtaining the Hartree correction. These points were situated at the field minima. Therefore, the mean value of the field calculated with the aid of the Hartree correction was slightly low. This systematic error has been verified recently and found to shift the Al resonance value towards lower energy by about (100 $\pm$ 100) eV.

We believe that the result of our measurement of the Al resonance which we obtained by the same method as BUMILLER *et al.* cannot have been affected by a systematic build-up of contamination layers on our targets. The present value of the $F^{19}(p; \alpha, \gamma)$ resonance is slightly higher than the one given by BUMILLER *et al.* But this deviation is relatively smaller than in the case of Al and well within the combined error of the two measurements.

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