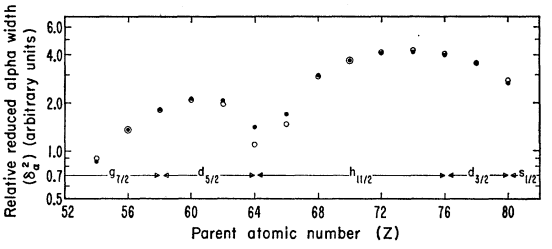


FIG. 6. Comparison of the theoretical reduced widths for the same BCS wave functions set ($V_0$) but in one case using the full BCS wave functions (•) and in the other case (○) using only the parts of the BCS wave function with correct proton number.

(4) for the absence of a pairing force and configuration mixing. It is seen that the $(d_{5/2})^n$ and $(h_{11/2})^n$ proton configurations make the largest intrinsic contributions to alpha decay. The $g_{7/2}$ orbital has a small alpha matrix element because of its relatively small radial wave function in the nuclear surface region.

Figure 6 compares for the free-space force strength wave functions the alpha-width calculations using the fixed-particle parts [Eq. (8)] and using essentially the whole BCS wave function in Zeh's modification[16] of Eq. (5). It is seen that there is little difference between the calculations except near the closed subshell 64, where the pairing correlation changes rapidly with $Z$.

Clearly the results are encouraging for these simple BCS calculations neglecting $n$-$p$ interactions, possible changes of neutron pair configuration with $Z$, and 4-quasiparticle contributions in ground. Probably alpha widths and spectroscopic factors for $(p,t)$ reactions and other direct interactions involving transfer of nucleon pairs are among the most sensitive experimental probes of the nucleon-nucleon correlations resulting from the pairing force. Further study along these lines should be most valuable in testing theory.

### ACKNOWLEDGMENT

We are grateful for valuable discussions with Dr. Dieter Zeh and Dr. Hans Jörg Mang. This work was done under the auspices of the U. S. Atomic Energy Commission.

PHYSICAL REVIEW VOLUME 134, NUMBER 6B 22 JUNE 1964

# Electric Quadrupole Transitions Near $A=16$: The Lifetimes of the First Excited States of $O^{17}$ and $F^{17}$†

J. A. BECKER
*Brookhaven National Laboratory, Upton, New York*

AND

D. H. WILKINSON
*Brookhaven National Laboratory, Upton, New York and Nuclear Physics Laboratory, Oxford, England*

(Received 30 January 1964)

As the beginning of a program to study $E2$ lifetimes in the neighborhood of $A=16$, we have remeasured the mean lifetimes of the first excited states of $O^{17}$ and $F^{17}$; we find $(2.587\pm0.042)\times10^{-10}$ sec and $(4.068\pm0.087)\times10^{-10}$ sec, respectively.

## INTRODUCTION

AS is well known, the independent particle model (IPM) has enjoyed remarkable success in describing level schemes in the $1p$ and $(2s,1d)$ shells.[1,2] This success has, in fair measure, extended to radiative transitions at least of dipole character. It is also well known, however, that the model has had very scant success in describing electric quadrupole transitions, even those between low-lying states that are themselves apparently well located by the model and which are involved in dipole transitions that go according to the predictions of the model. It is even true that in no case that has been well investigated does the $E2$ width agree acceptably with the value forseen by the IPM. It is important to understand this phenomenon and, in particular, to discover whether the situation can be remedied by some process of "fixing up" in which the wave functions remain essentially those of the IPM but with the systematic addition of some further feature that represents the hopefully small admixture to them of higher configurations or collective motion. To test this possibility, one should initially confine oneself to a limited range of nuclei in a region where the IPM wave functions are as simple as possible. Such a region is in the immediate neighborhood of $O^{16}$ where, according to

† Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] See, e. g., D. Kurath, Phys. Rev. **101**, 216 (1956); **106**, 975 (1957); A. M. Lane, Proc. Phys. Soc. (London) **A68**, 189 (1955); **A68**, 197 (1955).

[2] See, e. g., B. H. Flowers and J. P. Elliott, Proc. Roy. Soc. (London) **A229**, 536 (1955); J. P. Elliott and B. H. Flowers, *ibid.* **A242**, 62 (1957).

the IPM, the $1p$ shell has just filled and so where we are dealing with small numbers of particles and holes.

We have therefore embarked on a program of the measurement and remeasurement of $E2$ transition strengths near $O^{16}$. This paper is concerned with the beginning of this program, the measurements of the lifetimes of the first excited states of $O^{17}$ and $F^{17}$. This paper contains no discussion of the general problem, nor do we present the voluminous history behind these present transitions (see, e.g., Ref. 3); we reserve our analysis for a later time. We present these results separately because these transitions, representing according to the IPM single-particle $2s \rightarrow 1d$ jumps, are central to the whole problem of $E2$ enhancement in the light nuclei, and because the literature contains a severe and puzzling experimental discrepancy in one of them which will now be exposed. The first accurate measurement[4] of the $O^{17}$ lifetime gave a mean life of $(2.55\pm0.13)\times10^{-10}$ sec. The next measurement[3] gave $(4.30\pm0.21)\times10^{-10}$ sec. A following measurement[5] gave $(2.63\pm0.08)\times10^{-10}$ sec. In view of the importance of this number we have undertaken a fourth accurate measurement. We have also undertaken another measurement of the $F^{17}$ mean life for which there was agreement between the first two groups of experimenters: $(4.45\pm0.22)\times10^{-10}$ sec[4] and $(4.29\pm0.22)\times10^{-10}$ sec,[3] agreement which, however, could not be taken as wholly confirmatory in view of the disagreement between the two groups of experimenters over $O^{17}$.

## EXPERIMENT

The method used for both measurements was that of the pulsed beam. The slanted-target technique[6] was used; deuterons of 2.5- and 3.5-MeV bombarded oxygen targets and produced the bodies of interest through the reactions $O^{16}(d,p)O^{17}$ and $O^{16}(d,n)F^{17}$, respectively. Completely new fast-timing equipment[7] was used from that employed in the earlier pulsed beam work[5] at Brookhaven National Laboratory: The earlier work used an rf vernier method and the present a pulse-overlap method. Briefly, the incident deuteron beam is pulsed at the rate of 7.6 Mc/sec. Radiation resulting from the beam bursts incident on the target is detected with a cylindrical plastic scintillator optically coupled to a high speed photomultiplier tube. The plate current of the photomultiplier tube is limited and clipped directly at the anode of the multiplier tube to form a standard waveform for timing purposes; another standard waveform is derived from the rf deflecting voltage.

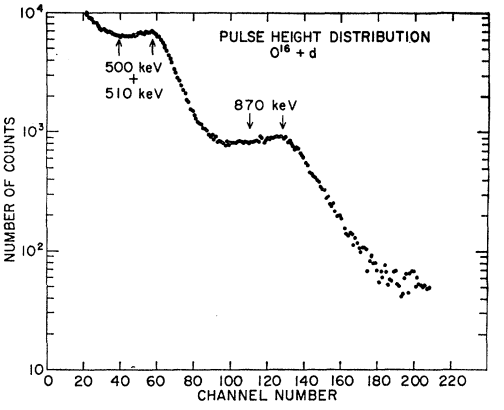


FIG. 1. Pulse-height distribution of events in the $1\frac{1}{2}$-in.-long $\times$1-in.-diam plastic scintillator observed during bombardment of the $La_2O_3$ target with 2.5-MeV deuterons. The Compton distributions are due to the 870-keV gamma ray from the first excited state of $O^{17}$ and the joint effects of the 500-keV gamma ray from the first excited state of $F^{17}$ and annihilation radiation. The pulse-height selection (channels) used in measuring the time distributions are indicated by vertical arrows in the figure.

These two standard signals are then mixed in a pulse overlap type time-to-height converter[7]; the output signal of the converter, after suitable amplification, is sorted and stored in a 400-channel analyzer. A signal proportional to the energy deposited in the scintillator is taken from a dynode of the photomultiplier and, after amplification, used for pulse-height analysis; when desired, the standard output signal of the pulse-height selector was used to gate the multichannel analyzer.

In the work on $O^{17}$ the gamma rays were detected in a cylindrical Nash and Thompson plastic scintillator of dimensions $1\frac{1}{2}$-in.$\times$1-in diam with its front face 13 cm from the target and at 90° to the beam direction. A pulse spectrum observed with this scintillator mounted on a RCA photomultiplier of type C-7260B is shown in Fig. 1. Two clear Compton shoulders are seen, one due to the 870-keV gamma ray from the first excited state of $O^{17}$ and one due to the joint effects of the 500-keV gamma ray from the first excited state of $F^{17}$ and annihilation radiation. Underlying the higher shoulder are pulses due to a variety of sources including (effectively prompt) gamma rays from higher excited states of $O^{17}$. As can be seen these are a minor contribution to the counting rate in the channel set as shown for the 870-keV radiation from $O^{17}$. With the pulse-height channel as shown in Fig. 1 many time spectra were taken for each of two targets, one of quartz and one of lanthanum oxide, $La_2O_3$. Interleaved with these spectra were prompt spectra due to radiations from the bombardment of graphite targets under identical conditions and with the same channel condition. Figure 2 shows typical time spectra from oxygen and carbon targets.

For the work on $F^{17}$ it is not adequate simply to use the lower of the channels shown in Fig. 1 owing to the admixture of the $O^{17}$ radiation. In order that the meas-

[3] N. H. Gale, J. B. Garg, and J. M. Calvert, Nucl. Phys. **38**, 222 (1962).
[4] J. V. Kane, R. E. Pixley, R. B. Schwartz, and A. Schwarzschild, Phys. Rev. **120**, 162 (1960).
[5] J. Lowe and C. L. McClelland, Phys. Rev. **132**, 367 (1963).
[6] J. Lowe, C. L. McClelland, and J. V. Kane, Phys. Rev. **126**, 1811 (1962).
[7] R. Sugarman, F. C. Merritt, and W. A. Higenbotham, Brookhaven National Laboratory Report 711 (T-248), 1962 (unpublished).

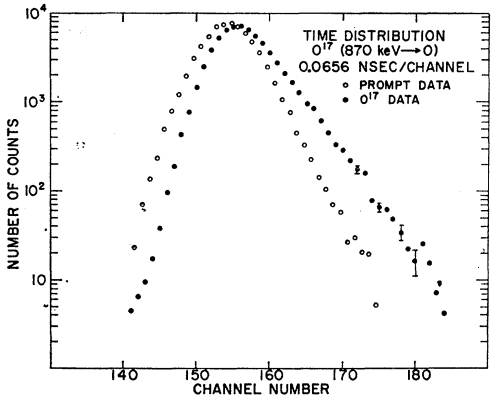


FIG. 2. Typical delayed and prompt time distributions obtained for the decay of the 870-keV first excited state of $O^{17}$. This particular delayed distribution was observed with a $La_2O_3$ target; the incident deuteron energy was 2.5 MeV. The background events were taken to be a straight line and are subtracted from the time distribution; in this case the background was 11.6 counts per channel. The prompt distribution was measured under identical conditions except that the $La_2O_3$ target was replaced with a graphite target. The gamma-ray pulse-height selection used to obtain both distributions is indicated in Fig. 1.

urements should refer to the $F^{17}$ radiation and not contain a component due to the $O^{17}$ radiation we imposed a neutron coincidence condition. A cylindrical Pilot B scintillator of dimensions 3 in.×4 in. diam was set up to 0° to the deuteron beam direction with its front face 8 cm from the target. Its response to neutrons in the energy range from the $O^{16}(d,n)F^{17}$ reaction was determined using neutrons from the $T(p,n)He^3$ reaction and a pulse-height selection criterion was imposed that eliminated pulses of size greater than could be due to neutrons from the $F^{17}$-producing reaction. For this work

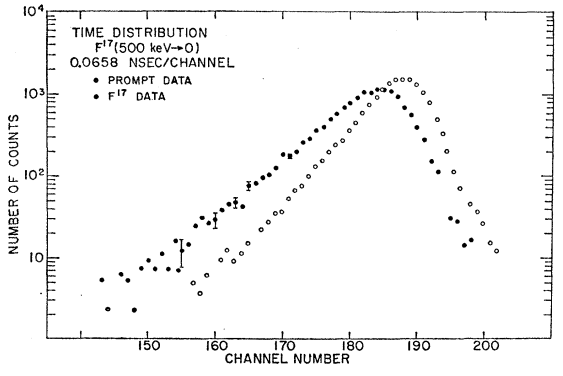


FIG. 3. Typical delayed and prompt time distributions obtained for the decay of the 500-keV first excited state of $F^{17}$. This delayed distribution was observed with a $La_2O_3$ target; the incident deuteron energy was 3.5 MeV. In order to sort out the 500-keV gamma rays a neutron coincidence condition was imposed. The background events were taken to be a straight line and are subtracted from the delayed time distribution; in this case the background was 7.2 counts per channel. The prompt distribution was measured by replacing the $La_2O_3$ target with a graphite target and removing the neutron coincidence condition. The gamma-ray pulse-height selection used to obtain both distributions is indicated in Fig. 1.

the gamma-ray detecting timing scintillator was placed at 90° to the beam and with its front face 3 cm from the target. This detector was a cylindrical Pilot B plastic scintillator, of dimensions 2 in.×2 in. diam. A sequence of many runs, again interleaved with prompt time spectra from a graphite target, was made using the lanthanum oxide target. Typical prompt and $F^{17}$ time spectra are shown in Fig. 3.

We must inquire into the possible dilution of the $F^{17}$ time spectra with $O^{17}$ radiation which would give a false lifetime. Such dilution could come about owing to the detection in the neutron scintillator of gamma rays from the second excited state of $O^{17}$ at 3.058 MeV that cascades to ground through the first excited state. To check on this the measurements were repeated with two changes. The gamma-ray channel was moved up to the "870-keV position" previously used for the $O^{17}$ measurements; the "neutron" channel was broadened to include effectively all the pulses due to the 2.19-MeV cascade transition between the second and first excited states of $O^{17}$. The first change eliminated the $F^{17}$ radiation and somewhat increased the efficiency for the $O^{17}$ line; the second change increased the efficiency of the "neutron" scintillator for the 2.19-MeV radiation by a factor of about 5. The coincidence rate in the region of the peak of the time spectrum fell by a factor of approximately 7. This shows that, at most, about 3% of the "$F^{17}$" spectrum can be due to the $O^{17}$ line. For the method of analysis of the time spectra that we adopted and shall shortly describe this possible contamination with $O^{17}$ would result in a wholly negligible change in the apparent $F^{17}$ lifetime. We shall not refer further to this matter.

The time calibration is critical in all such measurements. We effected this by inserting 110 cm of General Radio type-874 rigid air line into the lead carrying the $\gamma$-ray timing standard waveform and observing the shift of the prompt peak under exactly the same conditions as in the lifetime experiment. This time calibration was made before and after each of the three sets of runs. Each time calibration consisted of at least 5 measurements of the prompt peak with no delay inserted, interleaved with the same number of determinations with the 110 cm of air line in place. The prompt peak locations were found using a Gaussian fitting computer program.[8] The results are given in Table I.

It is in addition necessary to establish the linearity of the time calibration. This was done by running a radioactive source in random coincidence with the timing signal from the beam deflecting rf voltage. Counting continued until adequate statistics had been obtained to check the linearity to better than 1% over a wider range than that involved in the time calibration.

We estimate the contribution from the time calibration to the over-all error in the lifetimes as follows:

[8] P. McWilliams, W. S. Hall, and H. E. Wegner, Rev. Sci. Instr. 33, 70 (1962).

(1) The calibration of the air lines is better than $\pm 0.5\%$. We used four lines in series so this gives $\pm 0.25\%$.

(2) The statistical errors in the calibrations obtained from the fitting procedures are $\pm 0.5\%$ or less (see Table I). We take $\pm 0.5\%$.

(3) The limit of 1% on the possible non-linearity of the time-height converter corresponds to an error of $\pm 0.3\%$ or less in the lifetimes.

We combine these errors to find a total time calibration error of $\pm 0.8\%$.

## ANALYSIS

We must now extract the lifetimes from the data such as are shown in Figs. 2 and 3 (from which the small backgrounds observed at times remote from the peak have already been subtracted). Standard methods exist for estimating the effect of the prompt peak on the apparent decay of the radiation whose lifetime is being measured.[9] In particular, if the magnitude of the prompt distribution (suitably normalized) is $f$ in terms of that of the time spectrum with the lifetime (which is assumed to be undiluted with prompt radiation) at a certain point on the delayed side of the peak, then the slope of the decay curve at that point is less by the fraction $f$ than the slope appropriate to the true lifetime. However this gives wrong results in the present case: the exponential decays of Figs. 2 and 3 become good straight lines much more quickly than would be allowed by the above analysis. The reason for this is that the analysis uses, of course, the true prompt time spectrum for comparison with the decaying distribution, but this true prompt curve can never be ascertained. An effect which almost always comes into play concerns the pulse-height selection condition imposed on the energy analog signal for both prompt and decaying time distributions. Without pulse-height selection, the time distribution is rather broad, reflecting the wide range of photon statistics included in the pulse height distribution of events in the gamma-ray detector. When the pulse-height (channel) condition is imposed, selecting a narrow region from the pulse-height distribution, there results a greatly narrowed time distribution. However, our gating arrangement was not perfect, and time signals corresponding to pulse heights outside the nominal limits of the channel condition mix in with the legitimate signals in some small measure; this measure, however, depends on the form of the pulse-height distribution so that more illegal time pulses come through if the scintillator spectrum on which the channel condition is imposed is broad than if it contains relatively few events outside the narrow channel. This effect will not broaden the time spectrum at its half-way point significantly but will be much more important further from the peak where the true prompt distribution has fallen to a small fraction of its peak value. The net effect can be that the width of the prompt spectrum is not much affected but the slope of its sides changes significantly. The decaying time spectrum will not be affected identically because the ungated pulse spectrum will in general be different and so quantitative arguments based on the apparent value of $f$ as defined above are of no value.

In view of these considerations we have adopted a completely empirical approach to the extraction of the lifetime from the time spectrum. This is illustrated in Fig. 4 and is based on the certainty that, whatever the effect of the prompt peak on the apparent lifetime, this effect will diminish as one moves away from the prompt peak in time so that analysis of the decay curve far from the prompt peak will give a more nearly correct answer than analysis near the prompt peak. We first of all decide the time $t_1$, at which the counting rate is coming

TABLE I. Time calibrations.[a]

| | |
|---|---|
| Before $O^{17}$ lifetime using $La_2O_3$ target: | |
| | $(6539 \pm 41) \times 10^{-14}$ sec per channel. |
| After $O^{17}$ lifetime using $La_2O_3$ target: | |
| | $(6576 \pm 46) \times 10^{-14}$ sec per channel. |
| Mean: | $(6557 \pm 31) \times 10^{-14}$ sec per channel. |
| Before $O^{17}$ lifetime using quartz target: | |
| | $(6520 \pm 27) \times 10^{-14}$ sec per channel. |
| After $O^{17}$ lifetime using quartz target: | |
| | $(6528 \pm 30) \times 10^{-14}$ sec per channel. |
| Mean: | $(6524 \pm 21) \times 10^{-14}$ sec per channel. |
| Before $F^{17}$ lifetime measurement: | |
| | $(6583 \pm 57) \times 10^{-14}$ sec per channel. |
| After $F^{17}$ lifetime measurement: | |
| | $(6569 \pm 49) \times 10^{-14}$ sec per channel. |
| Mean: | $(6576 \pm 38) \times 10^{-14}$ sec per channel. |

[a] The errors given here come only from the fitting procedure and contain no allowance for errors in the calibration of the delay lines nor for any possible nonlinearity of the time-to-height conversion.

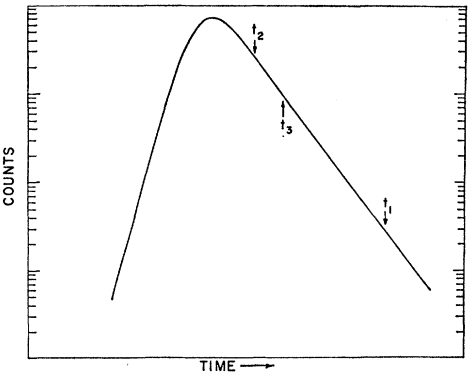


FIG. 4. Schematic representation of a delayed time distribution and the time intervals used in the analysis of the data. The method of analysis is described in the text.

[9] T. D. Newton, Phys. Rev. 78, 490 (1950).

TABLE II. Mean lifetime of first excited 870-keV state of $O^{17}$ (units of $10^{-13}$ sec).[a]

Lanthanum oxide target:

| Run | $\tau_I$ | $\epsilon_I$ | $\tau_{II}$ | $\epsilon_{II}$ |
|---|---|---|---|---|
| 61 | 2518 | 63 | 2742 | 63 |
| 63 | 2631 | 54 | 2559 | 44 |
| 65 | 2522 | 76 | 2574 | 48 |
| 67 | 2677 | 56 | 2563 | 44 |
| 69 | 2552 | 55 | 2589 | 48 |

Mean value of $\tau_I = 2589 \pm 27$
Mean value of $\tau_{II} = 2591 \pm 22$
Adopted value: $\tau = 2590 \pm 27$

Quartz target:

| Run | $\tau_I$ | $\epsilon_I$ | $\tau_{II}$ | $\epsilon_{II}$ |
|---|---|---|---|---|
| 21 | 2616 | 24 | 2611 | 30 |
| 23 | 2570 | 22 | 2552 | 27 |
| 25 | 2523 | 22 | 2582 | 32 |
| 27 | 2638 | 25 | 2615 | 30 |
| 29 | 2601 | 21 | 2574 | 27 |

Mean value of $\tau_I = 2587 \pm 10$
Mean value of $\tau_{II} = 2585 \pm 13$
Adopted value: $\tau = 2586 \pm 13$

[a] The errors stated here are those of the decay analysis only and contain no allowance for error in the time calibration.

towards the background beyond which we shall not consider it profitable to analyze the experimental data. We leave $t_1$ fixed for the subsequent analysis and its choice is completely uncritical. We then, as a trial, choose a time $t_2$. With $t_2$ left fixed for the time being we try a number of values for an intermediate time $t_3$. For each choice of $t_3$ we analyze the decay curve in the two independent regions: region I: $t_2$ to $t_3$ and region II: $t_3$ to $t_1$, by a computer program that gives an apparent mean lifetime $\tau$ and associate error $\epsilon$ for each region. For that choice of $t_3$ that gives $\epsilon_I \approx \epsilon_{II}$ we compare $\tau_I$ and $\tau_{II}$. We then vary $t_2$, repeating the whole procedure for each value of $t_2$, until $\tau_I$ and $\tau_{II}$ do not differ systematically within their common error $\epsilon$. We then say that $\tau$, the mean value of $\tau_I$ and $\tau_{II}$ is the right value for the mean lifetime with an associated error $\epsilon$. In this way we sacrifice some of the potential accuracy of the measurement since we are left with an error $\epsilon$ rather than one of approximately $\epsilon/\sqrt{2}$ that would result from an analysis between $t_2$ and $t_1$ but we have in return the assurance that the answer is reliable within its larger error.

TABLE III. Mean lifetime of first excited 500-keV state of $F^{17}$ (units of $10^{-13}$ sec).[a]

| Run | $\tau_I$ | $\epsilon_I$ | $\tau_{II}$ | $\epsilon_{II}$ |
|---|---|---|---|---|
| 02 | 3784 | 180 | 4106 | 168 |
| 04 | 3966 | 189 | 3991 | 154 |
| 06 | 4065 | 214 | 4088 | 166 |
| 08 | 4245 | 220 | 3971 | 154 |
| 10 | 4265 | 239 | 4146 | 179 |
| 12 | 4053 | 200 | 4149 | 165 |
| 14 | 4163 | 184 | 4201 | 184 |
| 16 | 4049 | 192 | 4025 | 149 |

Mean value of $\tau_I = 4056 \pm 70$
Mean value of $\tau_{II} = 4074 \pm 58$
Adopted value: $\tau = 4068 \pm 70$

[a] The errors stated here are those of the decay analysis only and contain no allowance for error in the time calibration.

The results of this analysis for the $O^{17}$ decay are presented in Table II for the $F^{17}$ decay in Table III.

As the result of these measurements we adopt the values for the mean lifetimes:

$$O^{17}: (2.587 \pm 0.042) \times 10^{-10} \text{ sec},$$

$$F^{17}: (4.068 \pm 0.087) \times 10^{-10} \text{ sec}.$$

We have arrived at the above errors by compounding:

(1) The $\pm 0.8\%$ of the time calibration already discussed;

(2) $\pm 1.0\%$ for the $O^{17}$ lifetime due to the decay analysis (Table II) and $\pm 1.7\%$ for the $F^{17}$ lifetime (Table III).

(3) An additional $\pm 1.0\%$ which we feel should cover possible systematic effects in the analysis procedures.