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Abstract: Internal conversion coefficients of transitions in ^{180}Os have been measured using a superconducting, solenoidal electron spectrometer, operated in the lens mode. The high energy resolution and efficiency allow a precise measurement of the conversion coefficients of the 528 keV yrast transition. The values obtained, $\alpha_K = 0.015$ (2), $\alpha_L = 0.004(1)$ define pure E2 multipolarity. Taken with the measured γ-ray angular distribution, the conversion coefficient leads to an unambiguous assignment of $16^+ \rightarrow 14^+$ for the 528 keV transition.

E

NUCLEAR REACTIONS ^{168}Er (^{16}O,4n), E = 87 MeV measured ICC. Deduced J,π, yrast sequence. Compton-suppressed Ge detector. Superconducting solenoidal electron spectrometer, Si(Li)detector

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1. Introduction

The spectroscopy of yrast states in ^{180}Os was reported in 1980 by Dracoulis, Fahlander and Fewell[1] based on γ-ray and electron measurements described in detail in ref [2]. Subsequently Neskakis et al and Lieder et al [3–6] proposed different spin assignments for one of the competing sequences observed near the spin 16^+ yrast states, the region of the first backbending, or alignment. The re-assignment led to an interchange of the proposed yrast and yrare sequences and consequently to different band-crossings, alignments and band intersections.

The re-assignment of ref [3-6] was based mainly on γ-ray branches not observed in earlier work [1, 2,7] and a measurement of the K-conversion coefficient of the 528 keV transition which was assigned as the $16^+ \rightarrow 14^+$ yrast transition in refs [1] and [2]. Although the upper limit on the conversion coefficient of the 528 keV transition given previously in ref [2] already excluded the multipolarity assignment in refs [3–6], a larger conversion coefficient was reported in ref [6] and taken as evidence for a mixed E2/M1 (predominantly M1) multipolarity, supporting the alternative $14^+ \rightarrow 14^+$ assignment.

The purpose of the present work is to report definitive conversion electron measurements which establish the multipolarity of the 528 keV transition. Taken with the measured γ-ray angular distributions, they lead to an unambiguous spin assignment for the 3406 keV state.

Before proceeding to the new experimental work a brief comparison of the different results is given in the following section.

2. Comparison Between Schemes

The two level schemes proposed are compared in figure 1. In refs [1,2] the 3406 keV state is assigned as the yrast 16^+ state, whilst in refs [3–6] it is instead assigned as a yrare 14^+ state. As well as leading to a different conclusion[5] regarding the yrast-yrare interaction, compared to that presented in ref[1], the re-assignment has significant consequences for the band-crossings and aligned angular momentum, as shown in figure 2. Figures 2(a) and 2(b) compare the alignment in the yrast sequence in ^{180}Os, obtained with the alternative assignments, with that for the yrast band ($\frac{1}{2}^-$ [541] configuration) in the neighbouring odd-proton nucleus ^{181}Ir, as established by Garg et al [8]. The two nuclei behave in a similar fashion with the earlier assignments, but in a dissimilar fashion with the later assignments, a difference which has proved difficult to reconcile[9].

The presence of the connecting γ-ray branches observed by Lieder et al [6] has been contested [7] but we are not, at present, able to resolve that dispute; all disputed branches are weak, for example the quoted [6] branching ratio for the 3406 keV state is $I_\gamma(1094)/I_\gamma(528) = 3 \pm 2\%$, consistent with the limit of < 2% set in ref [7].

3. Experimental Method

Excited states in ^{180}Os were populated using the ^{168}Er (^{16}O,4n) ^{180}Os reaction at 87 MeV. The target was a rolled 1.3 mg/cm^2 foil, enriched to 96% in ^{168}Er, with ~ 1.5 mg/cm^2 of lead evaporated on the rear surface to stop recoiling nuclei. The target thickness and angle to the beam direction, (target plane at 30° to the beam axis) were chosen to optimise electron energy resolution. The limiting factor in electron resolution remains the electron straggling through the thickness of target and backing determined by the range of the recoiling nuclei.

Gamma-rays were measured in a 24% efficient Ge detector surrounded by a NaI(Tℓ) anti-Compton shield. Electrons were detected simultaneously using a recently commissioned, superconducting, solenoidal electron spectrometer and a cooled Si(Li) detector. The solenoid is similar to that described by Guttormsen et al [10] and Stöffl and Henry [11]. It was operated in a swept field, lens mode[11] in which a well-defined sample of electron momenta, constrained by baffles, is transported to the Si(Li) detector, the solenoid field being stepped after equal values of integrated beam charge. The characteristics and operation of the device will be described in detail elsewhere[12].

All data were collected in event-by-event mode including the detected electron energy and a measure of the associated solenoid field. Subsequently a two-dimensional matrix of observed electron energy vs. field was constructed and the events selected on the basis of a match between the observed energy and the allowed electron momentum. This effectively eliminates incomplete events in the Si(Li) detector, due mainly to back-scattering but also to general scattering and γ-ray interactions, thus reducing the continuum background.

The lens-mode operation also eliminates the troublesome δ-ray flux which normally contributes to the background and, through rate effects, often degrades the Si(Li) detector resolution, particularly in heavy-ion induced reactions. The absence of δ-rays removes the need for an absorber foil in front of the detector which can also contribute to the degradation of energy resolution.

The efficiency of the system, fo. electrons and γ-rays, was calibrated using a ^{152}Eu source at the target position and confirmed using strong in-beam γ-rays and known activity lines produced in this bombardment and in contiguous experiments on other nuclei. The results were in good agreement with the form of the momentum dependence of the electron efficiency expected from calculations which model the spectrometer orbits and the detector response [12].

Two measurements were carried out, the first sweeping the solenoid field to cover the range 80–1500 keV in electron energy, to measure the full spectrum of ^{180}Os, the second over the restricted range ~300 – 750 keV, with a resultant increase in yield of a factor of 3.8 to optimise the statistical accuracy in the region of immediate interest.

4. Results and Discussion

A section of the electron spectrum is shown in figure 3 together with the equivalent region in the γ-ray spectrum. The dispersion in the electron spectrum is 0.48 keV/channel. The electron resolution obtained is 2.6 keV (FWHM) compared to that in our previous measurement [2] (using a mini-orange spectrometer) of 6.4 keV and ~ 10 keV reported in ref [6]. The good resolution and filtering properties of the lens-mode operation result in a peak-to-background ratio of ~6:1 for the K-line of the 463 keV $8^+ \rightarrow 6^+$ transition.

The prominent lines in figure 3 are all identified with established transitions in ^{180}Os, or lines following the β^- decay of ^{180}Os or neighbouring nuclei. The intense electron lines associated with weak 645 and 584 keV γ-ray transitions are mixed EØ/M1/E2 in character, assigned previously[2] to the $4^+_\beta \rightarrow 4^+$ and $6^+_\beta \rightarrow 6^+$ transition in ^{180}Os. A related comment on the 699 keV line is made below.

The K-line of the 528 keV transition is the weak shoulder on the complex of lines due to L–conversion of the intense 463 keV $8^+ \rightarrow 6^+$ transition and K–conversion of the 524 keV doublet. This is clearer in figure 4 which shows the region of interest and the fit and decomposition into individual lines. Electron and γ-ray intensities were obtained by the fitting of standard lineshapes (determined from isolated lines). The electron resolution was sufficient to partially resolve the L-subshell lines and in particular it was necessary to include the L_3 line explicitly. The 528 keV K-line is clearly defined and overlapped partially by the 463 keV L_3 line which falls 1.5 keV below.

Relevant conversion coefficients and theoretical values[13] are listed in table 1 where they are compared with the results of ref[2] and ref[6]. The value obtained for the 528 keV transition is $\alpha_K = 0.015(2)$, in excellent agreement with a pure E2 value. This confirms the previous limit of $\alpha_K < 0.021$ and is in disagreement, as is evident from a comparison of the spectra, with the large value obtained in ref[6]. The 528 L value given in table 1 <u>independently</u> confirms E2 multipolarity.

The conversion co-efficients alone do not fix the spin of the 3406 keV state, however, an unambiguous assignment can be made by using them in conjunction with the γ-ray angular distribution for the 528 keV transition. The measured distribution, (the basis of the results reported previously[2]), shown in figure 5, is compatible[14] with either a stretched $16^+ \rightarrow 14^+$ transition, as assigned in refs[1,2], or mixed E2/M1, $15^+ \rightarrow 14^+$ or $14^+ \rightarrow 14^+$ transitions, the last being the sequence assigned in ref[3-6]. (The γ-ray angular distributions measured in ref [1,2] and ref[6] agree.) The lower part of figure 5 shows the χ^2 fit to the distribution as a function† of the E2/M1 mixing ratio δ for the $14^+ \rightarrow 14^+$ alternative. Two minima are obtained with $\delta = -0.447^{+0.130}_{-0.114}$ or $\delta = +0.746 \pm 0.150$, the former of which is favoured. By taking the larger of these, at two standard deviations, a conservative limit of $|\delta_{max}| < 1.05$ is obtained, corresponding to a limit on the quadrupole admixture $\delta^2/(1+\delta^2) <$ 52%. The required conversion coefficient would be $\alpha_K > 0.033$, incompatible with the present measurement and, incidentally, with the limit of ref[2]. The limit on the mixing ratio obtained from the present conversion coefficient measurement# is, at the 2σ level, ($\alpha_K < 0.019$), $|\delta| > 2.8$ as shown by the hatched area in figure 5. The $14^+ \rightarrow 14^+$ possibility is eliminated. A similar result is obtained for the $15^+ \rightarrow 14^+$ possibility which requires $\delta = 0.269^{+0.030}_{-0.060}$. The only remaining alternative is a $16^+ \rightarrow 14^+$ assignment.

Finally, a comment on the conversion coefficient of the 699 keV transition assigned as $14^{+'} \rightarrow 12^+$ transition in ref [2] but, in line with their interpretation of the 528 keV line, as a $12^{+'} \rightarrow 12^+$ transition in ref [3-6], is appropriate. The 699 keV γ-ray is an unresolved doublet, with approximately

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† Alignment parameters were deduced from an evaluation of observed distributions for stretched transitions in the same measurement. Similar alignments were observed in a large range of reactions in this region.

The effect of the <u>electron</u> angular distribution on the observed electron intensity has been evaluated for the alternative spin combinations and mixing ratios and is negligible.

60% of its intensity contributed by the transition under discussion, the remaining 40% belonging to the 832 keV, $(2^+) \rightarrow$ 132 keV, 2^+ transition[6]. The composite electron line is relatively strong (see figure 3) and was interpreted by Lieder et al[6] as due to both components being mainly M1 multipolarity, supporting their re-assignment of the yrast sequence. However, we note that if the 832 keV state were the 2^+ member of the β-band (it falls within 14 keV of a linear extrapolation from the 4^+_β and 6^+_β states) it would have a significant EØ component, as do the 584 and 645 keV transitions mentioned earlier. Assuming an equivalent EØ admaixture ($\alpha_K \sim 0.09$) for the 699 keV $(2^+) \rightarrow 2^+$ component, the measured (combined) value shown in table 1 corresponds to the component value α_K (699, 3010→ 2311) ~ 0.012, compatible with the pure E2 value and the $14^{+\prime} \rightarrow 12^+$ assignment.

5. Summary

The conversion coefficients of the 528 keV yrast transition suggest pure E2 multipolarity. Together with the γ-ray angular distribution, they eliminate the $14^+ \rightarrow 14^+$ assignment and confirm the $16^+ \rightarrow 14^+$ assignment of refs [1,2]. A reversion to the earlier spin assignments would obviate the need for a special description of the differences in alignment between ^{180}Os and ^{181}Ir. This result underlines the need to re-examine the disputed γ-ray branches in ^{180}Os.

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Figure 1. Partial level schemes in ^{180}Os. On the left the assignments of ref [1,2], on the right those of refs [3–6]. The widths of the transitions represent approximately the relative γ-ray intensities quoted in those papers.

Figure 2. Comparison of net aligned angular momenta in the $(+, 0)_1$ band in ^{180}Os with the $(-,1/2)_1$ band(1/2⁻[541]) in ^{181}Ir with the alternative assignments; figure 2(a) ref [3-6], figure 2(b) ref [1,2]. The reference band parameters used are those of ref [6]; $\theta_0 = 24.0\hbar^2\ MeV^{-1}$ and $\theta_1 = 91.1\hbar^4\ MeV^{-3}$. The ^{181}Ir results are from ref[8].

Figure 3. Corresponding γ-ray and electron spectra for the ^{16}O bombardment of ^{168}Er. Asterisks indicate electron lines which are complex.

Figure 4. Detail of the electron spectrum showing the fit and component lines. The background level is determined from remote regions.

Figure 5. Gamma-ray angular distribution and χ^2 fit for the $14^+ \rightarrow 14^+$ and $15^+ \rightarrow 14^+$ possibilities for the 528 keV transition. The hatched area represents the E2/M1 mixing ratio allowed from the present conversion electron measurements.

Table 1

Conversion Coefficients for Selected Transitions in ^{180}Os

E_γ (kev)		Experiment x 100 Ref[2)]	Experiment x 100 Ref[6)]	Experiment x 100 Present	Theory x 100 M1	Theory x 100 E2
394.9	K			2.8(6)	10.7	3.0
462.9	K L M	2.5(6) <0.9	1.9(3)	1.97(9) 0.14(3)	7.06 1.11 0.255	2.06 0.59 0.135
510.6	K L_1,L_2	~1.8	1.9(7)	1.4(1) 0.27(3)	5.46 0.85	1.65 0.356
524[a)]	K	<2.1[b)]	1.9(12)	1.4(2)[c)]	5.11	1.55
527.7	K L	<2.1[b)]	5.0(15)	1.5(2) 0.4(1)	5.02 0.79	1.53 0.38
541.5	K L M	1.7(2) 0.4(1)	1.6(3)	1.31(4) 0.10(2)	4.69 0.74 0.17	1.44 0.35 0.083
566.6	K L	1.4(2)		1.3(1) 0.29(2)	4.18 0.65	1.31 0.31
584.2	K	9.0(9)	5.5(22)	9.4(7)	3.85	1.22
644.5	K L	9.4(8)	8.5(25)	8.1(4) 1.2(1)	2.99 0.47	0.99 0.21
699[d)]	K		2.5(7)	4.3(6)	2.43	0.83

a) sum of 523.6 and 524.2 keV transitions; both assigned stretched E2
b) limit quoted for 524 and 528 keV transitions
c) Corrected for contamination from the 463 keV L_1 and L_2 lines
d) unresolved doublet; see text for discussion

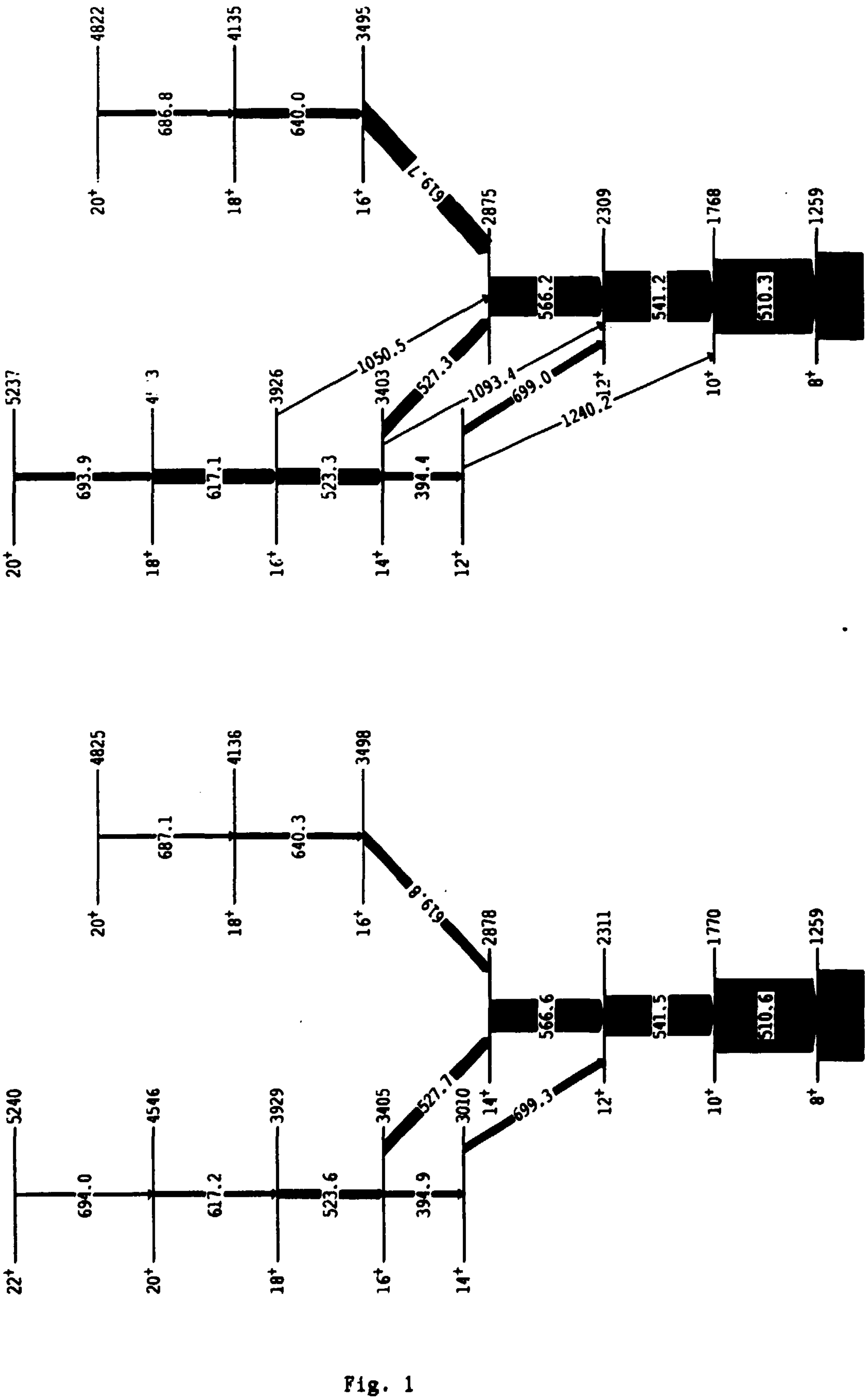

4822
4135
3495
686.8
640.0
619.7
2875
2309
1768
1259
566.2
541.2
510.3
5237
3926
3403
1050.5
527.3
1093.4
699.0
1240.2
693.9
617.1
523.3
394.4
4825
4136
3498
687.1
640.3
619.8
2878
2311
1770
1259
566.6
541.5
510.6
5240
4546
3929
3405
3010
527.7
699.3
694.0
617.2
523.6
394.9

Fig. 1

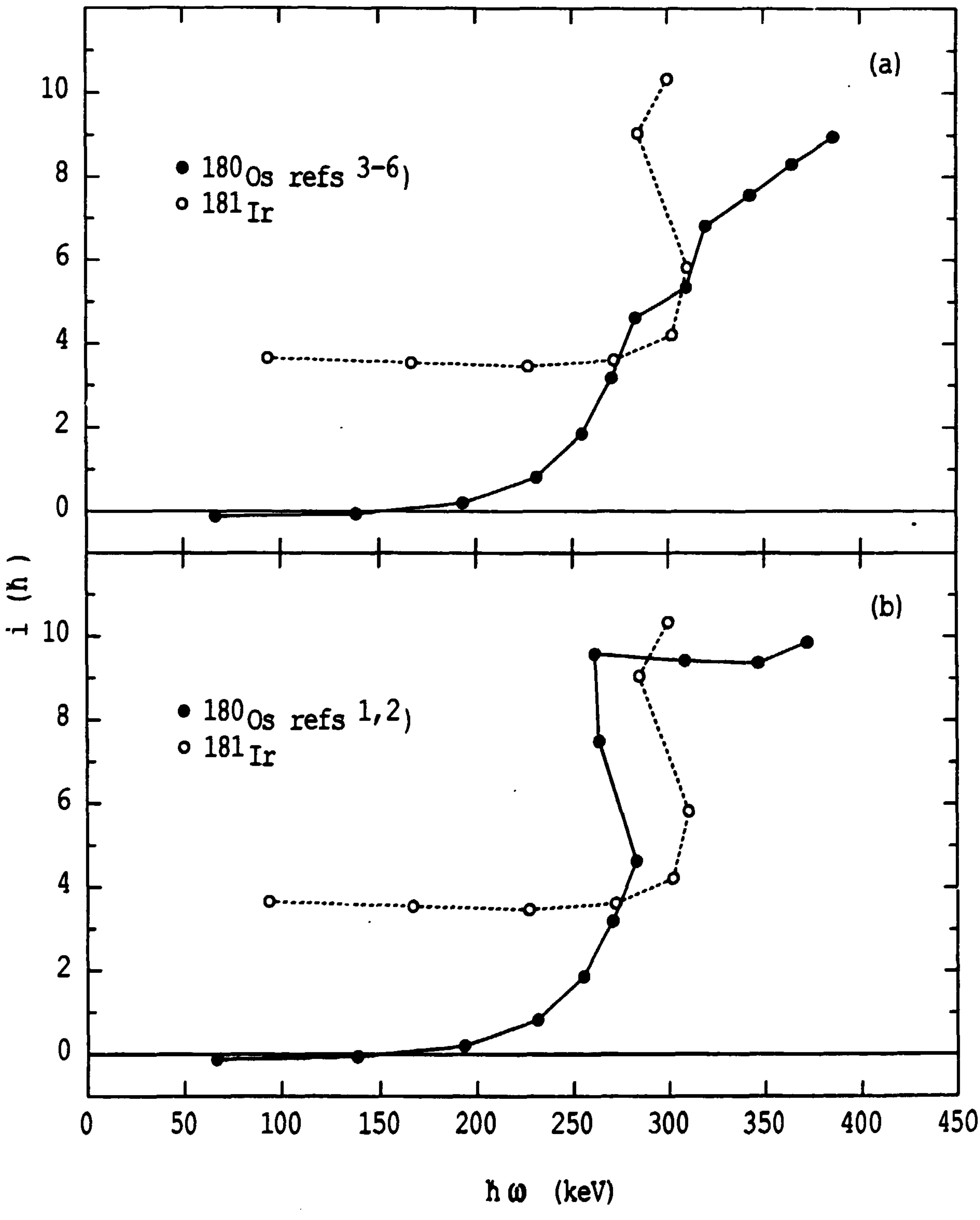

(a)
(b)
● 180Os refs 3-6)
○ 181Ir
● 180Os refs 1,2)
○ 181Ir
i (ħ)
ħω (keV)
0
2
4
6
8
10
0
50
100
150
200
250
300
350
400
450

Fig. 2

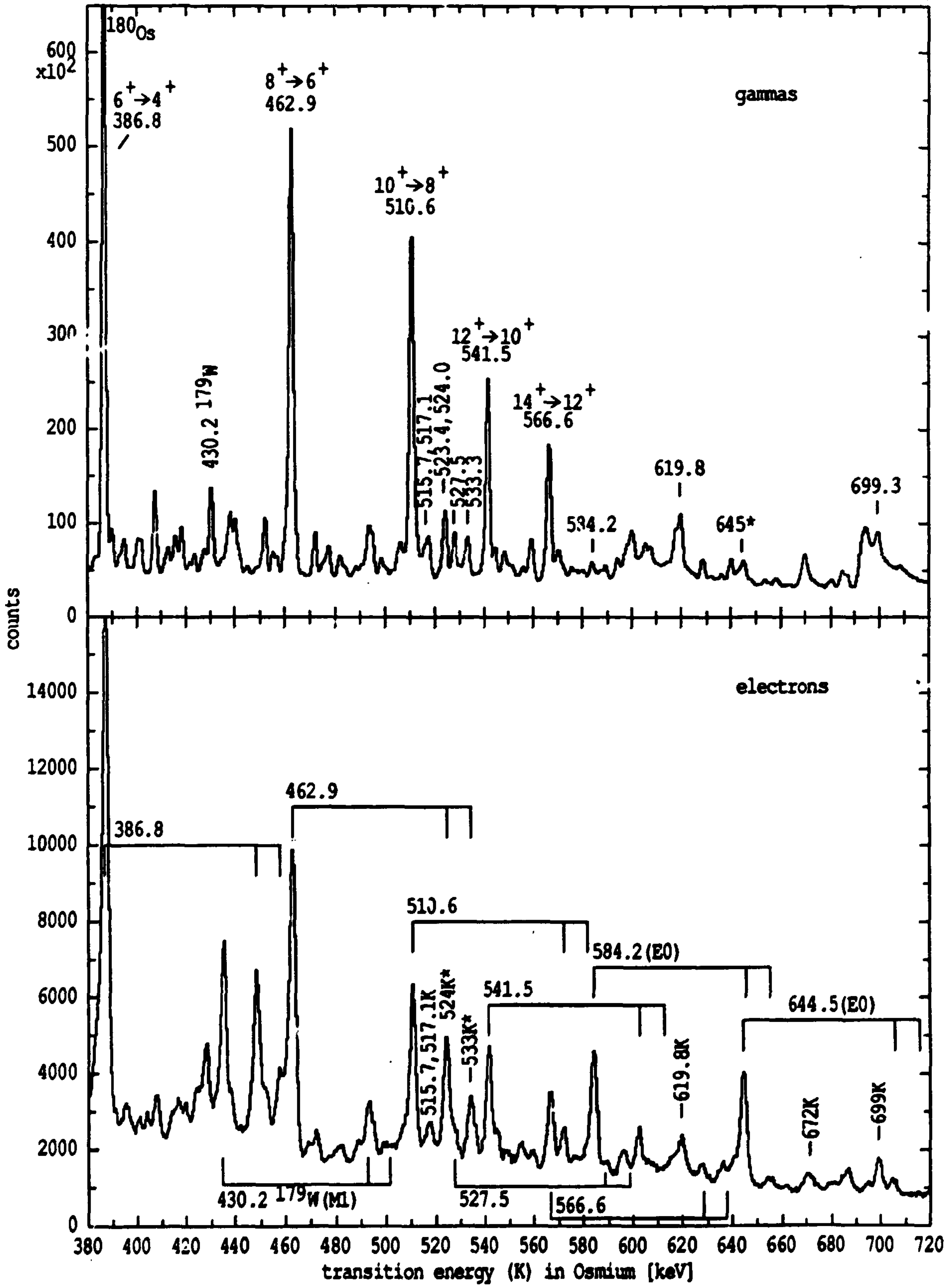
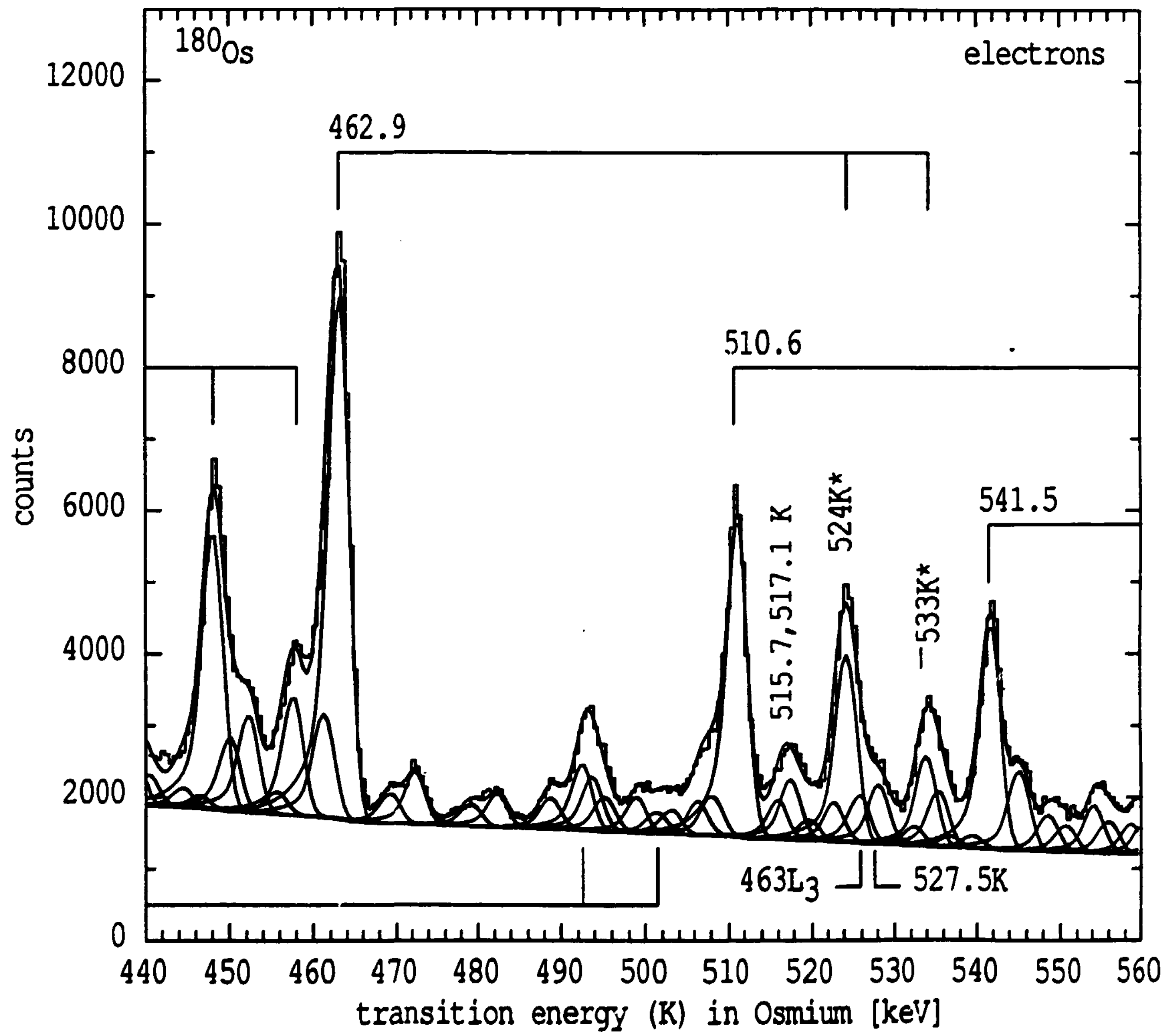
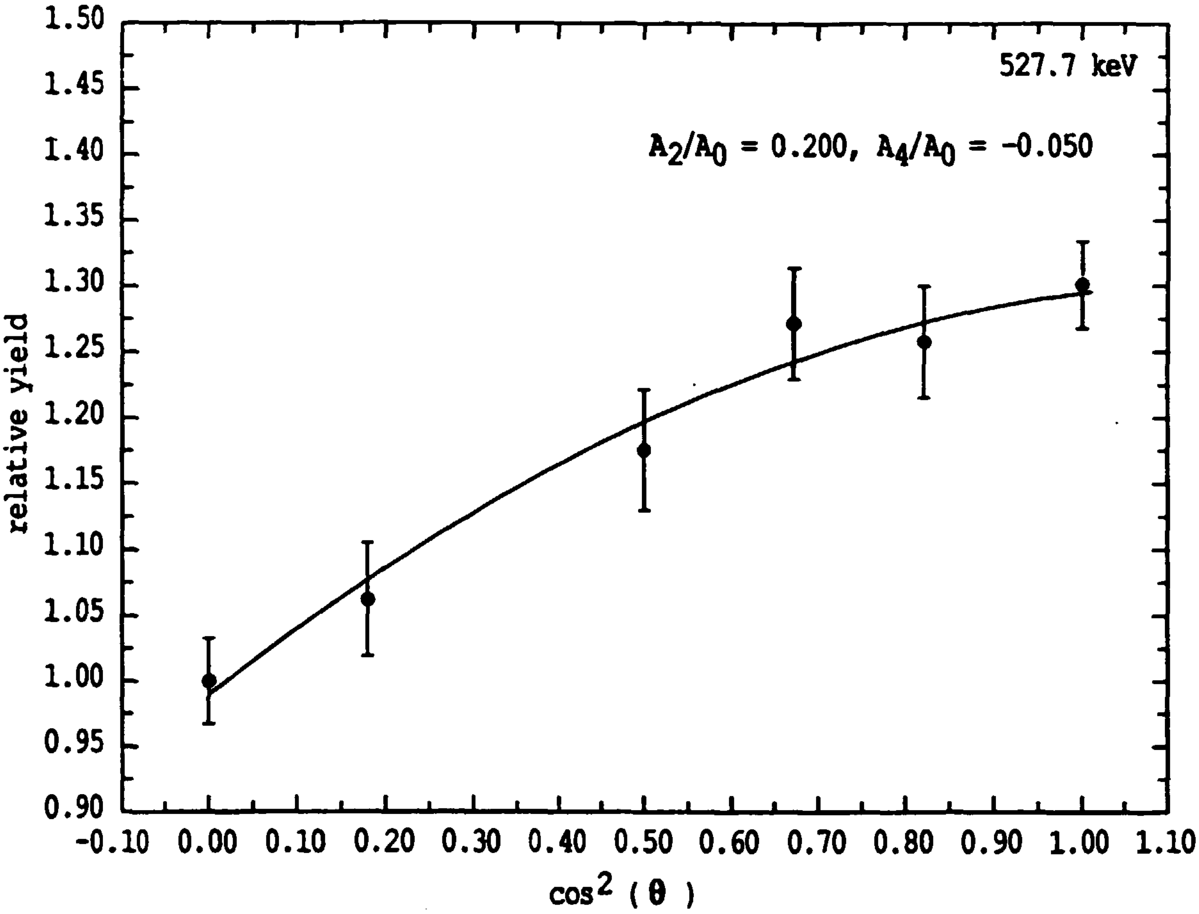

180Os
6+→4+
386.8
8+→6+
462.9
10+→8+
510.6
12+→10+
541.5
14+→12+
566.6
430.2 179W
515.7,517.1
523.4,524.0
527.3
533.3
584.2
619.8
645*
699.3
gammas
600
x10²
500
400
300
200
100
0
counts
electrons
14000
12000
10000
8000
6000
4000
2000
0
386.8
462.9
510.6
584.2(E0)
541.5
644.5(E0)
515.7,517.1K
524K*
533K*
619.8K
672K
699K
430.2 179W(M1)
527.5
566.6
380 400 420 440 460 480 500 520 540 560 580 600 620 640 660 680 700 720
transition energy (K) in Osmium [keV]

Fig. 3



180Os
electrons
462.9
510.6
541.5
515.7,517.1 K
524K*
533K*
463L3
527.5K
counts
transition energy (K) in Osmium [keV]

Fig. 4


527.7 keV
A2/A0 = 0.200, A4/A0 = -0.050
relative yield
1.50
1.45
1.40
1.35
1.30
1.25
1.20
1.15
1.10
1.05
1.00
0.95
0.90
-0.10 0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10
cos2 (θ)

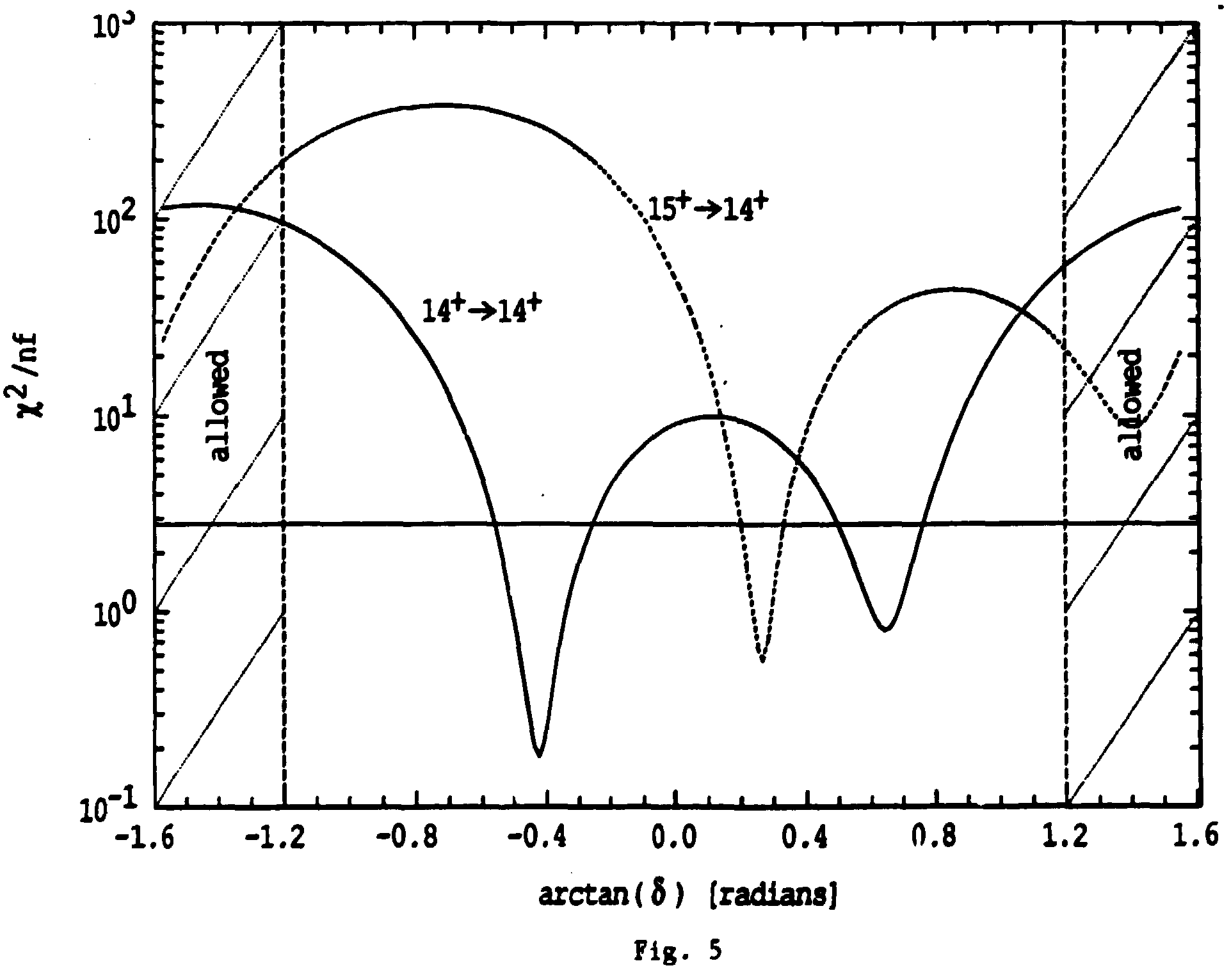

15+→14+
14+→14+
allowed
allowed
χ2/nf
10^3
10^2
10^1
10^0
10^-1
-1.6 -1.2 -0.8 -0.4 0.0 0.4 0.8 1.2 1.6
arctan(δ) [radians]

Fig. 5