THE DECAY SCHEME OF ^{232}Pa

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Magnetic and semiconductor (Ge and Si) spectrometers were used to study the ^{232}Pa → ^{232}U decay scheme. The following γ lines, new with respect to the earlier data reported by Bjørnholm *et al.*, were observed: 922.7, 1003.3, 1016.4, 1051.4, 1055.4, 1085.4, 1125.1, 1132.7 and 1164.5 keV. Conversion coefficients and multipolarity assignments were determined for several of these transitions. Due to the $e-\gamma$ coincidence studies it was possible to show that the 1125.1 and 1055.4 keV $E1$ transitions feed respectively the 2^+ and 4^+ levels of ^{232}U ground-state band. This indicates the existence of the new ^{232}U levels at 1172.8 and 1212.1 keV which are interpreted as 2^- and 3^- members of the $K^\pi = 1^-$ octupole band. Another new level is proposed at 1132.9 keV. The 1016.4 keV $M2$ transition is believed to connect the band-head state of the $K^\pi = 2^-$ octupole band with the ground state; the 1051.4 keV transition may possibly be an analogous $E3$ transition from the 3^- state of this band. As deduced from the $\beta-\gamma$ coincidence experiments, the β^- decay energy of ^{232}Pa is equal to 1337 ± 10 keV. The discussion of experimental data in terms of nuclear models is concentrated on the octupole bands and their Coriolis interaction.

1. Introduction

The β^- decay of the 1.34 d ^{232}Pa isotope has been studied by Bjørnholm *et al.* (1963) using a curved-cristal spectrometer, a six-gap β spectrometer and scintillation technique. Extensive coincidence measurements have been performed. Energy levels established for the daughter ^{232}U have been grouped into rotational bands typical for a strongly deformed even nucleus. In addition to the even-parity ground-state band and two quadrupole bands, the negative-parity $K = 0$ and $K = 2$ bands associated with the octupole vibrations have been observed. Actually, the $K = 2$ assignment to the latter band is proposed by the present authors, while Bjørnholm *et al.* have not excluded here $K = 1$, alternatively to $K = 2$.

The present investigation has been undertaken with the hope of obtaining new information on the ^{232}Pa decay scheme due to the application of semiconductor detectors in the experiments. Special attention has been paid to the study of the ^{232}U octupole states, including

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a search for the $K = 1$ band and for the expected Coriolis mixing of the octupole bands. Preliminary results were presented at the Dubna Conference (Chwaszczewska *et al.* 1968).

Some new data on the ^{232}Pa decay scheme are also brought by the recent paper by Varnell (1970). Results of the two works are compared in the present paper.

2. *Experimental procedure*

Investigation of the ^{232}Pa decay scheme included measurements of the γ-ray and internal-conversion spectra, some e—γ coincidence studies and a determination of the β decay energy in a $\beta - \gamma$ coincidence experiment.

2.1. Source preparation

The ^{232}Pa activity was produced in the (n, γ) reaction. Irradiations of samples containing ^{231}Pa were performed usually for about 24 or 48 h at a neutron flux $\approx 10^{14}$n/s · cm^2 in the Świerk reactor. The radioactive material was chromatographically purified. The β sources were prepared by the microcolumn technique (Bjørnholm *et al.*, 1963a). The strength of the two most intense sources for measurements of the high-energy internal-conversion spectrum was about 2 mCi.

2.2. Gamma-ray spectrum

The low-energy part of the γ-ray spectrum ($\leqslant 150$ keV) was measured with a 2.5 mm thick and 5 mm diameter Si(Li) detector (for the description of this spectrometer, see Belcarz *et al.*, 1969). Sources of ^{57}Co, ^{109}Cd, ^{169}Yb and ^{241}Am were used for energy and intensity calibration. One run with no absorber and two runs with a 0.1 mm Cu, 0.03 mm Al absorber were carried out. A section of the spectrum measured with the absorber is shown in Fig. 1.

The spectrum from ~ 100 to ~ 1200 keV was measured using several Ge(Li) detectors of a sensitive volume 1 to 7 cm^3. The ^{110m}Ag source was one of the calibration standards applied. The spectrum for energies $\geqslant 1$ MeV was measured with special care because it was believed that γ lines associated with the $K = 1$ octupole band may occur in this energy region. Fig. 2 shows the results of the main run carried out with the 7 cm^3 Ge(Li) coaxial detector made in Świerk.

Intensity normalization of the low-energy spectrum to the high-energy one was possible due to the 150.1 keV γ-rays observed as a relatively intense line in both the Si(Li) and Ge(Li) measurements.

2.3. Electron spectrum

The spectrum of internal-conversion electrons was studied, mainly at higher energies, in the Świerk six-gap β spectrometer (Preibisz *et al.*, 1969) and with a Si(Li) detector in the zero-dispersion magnetic β spectrometer.

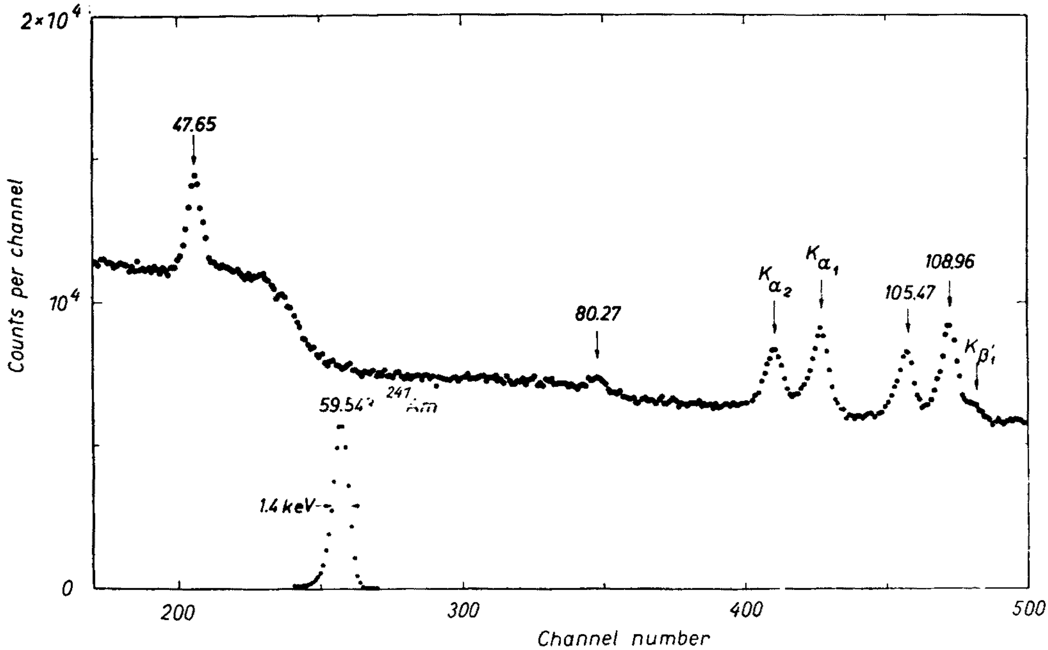

Fig. 1. Section of the low-energy ^{232}Pa γ-ray spectrum and the standard γ line of ^{241}Am measured with a Si(Li) detector

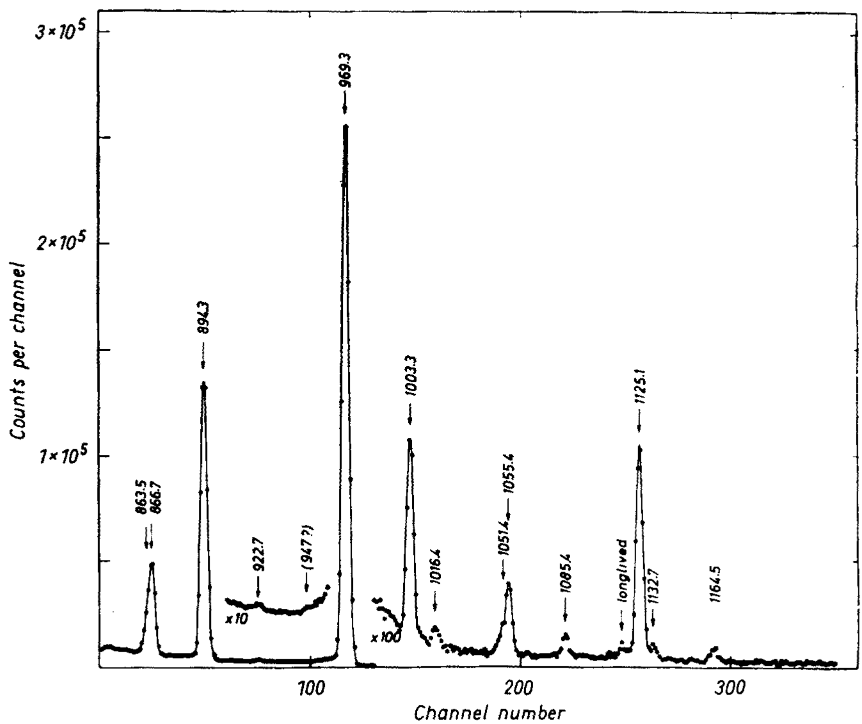

Fig. 2. High-energy part of the γ-ray spectrum measured with a Ge(Li) detector. Compared to our first preliminary data (Chwaszczewska *et al.*, 1968), this spectrum shows a new 922.7 keV line and non-existence of the 1193 keV line (earlier considered as uncertain)

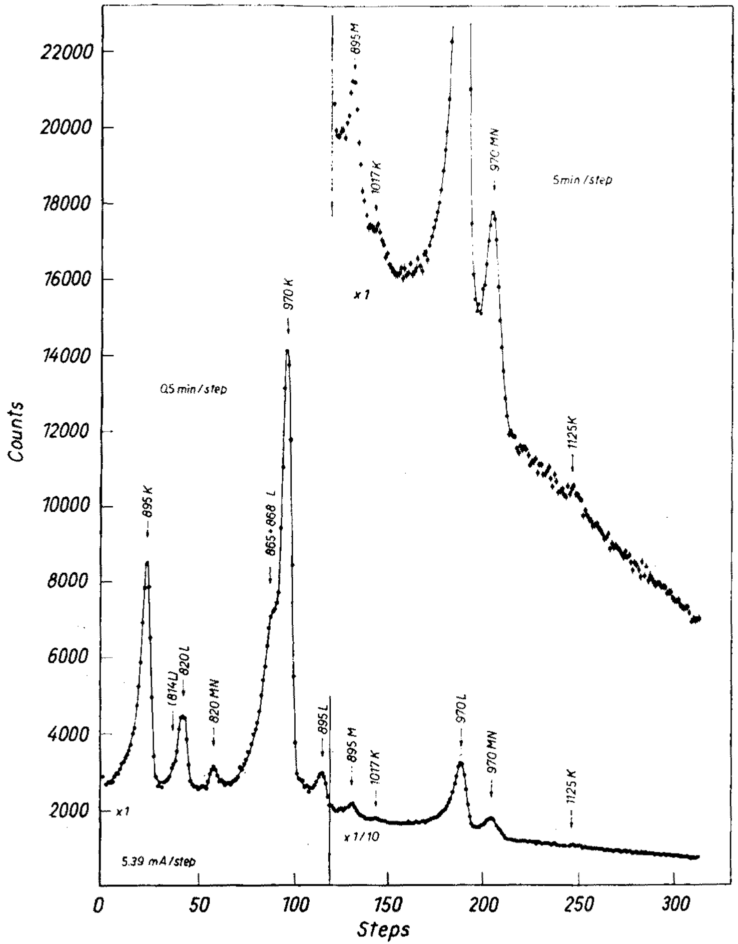

Fig. 3a. Results of the search for the conversion lines of the weak high-energy transitions carried out with the six-gap spectrometer

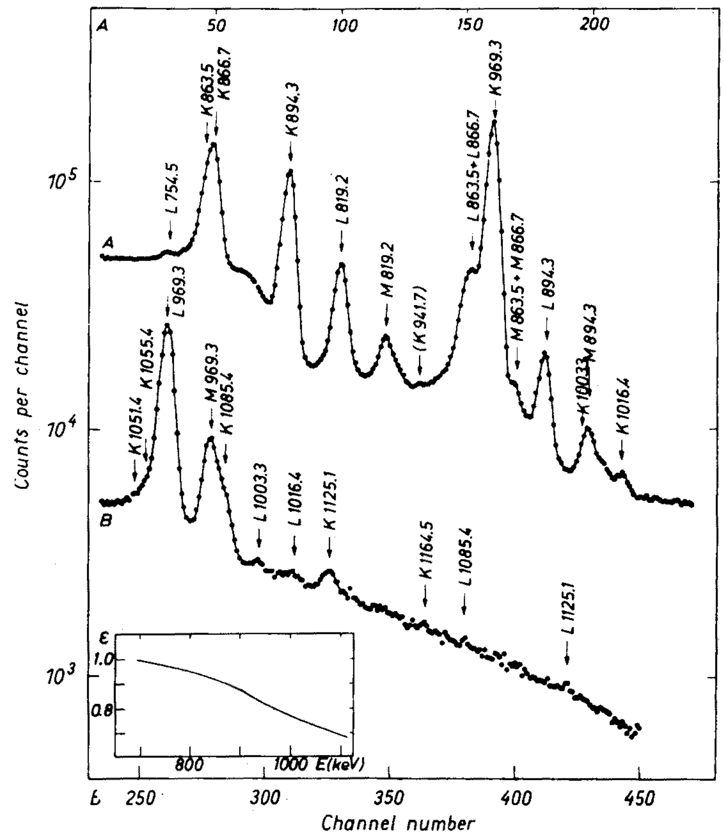

Fig. 3b. Results of the search for the conversion lines of the weak high-energy transitions carried out with a Si (Li) detector in the zero-dispersion magnetic β spectrometer

Fig. 3*a* shows the results of a run, with a 1 mm×6 mm ^{232}Pa source, for which the resolution of the six-gap spectrometer was set at ~0.5%. Only three gaps were employed in this measurement and the solid angle was properly limited by baffles. The resulting spectrometer transmission was 1.2%. For approximately the same energy region, Fig. 3*b* presents the spectrum measured with a Si(Li) detector. This detector was 2 mm thick and the active area was 5 mm×10 mm. Its resolution was 4 keV for the *K* 662 ^{137}Cs line. Due to the homogeneous magnetic field and a system of baffles, the detector was protected from overloading by intense low-energy electrons. Gamma-rays were partly absorbed by a 15 mm thick lead absorber inserted between the source and the detector. The detailed description of the spectrometer will be published elsewhere (Płochocki *et al.*, 1970).

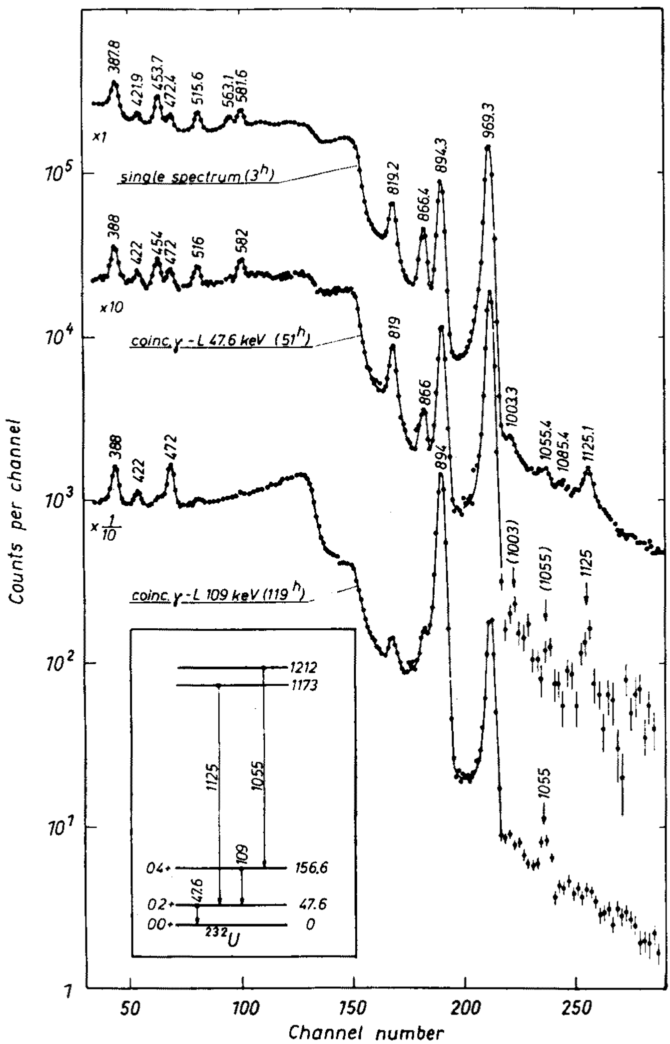

Fig. 4. Results of the $e-\gamma$ coincidence measurements carried out with the six-gap β spectrometer and a Ge(Li) detector

2.4. Coincidence measurements

The $e-\gamma$ coincidence studies were performed using the six-gap spectrometer with a 1.5 cm^3 Ge(Li) detector placed at a distance of 2 cm from the source. The aim of these measurements was to establish the position of the newly-observed high-energy transitions in the ^{232}U level scheme. The γ-ray spectra were recorded, therefore, in coincidence with the L-conversion lines of the 47.65 and 108.96 keV transitions. With the three gaps open, the β spectrometer had the transmission and the resolution equal to 4% and 1.5%, respectively. The resolution of the γ-ray spectrometer was only about 9 keV since the preamplifier could not be placed close enough to the Ge(Li) detector. The results of these coincidence measurements are presented in Fig. 4 together with the singles γ-ray spectrum.

In order to obtain the ^{232}Pa decay energy, the end-point energies were determined for β spectra measured in coincidence with the 894.3 and 969,3 keV γ-rays. The γ lines were selected with the 1.5 cm^3 Ge(Li) detector, while the β spectra were recorded in a Si(Li) detector. The energies of the β- and γ-rays involved in this experiment were close to those in the ^{60}Co decay scheme. The ^{60}Co source was applied, therefore, to test and callibrate the equipment.

3. *Energies and intensities of the internal transitions*

A summary of the experimental data on the energies and intensities of the ^{232}U internal transitions[1] is given in Table I.

The transition energies determined in this work have been obtained from the γ-ray studies and, in the case of the $E0$ transitions, from the spectrum of internal-conversion electrons. They are compared in Table I with the energies given by Bjørnholm *et al.*

The intensities of γ-rays and internal-conversion lines are given in per cent of the ^{232}Pa β decays.

For transition energies below 1 MeV the intensities of the K- and/or L-conversion lines in Table I are those measured by Bjørnholm *et al.* relative to the total intensity of the β continuum. The conversion-line intensities for the higher-energy transitions, newly observed in this work, were normalized to the data of Bjørnholm *et al.*

The normalization of the γ-ray intensities begins from the balance of the transition intensities for the ^{232}U ground-state rotational band (see the decay scheme in Fig. 6). According to Bjørnholm *et al.*, the intensity of the two β components feeding this band is 1.5% of the ^{232}Pa decays. The total intensity of all internal-conversion lines corresponding to the γ transitions between levels of the higher energy and the ground state band is 0.9%. Hence, the total γ-ray intensity of these transitions is 97.6%, with the uncertainty believed to be <1%. The knowledge of this figure and of the relative γ-ray intensities allows us to calculate the intensity in % of β decays for individual γ lines. The results obtained in this way are listed in Table I together with the intensity data of Bjørnholm *et al.* The latter are based on (*i*) the singles γ-ray spectrum measured with the curved-crystal spectrometer (at low

[1] The expression "internal transitions" is used here to account for the γ-ray and conversion-electron transitions.

TABLE I

Energies and intensities of the internal transitions

Transition energy[a] (keV)		Transition intensity[a] (per cent of β decays)			
		Gamma rays		Conversion electrons	
Bjørnholm *et al.* (1963 [c])	This work	Bjørnholm *et al.* 1963	This work	*K*	*L*
				Bjørnholm *et al.* (1963)	
(35)					
47.6 (1)	47.65 (5)		0.22 (4)		56.5[d]
80.2 (1)	80.27 (10)	0.13 (13)	0.19 (3)		
81.2 (1)		0.02 (2)			
105.4 (1)	105.47 (5)	2.1 (2)	1.9 (2)		
109.0 (1)	108.96 (5)	3.0 (3)	3.2 (4)		16.4[d]
132.5 (2)		0.02 (1)	<0.16		
139.2 (1)	139.6 (1)	0.7 (2)	0.62 (8)		
150.1 (1)	150.1 (1)	12	11.2 (12)	1.2	0.35
174.9 (2)		0.025[b]			
178[b]		0.020[b]			
183.9 (1)	184.0 (3)	1.65	2.3 (7)		
219[b]		<0.03			
283[b]					
388.0 (2)	387.8 (2)	7.2	7.9 (6)	0.46	0.225
422.0 (2)	421.9 (2)	2.5	2.9 (2)	0.24	0.073
454.2 (2)	453.7 (3)	5.0	9.1 (4)	0.51	0.198
472.8 (3)	472.4 (2)	4.1	4.5 (2)	0.05	0.024
516.1	515.6 (3)	3.3	5.8 (4)	0.048	0.009
564.5	563.1 (2)	2.3	3.5 (2)	0.020	0.005
583.8	581.6 (2)	6.2	5.8 (4)	0.047	0.010
645		0.033	<0.08	0.0006	
676.5	674.7 (10)	<0.03[b]	<0.08	0.012	0.004
687.5	686.1 (10)	<0.10[b]	<0.08	0.043	0.012
692.9	690.8 (10)	<0.04[b]	<0.12	0.022	0.005
711.6	709.8 (4)	0.23	0.24 (2)	0.0035	
735				<0.0004	
757.0	754.5 (4)	0.67	0.50 (4)	0.009	0.003
819.6	819.2 (2)	8.2	7.5 (4)	0.098	0.030
865.3	866.4[e]	2.8	7.5 (4)	0.031	0.30
868.0		6.3		0.069	
894.8	894.3 (1)	21	20.0 (8)	0.078	0.013
	922.7 (7)		0.037 (8)		
971.0	969.3 (1)	41	41.6 (12)	0.140	0.024
				This work	
	1003.3 (2)		0.16 (1)	<0.0013	0.00012 (4)
	1016.4 (4)		0.015 (4)	0.00088 (15)	0.00016 (4)

Table I (continued)

Transition energy[a] (keV)		Transition intensity[a] (per cent of β decays)			
		Gamma rays		Conversion electrons	
Bjørnholm *et al.* (1963)[c]	This work	Bjørnholm *et al.* 1963	This work	K	L
	1051.4 (10)		0.016 (5)	0.00085 (+20)	<0.00008
	1054.5 (3)		0.071 (4)	(−40)	<0.00008
	1085.4 (3)		0.022 (4)	⩽0.0009	<0.00005
	1125.1 (2)		0.21 (1)	0.00054 (8)	0.00005 (3)
	1132.7 (7)		0.013 (4)	⩽ 0.0001	
	1147[f]		<0.004		
	1164.5 (5)		0.016 (3)	0.000046 (30)	

[a] In parentheses: errors related to the last meaning figures.

[b] Data from $e-\gamma$ coincidence experiments.

[c] Above 500 keV, the absolute accuracy of the energy determination is claimed to be 0.2%.

[d] The intensities of the $(M+N)$ 47.6 and $(M+N)$ 109.0 conversion lines are 21.0% and 6.03%, respectively.

[e] The energies of the two transitions unresolved in the γ-ray spectrum are given in Fig. 6 according to the difference in energy of the corresponding ^{232}U levels.

[f] As to the possible ≈ 1147 keV line, see discussion in Section 6 and footnote[d] to Table III.

energies) and the scintillation spectrometer, (*ii*) the $e-\gamma$ coincidence measurements and (*iii*) the conversion-line intensities.

All γ-ray and electron intensities determined by the present authors are given in Table I with the estimated uncertainties. As to the internal-conversion data quoted in this Table after Bjørnholm *et al.*, the intensities of the stronger lines should be accurate to within 5% or better. Thus, 5% errors have been assumed when calculating the conversion coefficients, Table II. There is, however, some indication (see Section 5) that the actual error appreciably exceede 5% in the case of the L 47.65 line. For the weak K 709.8 and K 754.5 lines, the intensity uncertainty of 10% was assumed arbitrarily.

4. *Conversion coefficients and multipolarity assignments*

The conversion coefficients given in Table II were calculated directly as the ratios of the electron and γ-ray intensities taken from Table I, (columns 5, 6 and 4, respectively).

The multipolarity assignments are based on the comparison of the experimental and theoretical (Hager and Seltzer, 1967) conversion coefficients, see Fig. 5 and Table II. For transitions with energy below 1 MeV, these assignments coincide with those given by Bjørnholm *et al.* As regards the multipolarities of the new high-energy transitions, it has to be noticed that the errors in the experimental conversion coefficients correspond here roughly to one standard deviation (limits for the conversion coefficients are given approximately at the level of two standard deviations). One finds, therefore, that the $E1$ multipolarity

TABLE II

Internal conversion coefficients and multipolarity assignments

Transition energy (keV)	Experimental I. C. C[a].		Multipolarity[b]
	α_K	α_L	
47.65[c]		2.6±0.5 (2)	*E*2
108.96[c]		5.1±0.6 (0)	*E*2
150.1	1.10±0.12 (−1)	3.2±0.3 (−2)	*E*1
387.8	5.8±0.6 (−2)		*E*2+(3.5±1.3)% *M*1
421.9	8.2±0.7 (−2)		*E*2+(14±2)% *M*1
453.7	5.5±0.4 (−2)		*E*2+(8.5±1.3)% *M*1
472.4	1.1±0.1 (−2)		*E*1
515.6	8.3±1.0 (−3)		*E*1
563.1	5.5±0.6 (−3)		*E*1
581.6	8.0±1.0 (−3)		*E*1
674.7	>0.15		*E*0
686.1	>0.4		*E*0
690.8	>0.2		*E*0
709.8	1.5±0.2 (−2)		*E*2
754.5	1.8±0.2 (−2)		*E*2
819.2	1.3±0.15 (−2)		*E*2
863.6	1.3±0.1 (−2) (863.6 and 866.7 together)		*E*2
866.7			*E*2
894.3	3.9±0.4 (−3)		*E*1
969.3	3.40±0.35(−3)		*E*1
1003.3	<9.3 (−3)	7.5±2.7 (−4)	*E*1
1016.4	5.9±1.9 (−2)	$1.1^{+0.7}_{0.5}$ (−2)	*M*2
1051.4		<1.3 (−2)	?
1055.4	<1.3 (−2)	<1.3 (−3)	*E*1
1085.4	<6.5 (−2)	<3.3 (−3)	*E*1, *E*2
1125.1	2.6±0.4 (−3)	2.4±1.5 (−4)	*E*1
1132.7	<2.0 (−2)	<2.8 (−3)	*E*1, *E*2
1164.5	3±2 (−3)		*E*1

[a] In parentheses powers of ten.
[b] See Fig. 5.
[c] The theoretical I. C. C.:

$\alpha_{L47.65} = 3.4$ (2), $\alpha_{L108.96} = 6.8$ (0), $\alpha_{M47.65} = 9.4$ (1), $\alpha_{M108.96} = 2.0$ (0) (Hager and Seltzer, 1967)

$\alpha_{N47.65} = 3.0$ (1), $\alpha_{N108.96} = 5.4$ (−1) (Dragoun *et al.*, 1969)

of the 1125.1 keV transition is definitely established. The *E*1 character of the 1003.3 and 1055.4 keV transitions and the *M*2 character of the 1016.4 keV transition is most probable. On the other hand, the *E*1 assignment to the 1164.5 keV transition is uncertain. In the case of the 1085.4 and 1132.7 keV transitions it is not possible to distinguish between the *E*1 and *E*2 multipolarities.

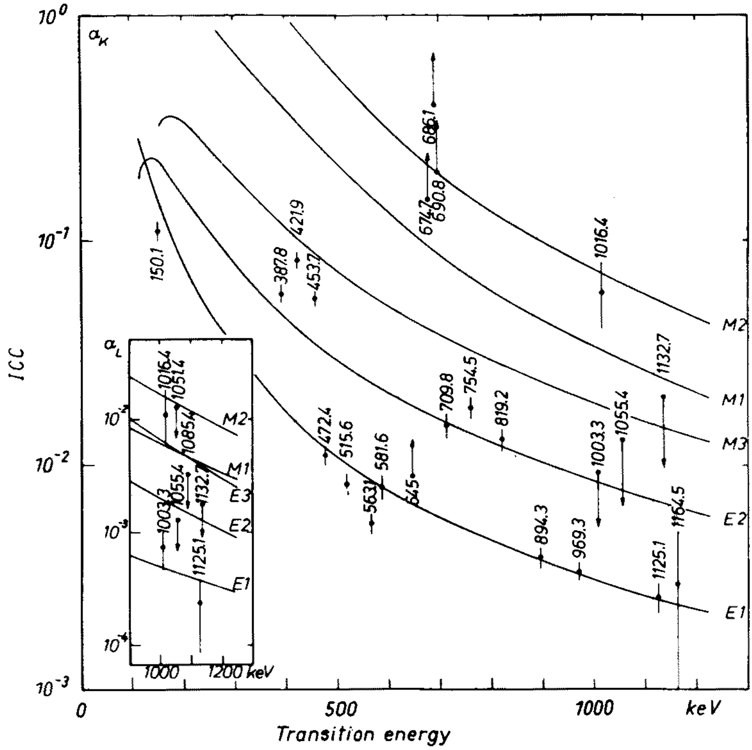

Fig. 5. The experimental internal-conversion coefficients compared to the theoretical predictions for different transition multipolarities

5. *Coincidence studies and the decay scheme*

The scheme of the ^{232}Pa decay to levels of ^{232}U is shown in Fig. 6. All ^{232}U levels up to the 1050.9 keV one have been introduced already by Bjørnholm *et al.* However, the energies of these levels as well as the energies of the internal transitions are based (with few exceptions mentioned in the caption to Fig. 6) on the present investigation.

Transitions placed in the decay scheme not only due to the energy fit, but also on the basis of the $e-\gamma$ coincidence experiments — carried out by Bjørnholm *et al.* and by the present authors — are marked in Fig. 6 with black circles.

The main purpose of the $e-\gamma$ coincidence experiments performed in this work was the placing of newly observed transitions in the decay scheme. Despite poor statistics obtained for the high-energy lines in the coincidence spectra (see Fig. 4), the position of two new transitions were actually established. The 1125.1 keV $E1$ transition appears in coincidence with the L 47.6 line, while it is not seen in the spectrum gated by the L 109 line. This allows us to introduce the new negative-parity ^{232}U level at 1172.8 keV. As no γ transition from this level to the 0^+ or 4^+ levels of the ground-state band is observed, its spin value may be 2. The 1055.4 keV transition, most probably of the $E1$ character, is in coincidence with the L 109 line. Hence, the next negative-parity level of ^{232}U is introduced at 1212.1 keV.

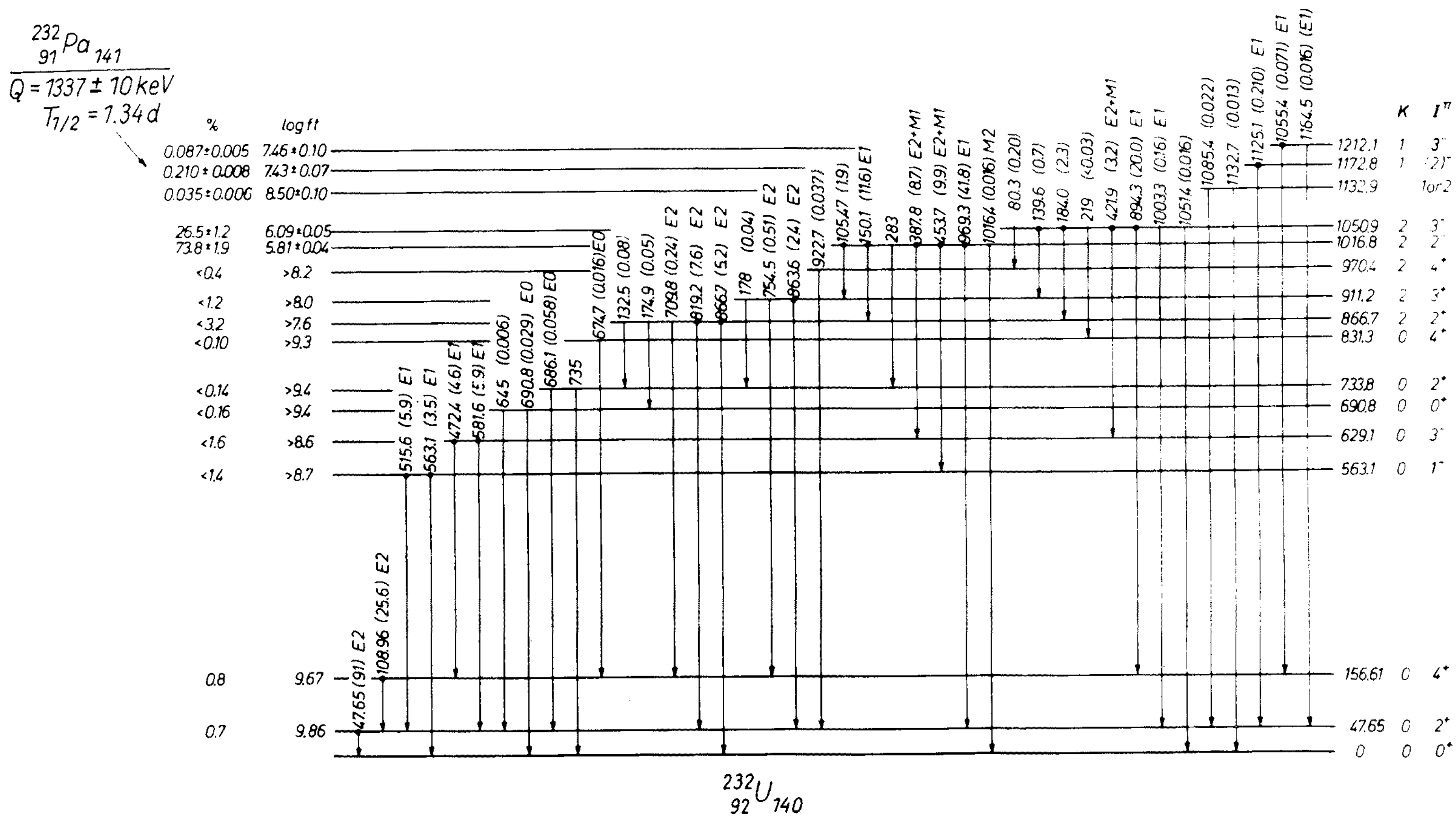

Fig. 6. The $^{232}Pa \rightarrow {}^{232}U$ decay scheme including the ^{232}U levels introduced by Bjørnholm *et al.* (1963) and three new ones at 1132.9, 1172.8 and 1212.1 keV. This accounts for all transitions observed in the present work and, additionally, for the 132.5, 174.9, 178, 219 and 283 keV lines reported by Bjørnholm *et al.* The transition intensities are given in percent of all β decays. For further comments see text

The spin value 3 is suggested for this level, because it seems to decay by the 1164.5 keV transition to the 47.65 keV 2^+ level, in addition to the considered 1055.4 keV transition to the 156.61 keV 4^+ level. The assignment of the quantum number K to the 1172.8 and 1212.1 keV levels (and to some levels of the lower energy) is discussed in the next Section.

Another new level, decaying to the ground and first-rotational state, is proposed at the energy of 1132.9 keV.

The end-point energies for β spectra measured in coincidence with the 969.3 and 894.3 keV lines are found to be 314 ± 8 and 294 ± 11 keV, respectively. The ^{232}Pa decay energy is equal, therefore, to 1337 ± 10 keV in a fairly good agreement with the value 1345 ± 20 keV obtained by Bjørnholm *et al.* from the Fermi analysis of the singles β spectrum. This decay energy and β-ray branchings have been used to calculate the log ft values.

The branchings of the two weak β components feeding the 47.65 and 156.61 keV levels are taken from the work of Bjørnholm *et al.* For other β transitions, the branchings in Fig. 6 are given according to the intensity balance of the internal transitions. The intensities of the latter transitions are sums of the corresponding γ-ray and conversion-electron intensities taken from the columns 4, 5 and 6 (and 3, for the 132.5, 174,9, 178 and 219 keV lines) of Table I. In the case of few transitions with missing experimental conversion data, the electron intensity was estimated with the use of the theoretical conversion coefficients for pure $E1$ or $E2$ transitions.

As regards the intensities of the low-energy internal transitions, the following comment should be given. From the intensity balance of the β- and γ-ray transitions leading to the ground-state band, one finds the intensity of the 47.65 transition equal to 91%. The corresponding value based on the data from Table I is only 77.7%. It is believed that this discrepancy has to be attributed to the systematic error in the intensity of the L 47.65 line measured by Bjørnholm *et al.* In the decay scheme in Fig. 6, the intensity of this transition is given as it follows from the intensity balance.

When the total intensity value of 91% is assumed for the 47.65 keV transition and the theoretical $E2$ conversion coefficient is taken into account (see footnote c) to Table II), one obtains γ-ray intensity equal to 0.20%. This figure has been used to renormalize the intensities of the low-energy γ-rays (the 80.27, 105.47, 108.96, 139.6 and 150.1 keV lines). In the decay scheme these renormalized intensities, corrected for the internal-conversion effect are given.

6. *Discussion*

In this section a brief comparison is made between the present-work data and the results obtained at Caltech, Pasadena, by Varnell (1970). Further discussion here is concentrated on properties of the octupole states, while for the discussion on even-parity states the reader is referred to Varnell's paper.

6.1. Caltech data on the ^{232}Pa $\to$ ^{232}U decay

Varnell has reported results of his extensive γ-ray studies performed with a Ge(Li) spectrometer and the Caltech bent-cristal spectrometer. The low-energy spectrum of γ-rays has also been measured in coincidence with the 150.1 keV γ line (Ge(Li) and NaI detectors).

The agreement between Varnell's and the present-work data on energies and intensities for the majority of γ transitions is rather good. Varnell observed new very weak γ lines at 165.0, 590.3, 814.2 and 911. 4 keV and placed them in the decay scheme between the previously established (Bjørnholm *et al.*, 1963) even-parity levels. Those lines above 1 MeV which were well established already in the first stage of our work (Chwaszczewska *et al.*, 1968) were also confirmed by Varnell. For the intensity of the 1162 keV γ line, earlier reported as uncertain, Varnell gives an upper limit which is ≈ 3 times lower than the intensity value determined in our present studies (Fig. 2, Table III) for the 1164.5 keV transition.

Measurements of the internal-conversion spectrum with a Si(Li) detector allowed Varnell to determine the K-electron intensities for 10 transitions of energies between 387.9 and 969.2 keV. His results are close to those listed in Table I after Bjørnholm *et al.*

In the decay scheme given by Varnell, two ^{232}U levels at 1172.6 and 1212.0 keV were introduced with reference to our first preliminary communication (Chwaszczewska *et al.*, 1968). The 1132.4 keV level, de-excited by γ transitions to the 0^+ and 2^+ states of the ground--state band (see also Chwaszczewska *et al.*, 1968 and Fig. 6 of the present paper) is suggested by Varnell to have spin-parity 1^-. The scheme of other ^{232}U levels agrees with that established by Bjørnholm *et al.*

6.2. Octupole bands in ^{232}U

The negative-parity ^{232}U levels fed in the decay of ^{232}Pa are interpreted as members of the $K = 0$, 1 and 2 octupole bands (Fig. 6, Table III).

The experimental level energies are compared in Table III to those resulting from microscopic theory. The theoretical data were taken from three different papers. In the last of these papers (Neergård and Vogel, 1970), in addition to some refinments of the basic theory, also the Coriolis interaction has been taken into account. This interaction is supposed to cause appreciable distortions of level energies within the rotational bands (departures from the simple $E_{rot} = AI(I+1)$ relation) and a mixing of states with different K values. Hence, when speaking about K-value assignments one has to consider the main K components of the wave functions.

The calculated energies of octupole states agree with experimental ones within a few hundred keV, or better. This agreement may be in general considered as rather satisfactory. It is not good enough, however, from the point of view of the K-value assignments. Actually, in the case of ^{232}U all three theoretical works predict for the levels of the $K^\pi = 1^-$ band energies lower than for the corresponding levels of the $K^\pi = 2^-$ band. This is in contradiction to the assignments in Table III which were deduced as the most probable from the analysis of the β- and γ-ray data.

Beta transitions to collective states have very often rather low probabilities, as usually only one or few components of the collective wave function give rise to the decay rate. With this in mind, one has to consider the β transitions to the 1017 keV 2^- and 1051 keV 3^- states ($\log ft \approx 6$) as rather fast and most probably of the allowed character. Hence, the spin-parity of the ^{232}Pa ground state can be 2^- or 3^-. The analysis of probabilities for the β transitions to the ground-state band led Bjørnholm *et al.* to the conclusion that spin 3 is preferable.

TABLE III

Energy levels of octupole bands in ^{232}U

K	I	Energy (keV)			
		Experiment this work	Theory		
			a	b	c
0	1^-	563	590	630	500
	3^-	629			540
1	1^-	(1147)[d]	1210	1030	880
	$2-$	1173			880
	3^-	1212			930
	4^-				930
2	2^-	1017	1440	1170	1000
	3^-	1051			1080
	4^-				1150
3	3^-	—		1180	1350
	4^-				1420

[a] Zheleznova *et al.* (1966).
[b] Błocki and Kurcewicz (1969).
[c] Approximate values read from Fig. 4 in the paper by Neergård and Vogel (1970).
[d] Energy calculated from the $E_{rot} = AI(I+1)$ formula; $A = 5.68$ keV.

With the assumption of $K^\pi = 3^-$ for the ^{232}Pa ground state, the following interpretation of the β-decay and octupole-states data has been proposed (Chwaszczewska *et al.*, 1968). The 1017 keV 2^- and 1051 keV 3^- levels are members of the $K^\pi = 2^-$ octupole band and they are fed by fast K-allowed β transitions. The 1173 keV 2^- and 1212 keV 3^- levels are members of the $K^\pi = 1^-$ band and their β feeding is possible due to the Coriolis admixtures of the $K^\pi = 2^-$ to the $K^\pi = 1^-$ wave functions; a direct β transition to the 1^- state would be 2-nd forbidden and therefore has not been observed. When interaction with other bands is neglected and the same moment-of-inertia parameter is assumed for both unperturbed bands, one obtains the following values for the Coriolis coupling element:

$|A_{1,2}| = 8.3 \pm 0.5$ keV from the energy spacing between the 2^- and 3^- levels[2,3],

$|A_{1,2}| = 11.6 \pm^{1.6}_{0.6}$ keV from the log ft values for the $3^- \rightarrow 2^-$ transitions,

$|A_{1,2}| = 9.9 \pm^{1.0}_{0.6}$ keV from the log ft values for the $3^- \rightarrow 3^-$ transitions.

[2] In our first communication (Chwaszczewska *et al.*, 1968) the errors of $|A_{1,2}|$ values deduced from log ft data were incorrect

[3] The Coriolis-coupling calculations performed for three octupole bands ($K = 0, 1$ and 2) give $|A_{1,2}| \approx$ 10 keV.

TABLE IV

Intensities of the selected allowed $^{232}Pa \rightarrow {}^{232}U$ β transitions

Levels fed in β decay		Transition intensities				
		theory[b]		(Alaga *et al.*, 1955)		experiment
		$I_i = K_i = 2$		$I_i = K_i = 3$		
E (keV)	I_f	$K_f = 1$	$K_f = 2$	$K_f = 1$	$K_f = 2$	%
(994)[a]	1^-	168	—	0	—	<1[c]
1017	2^-	73.8	73.8	0	73.8	73.8±1.9
1051	3^-	12.4	25.6	0	17.9	26.5±1.2
(1096)[a]	4^-	0	0	0	1.5	<0.1[c]

[a] Energies calculated from the $E_{rot} = AI_f(I_f+1)$ formula; $A = 5.68$ keV.

[b] Intensities normalized to the β feed of the 1017 keV 2^- state.

[c] Limits for the intensities estimated under assumptions that (*i*) the level energies are close to calculated and (*ii*) these levels would decay predominantly to the ground-state band.

The three $|A_{1,2}|$ values are not far one from another. There remains, however, an open question why is the 3^- state of the $K^\pi = 2^-$ band fed at a probability higher than that predicted by the Alaga rule, while the 4^- state of this band is not observed at all, Table IV. One obtains a better fit to the experimental β branching assuming both the initial and final K values equal to 2 (the $K = 1$ final value seems to be clearly excluded). Before making any definite conclusions, however, one would have to carry out calculations of the β branching ratios with the Coriolis coupling of all four octupole bands included. An especially important role may play the mixing of the states in question with the corresponding states of the unobserved $K^\pi = 3^-$ band.

Until now the Coriolis interaction of all four octupole bands has been taken into account in calculation of the level energies (as considered above) and branching ratios of the $E1$ transitions. The $E1$ branching ratios have been studied by Kocbach and Vogel (1970), whose results concerning ^{232}U are given in Table V, together with the predictions of the Alaga rule and the present-work experimental data. The theoretical results of Kocbach and Vogel explain, in a semiquantitative way, the observed branching ratios of the $E1$ transitions from the $K^\pi = 2^-$ levels to the ground-state band (K-forbidden decays) and to the γ band (K-allowed decays). There is a disagreement between this theory and experiment as regards the branching ratio of the $E1$ transitions from the 1212 keV 3^- level ($K^\pi = 1^-$) to the ground-state band, but it is clear that the Coriolis effect plays an essential role here. In the case of transitions between levels of the $K^\pi = 0^-$ and ground state bands, the experimental branching ratios agree with predictions of the Alaga rule and disagree with the data of Kocbach and Vogel.

A 5×10^{-11}s upper limit reported by Bjørnholm *et al.* for the halflives of the 1017 keV 2^- and 1051 keV 3^- levels correspond to the following retardation factors, calculated with the use of the Weisskopf estimate: $F_w < 300$ for the 1016.4 keV $M2$ transition and $F_w \leqslant 0.3$ for the 1051.4 keV $E3$ (?) transition.

TABLE V

Reduced-probability ratios for $E1$ transitions de-exciting octupole states in ^{232}U

I_i^π	I_f^π	$K_i = 0$ Theory a	$K_i = 0$ Theory b	$K_i = 0$ Experim.	$K_i = 1$ Theory a	$K_i = 1$ Theory b	$K_i = 1$ Experim.	$K_i = 2$ Theory a	$K_i = 2$ Theory b	$K_i = 2$ Experim.
1^-	0_g^+	1.0	1.0	1.0	1.0	1.0[c]				
	2_g^+	2.0	1.63	2.1 ± 0.2	0.5	3.40[c]				
2^-	2_g^+								1.0	1.0
	2_γ^+				1.0			1.0	94	72 ± 8
	3_γ^+				2.0			0.5	33	35 ± 4
3^-	2_g^+	1.0	1.0	1.0	1.0	1.0	1.0		1.0	1.0
	4_g^+	1.33	0.86	1.4 ± 0.1	0.75	300	5.9 ± 1.2		70	177 ± 14
	2_γ^+				1.0	770		1.0	570	2350 ± 800
	3_γ^+				8.7	630		1.4	650	1450 ± 500
	4_γ^+				11.2	1900		1.8	490	2300 ± 400

[a] Alaga *et al.* (1955).

[b] Kocbach and Vogel (1970).

[c] If the 1132.9 keV level is interpreted as $K, I^\pi = 1,1^-$, this ratio is 1.0 : (3.3 ± 1.2) in agreement with the theoretical value from Ref. [b]; see however comments at the end of the paper.

In some even nuclei like ^{234}U (Bjørnholm *et al.*, 1968b) and ^{230}Th (Kurcewicz *et al.*, 1970) $K^\pi = 2^+$ levels have been observed which reveal some properties expected for the two-phonon $\beta+\gamma$ states. They occur a few hundred keV above the $(K = I)^\pi = 2^+$ γ-vibrational states. Perhaps the 1133 keV level in ^{232}U belongs to this group of nuclear excitation. The 1^- assignment proposed to this level by Varnell seems not to be very likely. According to our calculations on the Coriolis mixing of two and three octupole bands, the 1^- level of the $K^\pi = 1^-$ bands is expected at 1147 keV and 1145 keV, respectively.

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REFERENCES

Alaga, G., Alder, K., Bohr, Aa., Mottelson, B., R., *Mat. Fys. Medd. Dan. Vid. Selsk.*, **29**, No. 9 (1955).

Belcarz, E., Chwaszczewska, J., Słapa, M., Szymczak, M., Tys, J., *Nuclear Instrum. Methods*, **77**, 21 (1970).

Bjørnholm, S., Boehm, F., Knutsen, A. B., Nielsen, O. B., *Nuclear Phys.*, **42,** 469 (1963).

Bjørnholm, S., Johansen, E. R., Nordby, H., *Nuclear Instrum. Methods*, **27**, 243 (1963 a).

Bjørnholm, S., Borggreen, J., Davies, D., Hansen, N. J. S., Pedersen, J., Nielsen, H. L., *Nuclear Phys.*, **A118**, 261 (1968 b).

Błocki, J., Kurcewicz, W., *Phys. Letters*, **30B**, 458 (1969).

Chwaszczewska, J., Kaczarowski, R., Rudzińska, J., Kurcewicz, W., Żylicz, J., *Contributions to the International Symposium on Nuclear Structure*, Dubna 1968, USSR, p. 59.

Dragoun, O., Pauli, H. C., Schmutzler, F., *Nuclear Data Tables*, **A6**, No 3 (1969).
Hager, R. S., Seltzer, E. C,. *Report* CALT-63-60, 1967.
Kocbach, L., Vogel, P., *Preprint* No. 14, Univ. of Bergen, March 1970.
Kurcewicz, W., Stryczniewicz, K., Żylicz, J., Chojnacki, S., Morek, T. , Yutlandov, I., *Acta Phys. Polon.*, **B2**, *451* (1971).
Neergård, K., Vogel, P., *Nuclear Phys.*, **149A**, 209 (1970).
Nilsson, S. G., *Intern. School of Physics "Enrico Fermi,"*, Varenna 1967.
Płochocki, A., Belcarz, E., Słapa, M., Szymczak, M., Żylicz, J., *Nuclear Instrum Methods*, (in print).
Preibisz, Z., Kurcewicz, W., Zgliński, A., *Nukleonika*, **14**, 743 (1969).
Varnell, L., *Nuclear Phys.*, **144A**, 429 (1970).
Zheleznova, K. M., Kornejtchuk, A. A., Soloviev, V. G., Vogel, P., Jungklaussen, G., *JINR Report* D-2157, Dubna 1965.