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August 1969 KFK 1097

Institut für Angewandte Kernphysik

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KARLSRUHE

Reprint from

"NEUTRON CAPTURE
GAMMA-RAY SPECTROSCOPY"

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 1969

RADIATIVE NEUTRON CAPTURE STUDIES OF NUCLEAR EXCITATIONS IN ^{68}Zn

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Abstract

RADIATIVE NEUTRON CAPTURE STUDIES OF NUCLEAR EXCITATIONS IN ^{68}Zn. Nuclear excitations in ^{68}Zn were investigated via the (n, γ) reaction on a highly enriched ^{67}Zn sample. Four different spectrometers, a Ge(Li) anti-Compton spectrometer, a Ge(Li)-4 NaI(Tl) pair spectrometer, a Ge(Li)-NaI(Tl) coincidence device and an angular correlation system, were used to establish a reliable decay scheme.

1. INTRODUCTION

Even nuclei in the mass region around A = 70 reveal interesting features in their nuclear structure. The occurrence of low-lying 0^+ states is a puzzling problem and as yet not well understood. Therefore much experimental work has been done in this mass region during the last few years, most of it via particle reactions and radioactive decay. An additional helpful tool for nuclear structure studies is the (n, γ) reaction. At the present state of the art this allows not only a very precise energy determination of nuclear levels but also the measurement of transition probabilities and mixing ratios of gamma transitions, i.e. quantities very sensitive to nuclear models.

The only even nuclei in the above mass region accessible to study by the (n, γ) method are ^{68}Zn and ^{74}Ge. Results on ^{74}Ge were reported earlier [1]. In this paper we will present data which we obtained from the reaction ^{67}Zn(n, γ)^{68}Zn at the Karlsruhe research reactor FR-2.

2. SOME DATA ON ZINC ISOTOPES TARGET

The abundance of ^{67}Zn in natural zinc amounts only to 4.11%. We used, therefore, a target enriched to 89.55% in ^{67}Zn. Unfortunately the contribution of ^{67}Zn to the total contribution of this sample could not be calculated because the cross-sections for both ^{67}Zn and ^{66}Zn are not known. Our spectra reveal, however, only minute contributions from the other zinc isotopes. Nevertheless we tried to determine the previously unknown cross-sections of ^{66}Zn and ^{67}Zn from their intensity contributions in the natural mixture by assigning primary transitions [2] to the corresponding isotopes. We assumed thereby that for each of the participating isotopes, ^{64}Zn, ^{66}Zn, ^{67}Zn and ^{68}Zn, comparable portions of their total intensity have been detected. The contribution of ^{70}Zn can be neglected. The

TABLE I. DATA ON ZINC ISOTOPES

	^{64}Zn	^{66}Zn	^{67}Zn	^{68}Zn	^{70}Zn
Natural abundance (%)	48.89	27.81	4.11	18.56	0.62
σ (b)[a]	0.77 ± 0.03	?	?	1.07 ± 0.15	0.1 ± 0.02
Capture contribution (%)	34.2	?	?	18.1	0.6
Contribution derived from γ-intensity	36.7	20.5	25.1	17.7	
σ from γ-intensity (b)		0.85 ± 0.2	6.9 ± 1.4		
B_n of product nucleus (keV)	7979.2	7052.3	10197.9	6482.6	5833[b]
Contribution in 89.55% ^{67}Zn enriched sample	0.23	0.62	98.4	0.75	

[a] Refs [3,4]

[b] Ref. [5]

assignment of gamma rays in the natural mixture was considerably facilitated by the knowledge of all ^{68}Zn gamma lines originating from the present measurements with the enriched target. The results of this procedure are listed in Table I.

The agreement of the contributions of ^{64}Zn and ^{68}Zn calculated from the known cross-sections with the contributions derived from the gamma intensities assigned gives confidence that the contributions of ^{66}Zn and ^{67}Zn and hence their cross-sections, determined from these contributions and the known cross-section for the natural mixture [4], are correct within 20%.

3. EXPERIMENTAL TECHNIQUES

3.1. Spectrometers

Four different spectrometers were used for the (n,γ) studies. Precise energy measurements of transition energies in the energy region up to 3 MeV were carried out in a Compton-suppressed system. The most significant feature of this system is the high suppression of the Compton distribution. This is demonstrated in Fig.1 which shows a portion of the (n,γ) spectrum of ^{68}Zn. Transitions with intensities 5×10^{-5} of the intensity of the 1077-keV transition can be detected. For a detailed description of the system see Ref.[6].

In the mean energy region from 2 to 6 MeV we recorded the gamma spectra in a 5-crystal pair spectrometer consisting of a 4-cm^3 Ge(Li) detector with a cooled FET-preamplifier and four bevelled 3×3-in. NaI(Tl) detectors. The extrinsic detection probability of a double-escape event in the Ge(Li) detector via the selected photopeaks of the annihilation radiation amounts to 5%. In Fig.2 a part of the pair spectrum of ^{68}Zn is shown. To preserve the good resolution of 5.9 keV at 6 MeV over a long time, the spectrometer is digitally stabilized with a stable double-pulse generator against zero and gain shifts of the electronics including the 4096-channel ADC. In the energy region above 6 MeV the spectra were recorded as singles spectra.

To establish a reliable decay scheme much work was done in γ-γ coincidence and angular correlation measurements. For these investigations we have two spectrometers connected to an on-line computer, thus allowing the simultaneous measurements of all interesting coincidences and angular correlations with the aid of the double-window technique. The coincidence arrangement used for these measurements comprised a 34-cm^3 Ge(Li) detector and a 3×3-in. NaI(Tl) detector. Later the NaI(Tl) detector was replaced by another large-volume Ge(Li) detector. The angular correlation spectrometer and the data processing therefrom are described in Ref.[7].

3.2. Calibration

To make full use of the high resolution of the anti-Compton and pair spectrometers with respect to precise energy determination, the gamma spectra were analysed with a computer fit program [6]. An example of the analysis of the spectra is given in the inset of Fig.2 showing a fitted

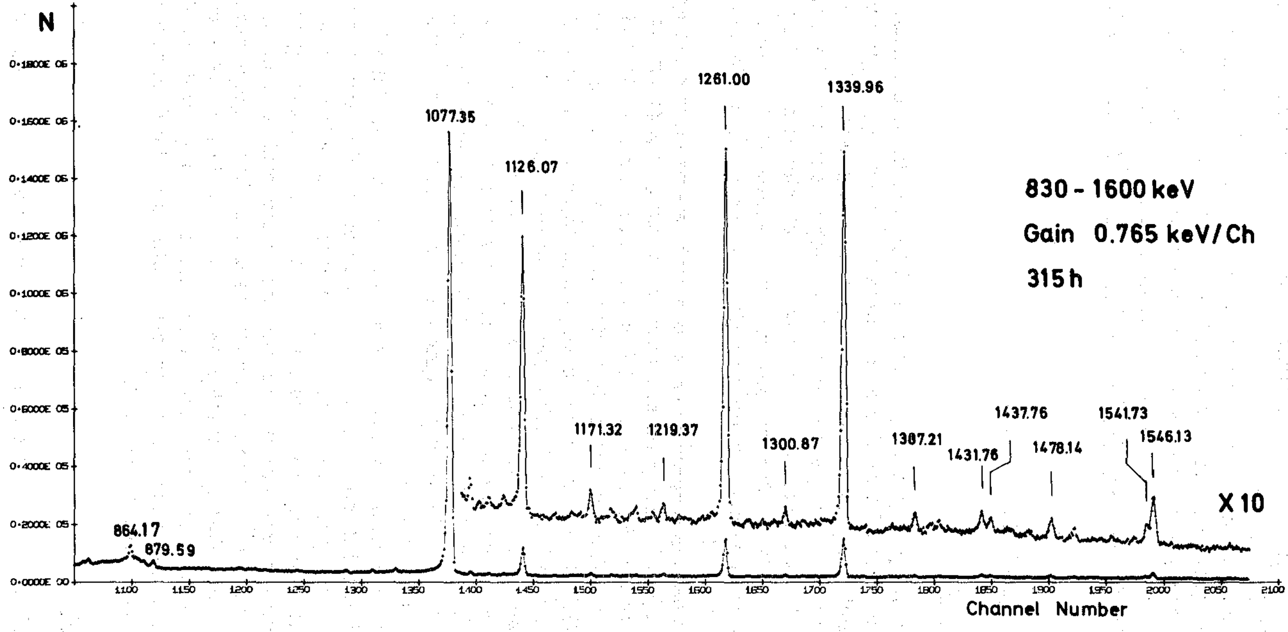

FIG. 1. Portion of the anti-Compton spectrum of $^{67}Zn(n,\gamma)^{68}Zn$.

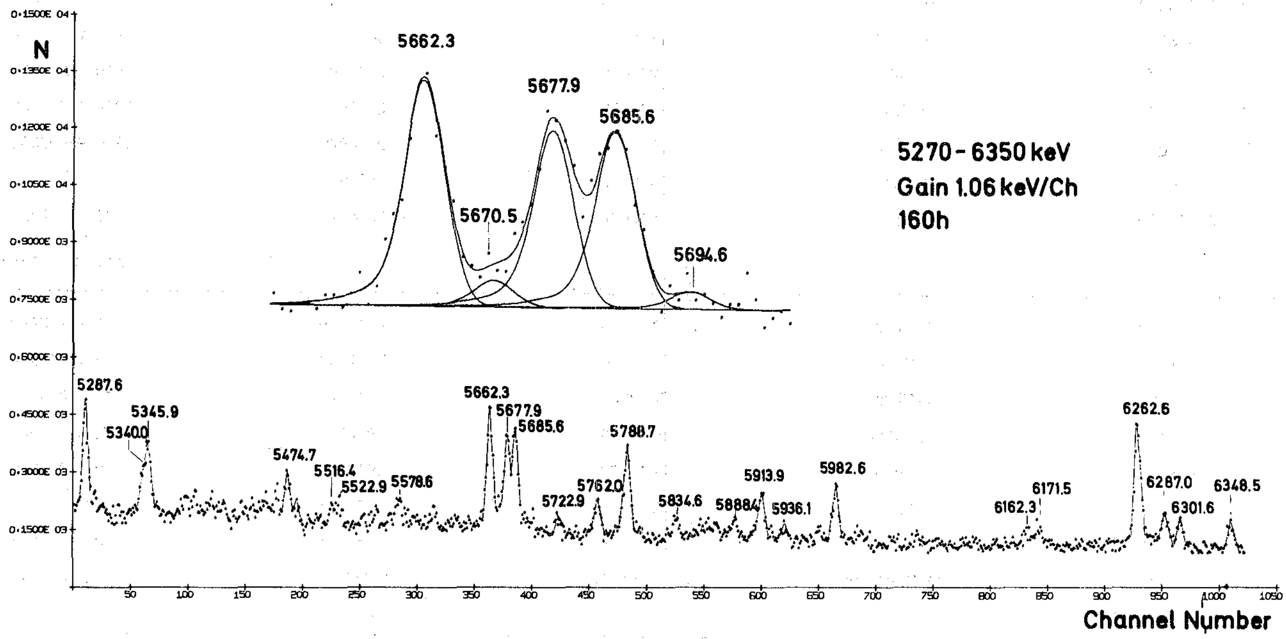

FIG. 2. Portion of the pair spectrum of $^{67}Zn(n,\gamma)^{68}Zn$.

TABLE II. POLYNOMIAL FIT OF NITROGEN CALIBRATION LINES

Input data (keV)	Output data (keV)			
Marion [10]	Measurement 1	Measurement 2	Measurement 3	Mean value
4508.8 ± 0.3	4508.81	4508.83	4508.82	4508.8
	4945.07	4945.14	4945.07	4945.1
5268.5 ± 0.2	5268.90	5268.92	5268.88	5268.9
5297.4 ± 0.3	5297.60	5297.46	5297.62	5297.6
5533.0 ± 0.3	5533.01	5533.01	5532.97	5533.0
5562.0 ± 0.3	5561.91	5561.69	5561.78	5561.7
6322.1 ± 0.4	6322.12	6322.10	6322.12	6322.1
Greenwood [11]				[a]
4508.8 ± 0.3	4508.88	4508.86	4508.88	4508.9 ± 0.3
	4945.42	4945.32	4945.32	4945.35[b]
5269.2 ± 0.35	5269.26	5269.26	5269.21	5269.2 ± 0.3
5297.8 ± 0.35	5297.80	5297.96	5297.95	5297.9 ± 0.3
5533.2 ± 0.35	5533.29	5533.31	5533.33	5533.3 ± 0.3
5562.2 ± 0.35	5562.09	5561.98	5561.99	5562.0 ± 0.3
6322.0 ± 0.4	6322.0	6322.01	6322.01	6322.0 ± 0.4

[a] Used for calibrating the gamma rays in ^{68}Zn.
[b] E_γ = 4945.46 ± 0.17 keV. Calibration standard from ^{13}C [12].

line group in the pair spectrum. This fitting with modified Gaussian functions, i.e. Gaussian function plus exponential function taking into account the low-energy tailing of the peaks, allows the exact determination of peak locations. The system non-linearity was measured by feeding pulses from a highly stable pulse generator with a linearity better than 1 part in 10^5 and a resolution of 1 part in 10^6 [8] into the preamplifier. The pulser peak locations resulting from the fitting procedure were then fitted by the least-squares method to a polynomial of order up to four. For the calibration the peak positions of the calibration lines taken together with the spectrum were fitted with a polynomial of same order. The polynomial best describing the system non-linearity was then chosen for calibration. To obtain best results the polynomial sometimes had to be divided into two or three parts.

In the low-energy region the well-known calibration lines were used [9]. In the high-energy region, unfortunately, there is still a lack of precise calibration standards. Lately the capture lines of ^{15}N have been commonly used as energy as well as intensity standards. However, there remain some ambiguities because the data of different authors do not coincide within the errors indicated. This is especially true for the intense lines between 5 and 6 MeV. Recently Marion [10] has published a set of adopted values. While calibrating different independent measurements with different peak channel locations of the calibration lines we got indications that these values are not quite correct. Table II shows the results of the polynomial fit of two different sets of nitrogen calibration lines between 4.5 and 6.3 MeV: in one we used the adopted values of Marion and in the second the data of Greenwood [11]. One can see from the table that the calibration set of Greenwood reproduces the best known energy in this region – the 4945.46 ± 0.17-keV capture line of ^{13}C [12] – much better than that of Marion. For calibrating our high-energy spectra we used, therefore, the values of Greenwood for calibration lines above 6 MeV together with our slightly different values from Table II.

4. EXPERIMENTAL RESULTS

The results of all measurements are summarized in the level scheme in Fig.3. All transition energies therein are corrected for recoil. Up to 3 MeV all levels with spins between 0 and 4, seen in different reactions [13-17], are excited in the (n, γ) process and are now precisely fixed. All levels in the decay scheme are fed by primary gamma rays from the capture state except the 0^+ level at 1655.90 keV and the 2821.54-keV level. A primary transition to the 3281.5-keV level could be masked by the intense transition to the close-lying 3286.93-keV level. Though the precise energy determination allows one to apply the Ritz combination principle with confidence, most of the transitions have been well established by coincidence measurements. Such well-established coincidences of transitions are marked with dots at their arrowheads in the level scheme. Only one ambiguity arises: thorough investigation of the spectrum coincident to the 1077.36-keV transition reveals a line at 1883 keV, although the coincident background and the contribution from the nearly 1126.08-keV transition have been subtracted appropriately with the double-window technique. A recent coincidence measurement on natural zinc with

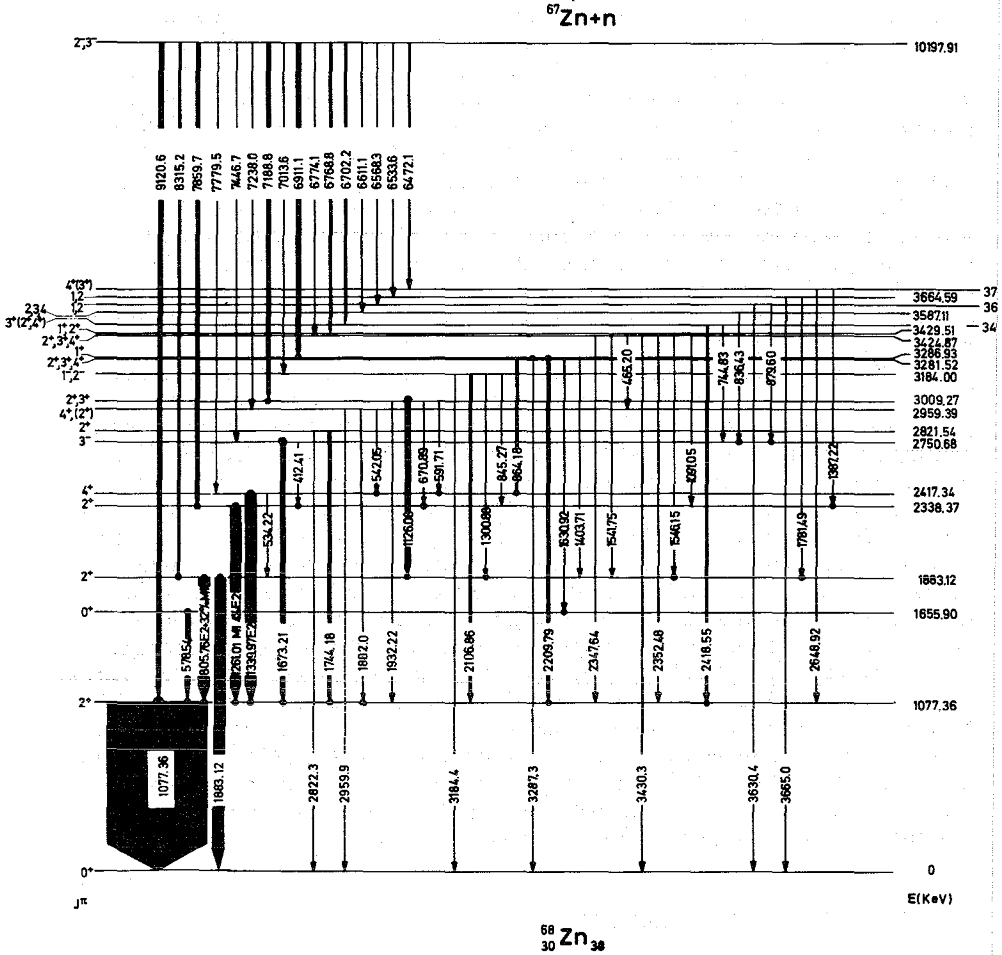

FIG. 3. Level scheme of ^{68}Zn from the reaction ^{67}Zn(n, γ) ^{68}Zn.

our new Ge(Li)-Ge(Li) coincidence arrangement supports this result. This involves, most probably, a cascade 1882.0 keV-1077.36 keV between the known levels at 2959.39 keV, 1077.36 keV and the ground state. Not more than 10% of the total intensity of the 1883.09-keV transition is involved in this 1882.0-keV transition. This latter transition could not be resolved from the intense 1883.12-keV transition in the singles spectrum.

The results of our angular correlation analysis done for eight cascades are shown in a parametric A_2, A_4 plot in Fig.4. From these results the following unambiguous spin and parity assignments are derived: 0^+ for the 1655.90-keV level, 2^+ for the 1883.12-keV level, 2^+ for the 2338.37-keV level and 4^+ for the 2417.34-keV level. These confirm the results of earlier measurements. However, we get quite different mixing ratios for the 805.76-keV transition between the 1883.12 and the 1077.36-keV levels and for the 1261.01 transition between the 2338.37 and the 1077.36-keV levels.

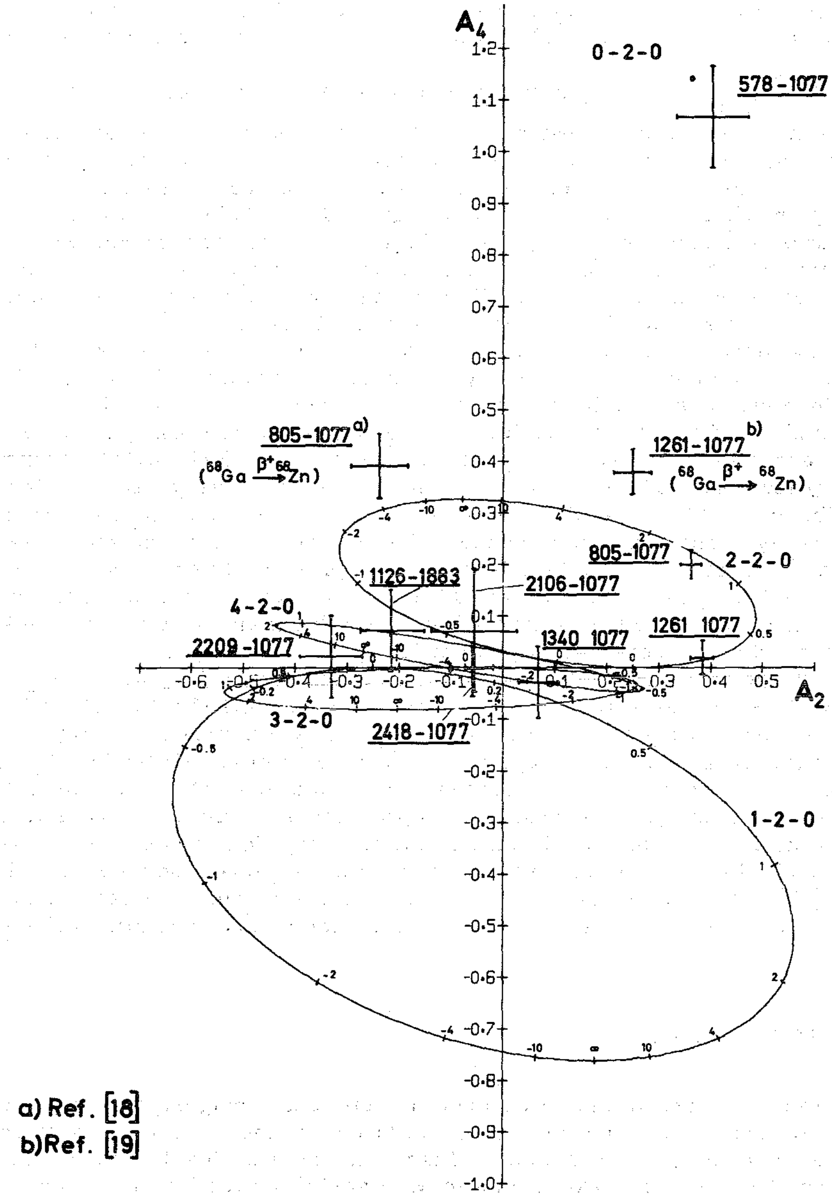

FIG. 4. Angular correlation coefficients for transitions in ^{68}Zn from the reaction ^{67}Zn(n, γ)^{68}Zn.

The results of the studies in radioactive decay of ^{68}Ga, also shown in Fig.4, yield a $\delta = -(4 ^{+3}_{-2})$ or 94% E2 contribution for the 805.76-keV transition [18] whereas the analysis of our (n, γ) measurement yields a $\delta = 1.45 \pm 0.15$ or 68% E2 contribution for the same transition. For the

1261.01-keV transition Taylor and McPherson [19] obtained from radioactive decay of ^{68}Ga a $\delta = 2.25 \pm 0.30$ or 84% E2 contribution, however, our $\delta = 0.21 ^{+0.06}_{-0.04}$ yields only a small amount of 4% E2 contribution to this transition. These discrepancies may have two reasons: first both transitions appear in the β^+ decay of ^{68}Ga with much less intensity than in the (n, γ) reaction, on the other hand the spectra obtained from the radioactive decay are characterized by a high background caused by annihilation radiation and bremsstrahlung. This requires a large background subtraction and therefore there remains some uncertainty as to what extent this was correctly done. A detailed description of our angular correlation analysis of the 1260.01 transition is given in Ref.[7].

The angular correlation analysis of the other cascades shown in Fig.4 yields, in conjunction with the excitation and de-excitation behaviour of the involved levels, spin and parity 2^+ or 3^+ for the 3009.27-keV level and 1^- or 2^- for the 3184.00-keV level. The negative parity assignment to this level was taken from (d, p) measurements [17] which reveal a negative parity level at 3180 keV. This is compatible with the very weak primary feeding of the 3184.00-keV level found in the present investigation. Spin and parity assignments for the 3286.93-keV level come out unambiguously to be 1^+, while the 3495.74-keV level most probably has the assignment 3^+. The 4^+ (3^+) assignment to the 3725.92-keV level, also taken from the (d, p) measurements [17] where a level with this spin was seen at 3730 keV, agrees with its feeding and de-excitation.

The spin 3^- for the 2750.68-keV and 2^+ for the 2821.54-keV levels seem to be well established from other measurements [14, 15, 20]. It is astonishing that the latter level is not excited by a possible primary E1 transition from the 2^-, 3^- capture state. Hudson et al.[14] assigned from (t, p) measurements an unambiguous spin 4^+ to a level at 2954 ± 8 keV. If, however, the 2959.9-keV transition represents a ground-state transition from the 2959.39-keV level found in our investigation and assumed to be identical with the level of Hudson, the spin of this level should be 2^+. The assignments to the remaining levels in the level scheme represent most probable values with respect to their excitation and de-excitation behaviour.

5. CONCLUSIONS

Coulomb excitation and various inelastic scattering experiments leave no doubt that most of the low-lying excitations of the so-called 'spherical' nuclei have collective character. Discussing nuclear level patterns one enters, however, the problem as to what sort of collective motion one should ascribe to these excitations. It seems now to be rather certain that the model most applied to these nuclei – the vibrational model – does not give an adequate description of their excitations. Looking at the level scheme in Fig.4 with the phonon picture of this model in mind, one might consider the first excited 0^+ level, the second 2^+ and the first 4^+ level as two-phonon candidates though these three levels are relatively widely spaced The 2^+ level at 2338 keV can be completely ruled out as a phonon-state because of the pure M1 character of its de-excitation transition.

A deeper insight in the level structure may be obtained by comparing the level patterns of neighbouring nuclei. This is done in Fig.5 for even nuclei between ^{64}Zn and ^{72}Ge. Included in the figure are all the data available in literature about the levels up to the 3^- octupole state. The comparison shows very nice analogies between different isotopes for the first and second 2^+ levels and for the first 4^+ level. While these levels vary only slowly in their energies from one nucleus to the other, the first 0^+ level comes down very rapidly in its energy – more than 1.5 MeV. In ^{64}Zn the situation is complicated by the presence of two 0^+ levels. Nevertheless, the quite different behaviour of these 0^+ states implies that they represent another type of excitation than other states in this region.

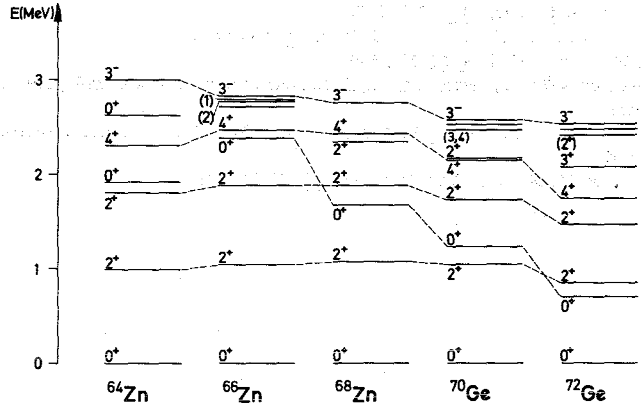

FIG. 5. Comparison between level schemes of even nuclei around A = 68 including all experimental data available in the literature.

The recently observed large quadrupole moments of the first excited 2^+ states [21], also in nuclei commonly believed to be spherical, indicate that anharmonic effects probably play an important role. There have been empirical attempts to treat the vibrational spectra as quasi-rotational spectra [22] and to decompose them into quasi-rotational bands, beta-like bands and gamma-like bands. The first excited 0^+ state is thus considered as a band head of a quasi-beta band. The numerical calculations recently started [23] involving the exactly treated coupling of these three motions yielded promising results for nuclei with masses around A = 190, i.e. in the transition region from deformed to spherical shapes. One may hope that this will also be true for the lighter nuclei.

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