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Nuclear Structure Studies with Radiative Neutron Capture

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1. Introduction

The recent advances of experimental techniques in gamma-ray spectroscopy provide an excellent basis for studying nuclear structure by (n,γ) reactions. At the Karlsruhe research reactor FR-2 the excited states of several nuclei have been investigated by thermal neutron capture using a 5-crystal Ge (Li) pair spectrometer [1], a Ge (Li) anti-Compton device [2,3], a Ge (Li) - NaI (Tl) coincidence system [1] and an angular correlation spectrometer. Studies were made both in the region of nearly spherical nuclei and in the region of strongly deformed nuclei.

2. Level Structure of Fe^{58} and Ni^{62}

Since the isotopic abundance of Fe^{57} and Ni^{61} is low in the natural elements (2.19 % and 1.19 %, respectively), highly enriched samples of 90.73 % Fe^{57} and 92.11 % Ni^{61} were used as a target.

Level energies for Fe^{58} and Ni^{62} are summarized in Table I. The transition diagrams are shown in Figs. 1 and 2, respectively. Large dots indicate experimentally established coincidence relationships. Gamma rays entering a level and dotted at their arrowheads have been shown to be in coincidence with at least one gamma ray leaving the same level and dotted at its origin.

The first excited level at 810.5 keV in Fe^{58} is the well known one-phonon vibrational state. A new level with spin and parity 0^+ or 4^+ has been introduced at 1335.3 keV. This level together with the 2^+ state at 1674.6 keV belongs to the two-phonon triplet. From the higher-lying states the levels at 2133.9 keV and 2781.8 keV possibly contain marked admixtures from the three-phonon excitations. This may be concluded from the branching of transitions deexciting these states. In terms of the vibrational model the assignment of the 2133.9 keV level to the two-phonon triplet must be ruled out since a transition to the second 2^+ state is forbidden.

Table I

Excited states in Fe^{58} and Ni^{62}

Fe^{58}				Ni^{62}			
E /keV/	J π	E /keV/	J π	E /keV/	J π	E /keV/	J π
810.5	2^+	3538.2	$1^+,2^+$	1172.3	2^+	3268.6	$1^+,2^+$
1335.3	$0^+,4^+$	3881	1, 2	2047.7	0^+	3368.6	$1^+,2^+$
1674.6	2^+	4139	1, 2	2300.9	2^+	3517.8	$1^+,2^+$
2133.9	$3^+,4^+$	4322	1, 2	2335.2	4^+	3961.9	$1^+,2^+$
2781.8	$1^+,2^+$	4443	1, 2	2889.9	$2^+,3^+$		
2876.1		4550	$0^+,1^+,2^+$	3057.6	$2^+,3^+$		
3084.0	$0^+,1^+,2^+$	5001	$1^+,2^+$	3156.8			
3244.0				3256.0			

In Ni^{62} the levels at 1172.3, 2047.7, 2300.9 and 2335.2 keV correspond to the one- and two-phonon excitations, respectively. From the levels observed at higher energies the excited states at 3057.6, 3268.6 and 3368.6 keV show enhanced transitions to the vibrational triplet. These states therefore may be regarded as possible candidates for states with strong admixtures from the three-phonon quintuplet.

A comparison of the experimental excitation energies with the predictions of pure vibrational models /4-7/ remains unsatisfactory though, e.g. in Fe^{58}, a 4^+ state is predicted at 2100 keV by the group theoretical approach of Ferreira and coworkers /5/ (oscillator including quartic terms) when the spin of the 1335.3 keV level is assumed to be 4^+ and a fit is made to the first three excited states. For Ni^{62} Kerman and Shakin /4/ who have included cubic terms in the nuclear vibrational Hamiltonian achieved a good fit to the two-phonon levels. However, when their formulas and parameters are used to compute the three-phonon quintuplet, a comparison with Fig. 2 gives no promising results. One might speculate about more realistic models such as the microscopic approaches made by Hsu and French /8/ and indeed, the spectra calculated for Ni^{62} in the seniority approximations seem to give the right trend, at least as concerns the level sequence.

Angular correlation measurements on Fe^{58} and Ni^{62} are in progress. These experiments are expected to allow more precise spin determinations.

3. Gamma-Gamma Angular Correlations in Sr^{88}

Gamma-gamma angular correlations have been measured for various cascades from the reaction Sr^{87} (n,γ) Sr^{88}. Natural strontium was used as a target. The cross section contribution of Sr^{87} is 87.4 %. Due to the complex structure of capture spectra angular correlation measurements are extremely difficult. In order to minimize systematic errors extensive use was made of the capabilities of an on-line computer system. Some results are summarized in Table II. Column 1 gives the gamma-ray cascade. Column 2 and 3 list the coefficients for an expansion in Legendre polynomials together with the experimental errors which include both statistical and systematic uncertainties. Excitation energy, spin and parity of the initial states are given in column 4 and 5. Possible shell model configurations for the initial states are listed in column 6.

A transition diagram for Sr^{88} may be found in a recently published study [9] on neutron capture in Sr^{87}.

Table II.

Angular Correlations in Sr^{88}

Cascade [keV]	A_2	A_4	Initial state E_i [keV]	$J_i \pi_i$	Possible structure
850 - 897	-(0.083 ± 0.010)	-(0.009 ± 0.016)	3583	$4^-, 5^-$	(p3/2) (g9/2) or (f5/2) (g9/2)
897 - 1836	-(0.079 ± 0.013)	-(0.003 ± 0.005)	2733	3^-	Q_3
3010 - 1836	-(0.089 ± 0.007)	-(0.002 ± 0.011)	4846	3^-	(p3/2) (g9/2) or (f5/2) (g9/2)

Table III.

Level structure of the isotonic species Dy^{165}, Er^{167} and Yb^{169}

Structure	Level energies [keV]		
	Dy^{165}	Er^{167}	Yb^{169}
$1/2^-$ [521]	108.2	207.8	24.2
$5/2^-$ [512]+ $1/2^-$ [510]+Q_{22}	184.3	346.5	191.4
$5/2^-$ [523]	533.5	667.9	569.9
$5/2^+$[642]+ $5/2^-$[523]+ Q_{30}			580.5
$5/2^-$ [512]+ Q_{22}+ $1/2^-$[510]	570.3 (a=0.048)	763.5	806.9 (a=0.097)
$7/2^+$ [633]+ Q_{22}+ $3/2^+$[651]	538.6	531.5	590.3
$3/2^-$ [521]+ $1/2^-$ [521]+Q_{22}	573.6	752.8	659.5
$1/2^-$ [521]+ Q_{22}+ $3/2^-$ [521]	1103.3	(1227)	1262

4. Level Structure of Deformed Odd-Mass Nuclei

In the region of deformed odd-A nuclei the nature of various excited states has been determined using neutron capture. The results can be well understood in the framework of theoretical calculations [10] which take into account quasiparticle-phonon interaction. When the spacings of single-particle states are such that levels connected by large E2 matrix elements occur separated by approximately the quadrupole phonon energy, a break-down of the pure single-particle description and considerable mixing are expected.

In Table III bandhead energies are summarized for the isotonic nuclei Dy^{165}, Er^{167} and Yb^{169}. Enriched samples of 92.71 % Dy^{164}, 95.6 % Er^{166} and 19.5 % Yb^{168} were used as a target.

A striking feature of the quasiparticle-phonon interaction is the appearance of large components of high-lying Nilsson states in the low-energy region. A typical example is the admixture of the $1/2^-$ [510] state into the K-2 vibration on the $5/2^-$ [512] state. The observed nonvanishing decoupling parameter may be ascribed to such an admixture. According to the present experimental results the contribution of the 1/2$^-$ [510] state seems to increase from Dy^{165} to Yb^{169}. In Yb^{169} the decoupling parameter and the rotational factor are $a = 0.097$ and $\hbar^2/2\,\Theta = 13.5$ keV, whereas the rotational factor for the 5/2$^-$ [512] band is 12.4 keV.

For a detailed discussion of the results on Dy^{165} see ref. [1]. An extensive analysis of the data on Er^{167} and Yb^{169} will be published in the near future. A preliminary transition diagram of Yb^{169} may be found in ref. [11] .

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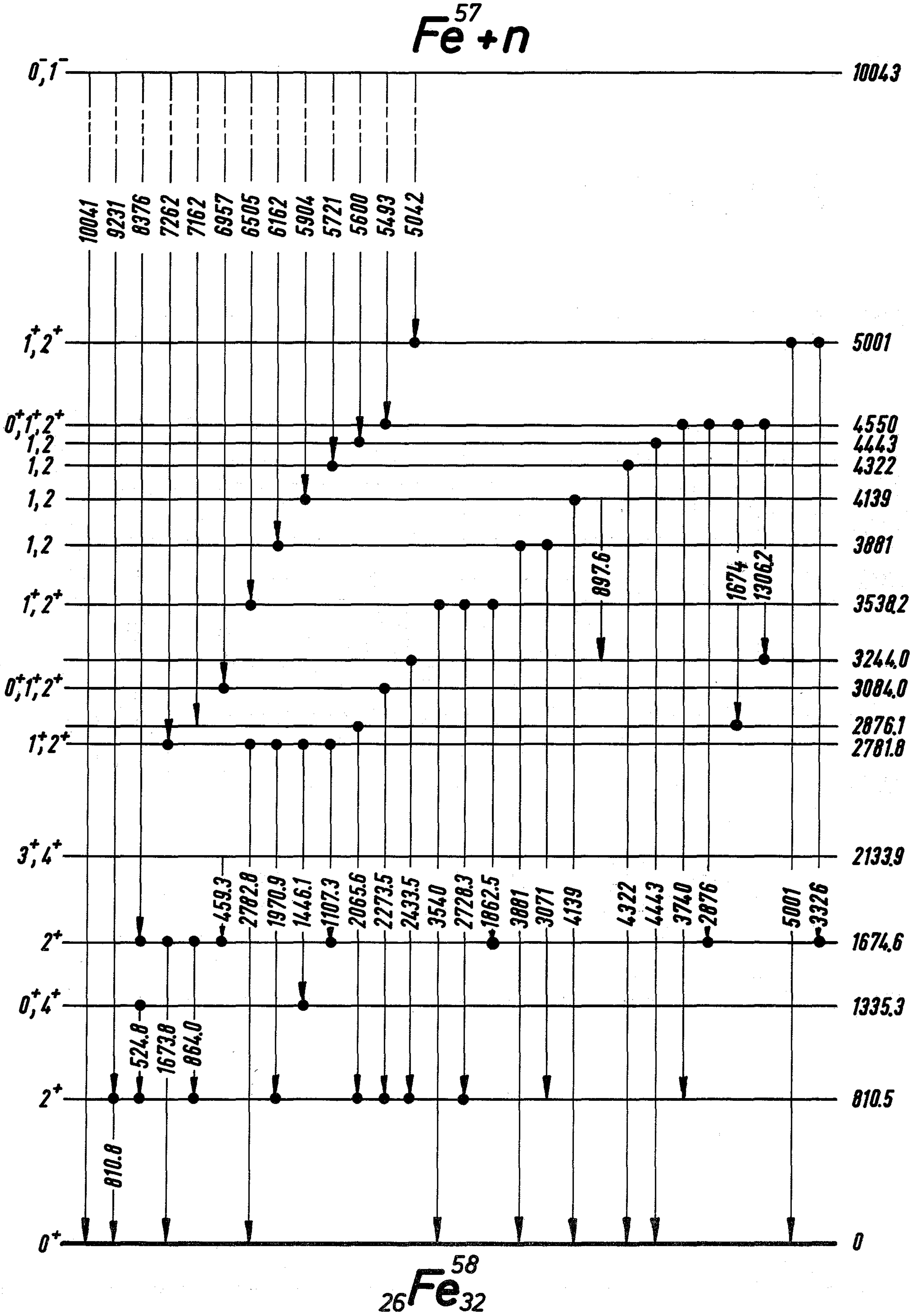

$Fe^{57}+n$
$0^-,1^-$
10043
10041
9231
8376
7262
7162
6957
6505
6162
5904
5721
5600
5493
5042
$1^+,2^+$
5001
$0^+,1^+,2^+$
4550
1,2
4443
1,2
4322
1,2
4139
1,2
3881
897.6
1674
1306.2
$1^+,2^+$
3538.2
3244.0
$0^+,1^+,2^+$
3084.0
2876.1
$1^+,2^+$
2781.8
$3^+,4^+$
2133.9
459.3
2782.8
1970.9
1446.1
1107.3
2065.6
2273.5
2433.5
3540
2728.3
1862.5
3881
3071
4139
4322
4443
3740
2876
5001
3326
2^+
1674.6
$0^+,4^+$
1335.3
524.8
1673.8
864.0
2^+
810.5
810.8
0^+
0
$_{26}Fe^{58}_{32}$

Fig. 1

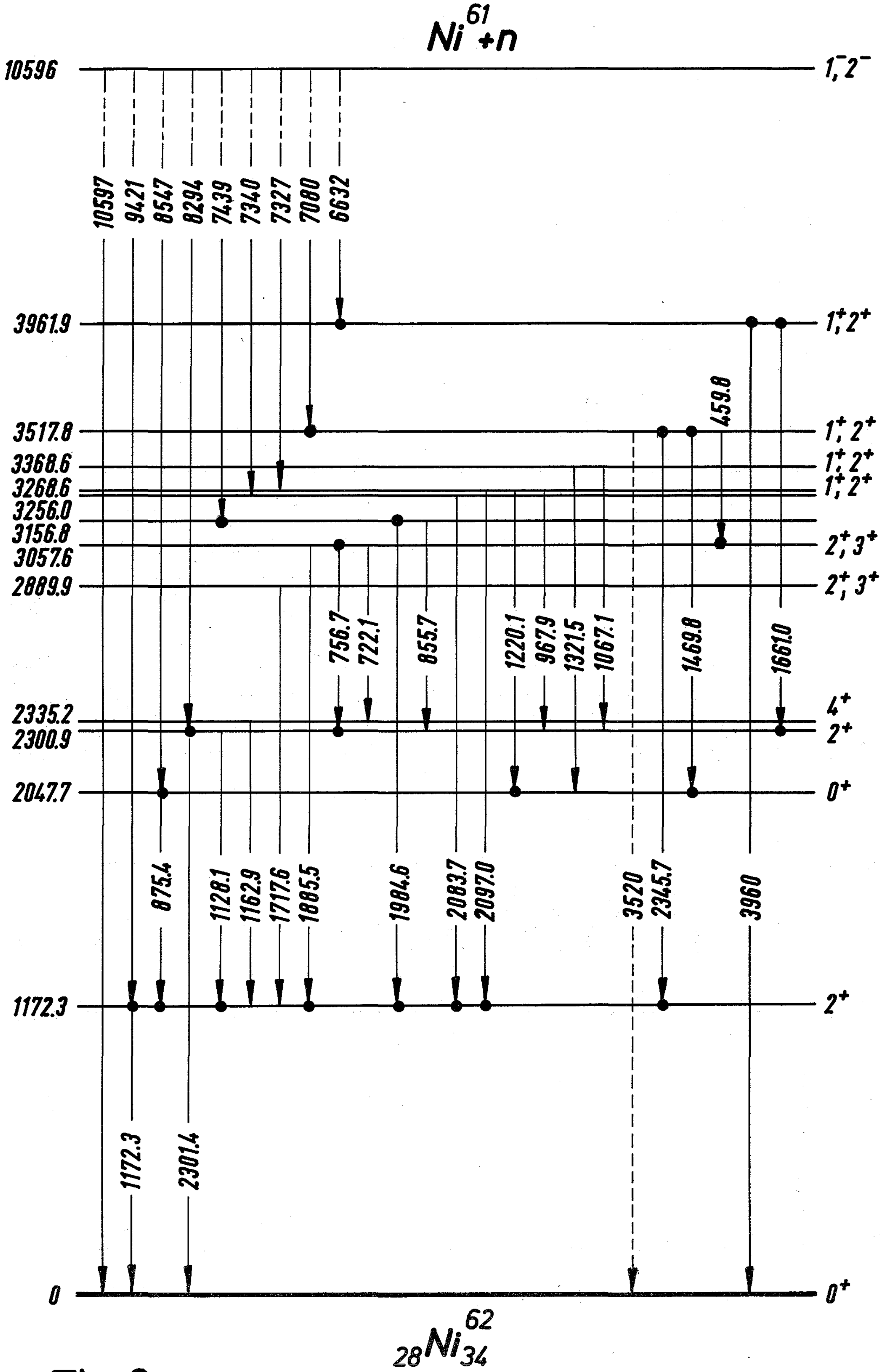
Ni61 +n
10596
1-, 2-
10597
9421
8547
8294
7439
7340
7327
7080
6632
3961.9
1+, 2+
3517.8
1+, 2+
459.8
3368.6
1+, 2+
3268.6
1+, 2+
3256.0
3156.8
2+, 3+
3057.6
2889.9
2+, 3+
756.7
722.1
855.7
1220.1
967.9
1321.5
1067.1
1469.8
1661.0
2335.2
4+
2300.9
2+
2047.7
0+
875.4
1128.1
1162.9
1717.6
1885.5
1984.6
2083.7
2097.0
3520
2345.7
3960
1172.3
2+
1172.3
2301.4
0
0+
28Ni62 34

Fig. 2