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SHELL MODEL CONFIGURATIONS IN EVEN SPHERICAL NUCLEI

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Abstract

SHELL MODEL CONFIGURATIONS IN EVEN SPHERICAL NUCLEI. Latest results of thermal neutron capture gamma-ray investigations of ^{62}Ni are reported. Enriched samples of 92.11% ^{61}Ni were used as external targets at the Karlsruhe reactor FR-2. The gamma radiation has been studied with a Ge(Li) anti-Compton device, a 5-crystal Ge(Li) pair spectrometer, and both a Ge(Li)-NaI coincidence and a NaI-NaI angular correlation spectrometer coupled to an on-line computer. On the basis of these measurements a considerably extended level scheme of ^{62}Ni is proposed. Several new spins were assigned. The experimental levels and transition rates are compared with results of various shell-model calculations which reproduce the low-lying experimental ^{62}Ni states fairly well. The comparison is extended to the ^{58}Fe level scheme discussed in more detail elsewhere.

1. Introduction

The even nuclei not far away from a closed 1 f 7/2 shell for neutrons and/or protons have generally been considered to be spherical and to tend to surface oscillations. Especially the nickel isotopes ^{60}Ni and ^{62}Ni have been cited by several authors [1, 2, 3] as good examples for collective quadrupole vibrations - at least with respect to the one- and two- phonon states. On the other hand, recent detailed shell-model calculations performed by Auerbach [4] and Cohen et al. [5] reproduce the low-lying energy levels of even and odd-neutron Ni isotopes quite well within about 200 keV. For nuclei with $20 \leq Z \leq 27$ and N = 30, 32 there exist also theoretical level schemes calculated by McGrory [6, 7] which can be compared with the results of our ^{58}Fe measurements [8]. In these papers no theoretical transition probabilities are given, whereas Cohen et al. and Auerbach have calculated some B(E2)-transition rates. The prediction of transition rates is of great interest, also with respect to transition rules of vibrational models.

Experimentally the thermal neutron capture γ-ray method is a valuable tool for checking transition modes and rates up to high excitation states. The determination of level positions might be somewhat more complicated than in other reactions, but involves very precise values. The reaction ^{61}Ni(n,γ)^{62}Ni has not been studied before. The mechanism of deexcitation of ^{62}Ni states was therefore essentially unknown except for the first four levels which had been investigated by β^- decay of ^{62}Co [9, 10], β^+ decay of ^{62}Cu [11, 12], and the (p,p'γ) reaction [13].

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Table I

Sample used for the $^{61}Ni(n,\gamma)^{62}Ni$ investigation

Isotope	Binding energy of the neutron in the product nucleus [a] (MeV)	Capture cross section[b] for thermal neutrons (b)	Ni^{nat} Content (%)	Ni^{nat} Capture contribution (%)	^{62}Ni enriched sample Content (%)	^{62}Ni enriched sample Capture contribution (%)
^{58}Ni	9.00	4.4	67.88	70	1.62	3
^{60}Ni	7.82	2.6	26.23	16	5.18	6
^{61}Ni	10.59	2.0	1.19	0.6	92.11	83.5
^{62}Ni	6.84	15	3.66	13	1.08	7.5
^{64}Ni	6.13	1.52	1.08	0.4	< 0.05	< 0.03

a) Ref. [26]

b) Ref. [14]

2. Experimental Procedure

The experimental procedure will only be mentioned briefly, as it is similar to that followed for the $^{57}Fe(n,\gamma)$ measurements and extensively described in Ref. [8].

The isotope ^{61}Ni has a thermal neutron cross section of 2 b [14] and is represented only to 1.2 % in the natural element, thus yielding a capture contribution of 0.6 % (cf. Table I). This contribution in our samples had been increased to 83.5 % by an enrichment in ^{61}Ni to 92.11 %. In spite of this relatively high enrichment care had to be taken in the isotope assignments of lines appearing in the γ-ray spectra. - The metallic powder samples in 0.5 mm thin polythene containers were used as external targets for thermalized neutrons at the Karlsruhe research reactor FR-2. The γ radiation following the capture of neutrons was detected with four devices: 1) an anti-Compton arrangement [15] with a 4.9 cm^3 Ge(Li) diode for the low energy portion up to 2.8 MeV, 2) a 5-crystal pair spectrometer with a 2 mm x 2.7 cm^2 Ge(Li) detector [16]; 3) a 34 cm^3 Ge(Li)- 7.6 x 7.6 cm NaI(Tl) coincidence system [17], and 4) an angular correlation spectrometer with two 10.2 x 12.7 cm NaI(Tl) crystals [18]. The latter two were coupled to an on-line computer [19]. The energy calibration is based on the decay lines of ^{57}Co [20], ^{192}Ir, ^{137}Cs, ^{88}Y, ^{60}Co [21] and capture γ-rays of the reaction $H(n,\gamma)$ [22] up to 2.8 MeV and on capture lines in ^{56}Fe [23], ^{164}Dy [24] and ^{14}N [25] in the higher energy region.

As an example for the γ-ray spectra taken with the pair spectrometer the portion from 6.4 to 8.6 MeV is shown in Fig. 1. As expected from the 16.5 % capture contribution of isotopes other than ^{61}Ni, strong lines of ^{59}Ni, ^{61}Ni and ^{63}Ni also do appear. These lines enable us to calculate absolute ^{62}Ni γ-ray intensities (per capture in ^{61}Ni) on the basis of the $Ni^{nat}(n,\gamma)$ reaction investigated by Groshev [26], if we take into account the different capture contributions in the samples. As can be seen from intensity ratios compared with the measurements of Groshev, only weak ^{62}Ni lines may be masked by γ-rays from other isotopes.

Fig. 2 represents Ge(Li) γ-ray spectra of ^{58}Fe as an example for the coincidence technique which has been applied for ^{62}Ni as well. The spectra shown are coincident with two unresolved lines at 810 keV and 864 keV in the NaI(Tl) spectrum, for which the window positions are marked in the inset. The first (upper) spectrum represents the coincidences with the full peak, the second one with the 810 keV line, the third one with the 864 keV line. The coincident background has been subtracted in all cases. The coincidences of the 810 keV and 864 keV lines could be separated by computing appropriate differences of the spectra.

As a last example for techniques of measurement and evaluation, Fig. 3 demonstrates a parametric plot of A_2, A_4 coefficients of the angular correlation function $W(\vartheta) = \sum_k A_{2k} P_{2k}(\cos\vartheta)$ for some I - 2 - 0 spin sequences. The crosses correspond to values of measured cascades in ^{58}Fe [8], again.

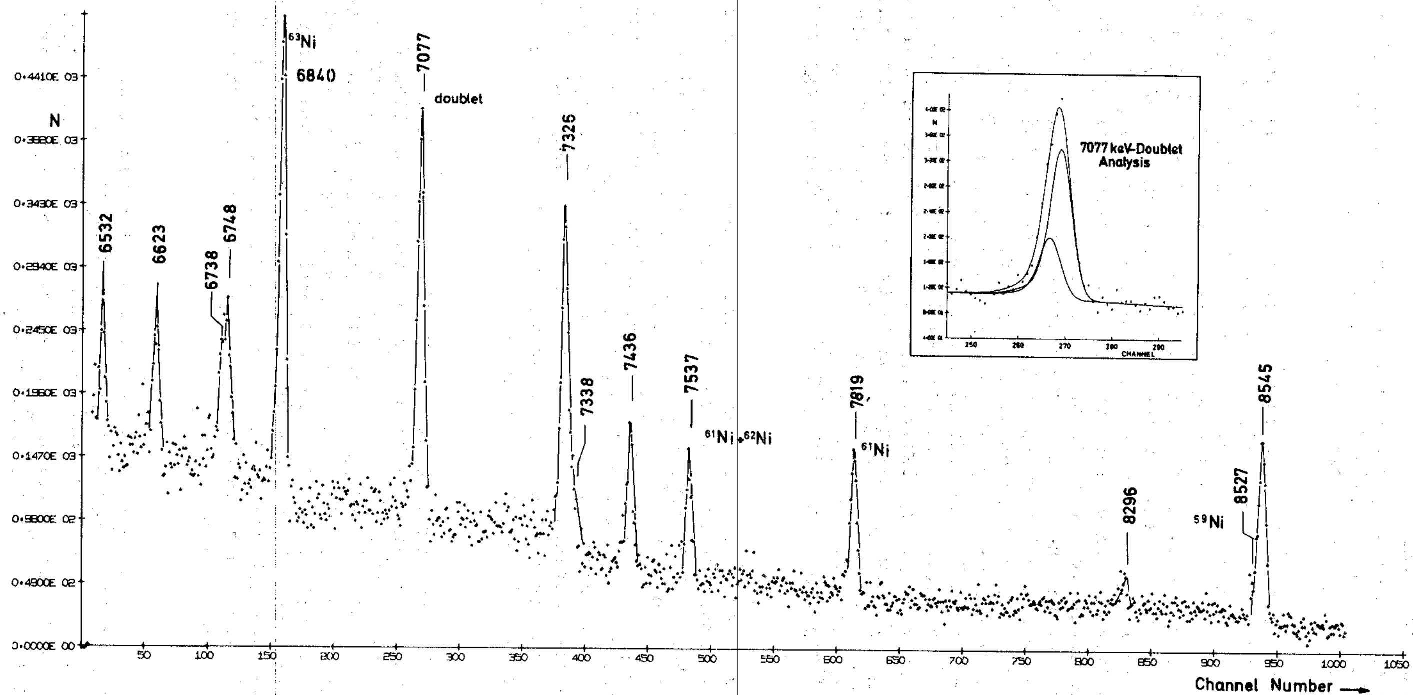
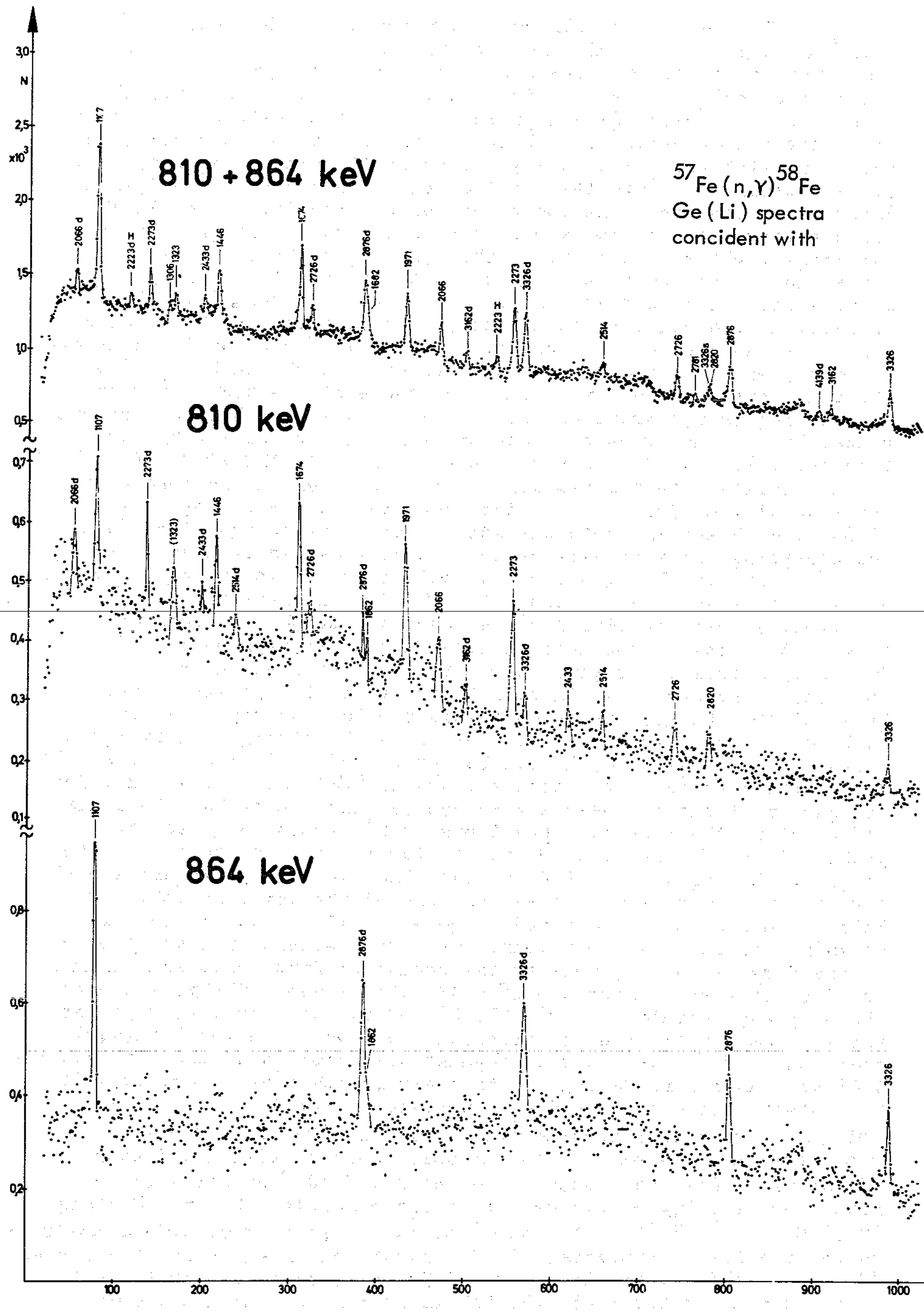


FIG.1. $^{61}Ni(n, \gamma)\,^{62}Ni$ portion of the pair spectrum, energy range 6.4 to 8.6 MeV.

3. Level Scheme of ^{62}Ni

The results of all our measurements on the reaction ^{61}Ni $(n,\gamma)^{62}$Ni suggest a level scheme as represented in Fig. 4. The intensities of the transitions are expressed by the line widths. Well established coincidences are indicated by full circles, probable ones by open circles. Five coincidence relations between primary and groundstate transitions have been established by the sum-coincidence technique with the sum window position at the binding energy. Only lines fitting well into the level scheme within their experimental error have been used. The energy values of transitions and levels are considered to be accurate within less than 500 eV when given to two decimal places. In spite of this precision there are two transitions - marked by asterisks - that fit the level energy differences twice in that scheme. In the case of the 968.16 keV transition this might be fortuitous; this is signified by a dashed line. But the second placement of the 1220.76 keV γ ray is postulated by coincidence relations, and both transitions should be of about the same intensity. Studying the line shape of the 1220 keV γ ray in the singles spectrum, one finds that peak wider than neighbouring peaks, but the energies of these two lines cannot differ by more than about 400 eV. - As could be seen in Fig. 1, the 7077 keV doublet can be resolved, thus revealing two primary transitions feeding the level doublet at 3520 keV. In the same spectrum there appear two lines at 7537 keV and 7819 keV which have to be assigned to ^{61}Ni. But comparing the intensity ratio to that measured by Groshev et al. [26] in natural Ni, one must conclude that the lower peak contains a weak ^{62}Ni line to a fraction of 13 %. Such a transition fits excellently into the ^{62}Ni level scheme. Due to the weakness of this primary transition, the general rule that strong high-energy deexcitations from the capture level have E1 character cannot be applied. Therefore it is impossible to decide the parity of the level at 3058.63 keV. The same argument holds for the level at 4627 keV. - For a great part of levels fed by strong primary transitions , the possible spins can be restricted to $I^{\pi} = 0^+, 1^+, 2^+, 3^+$ due to the fact that the capture state in ^{62}Ni has $I^{\pi} = 1^-, 2^-$. From the deexcitations of these levels one can exclude either the spins 0^+ and 3^+ in the case of transitions to 0^+ states (e.g. to the ground state) or the spins 0^+ and 1^+ for transitions to a 4^+ state (e.g. to that known one at 2336 keV). That was the procedure for all levels designated by two spin values, except the level at 2891 keV. This state has to be discussed in more detail. First, a feeding primary transition was not found. Only one deexcitation of 1718 keV to the first 2^+ state, none to the ground or first excited 0^+ state could be observed. Therefore $I^{\pi} = 1^+$ doesn't seem likely, although the spin assignments $I^{\pi} = 0^+, 1^+, 2^+, 3^+$ for the level at 2891 keV are all compatible with the observed $l = 1$ value in the ^{61}Ni(d,p) reaction [27]. Our measured angular distribution of the 1718 keV - 1173 keV cascade revealing a rather strong positive anisotropy, is consistent with a 2 - 2 - 0 spin sequence. Earlier not quite convincing investigations of the ^{62}Co decay [9] postulated a 3^+ level at 2.89 MeV which must be identified with our state at 2891 keV. Recently Mo et al. [10] repeated those measurements using Ge(Li) detectors and concluded that no 3^+ state is populated by ^{62}Co decay. The ^{61}Ni(n,γ) angular correlation analysis which is still in progress, yields unambiguous results for the strong 875 keV - 1173 keV and 2346 keV - 1173 keV cascades. Thus the spin 0^+ for the known level at 2048 keV is confirmed, and a new spin


810 + 864 keV
810 keV
864 keV
$^{57}Fe(n,\gamma)^{58}Fe$
Ge(Li) spectra
concident with
N
$x10^3$

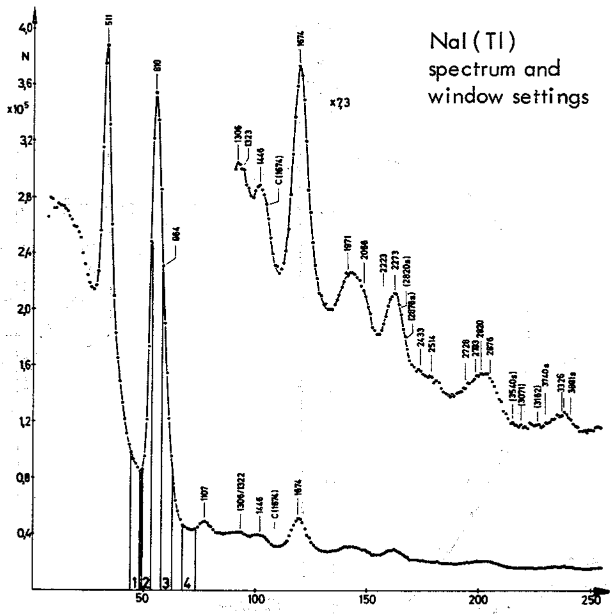


FIG.2. Sections of the ^{58}Fe germanium spectra coincident to digital windows in the Na(I) spectrum.

assignment $I^{\pi} = 2^{+}$ for the state at 3519 keV has been established. Another result of a preliminary analysis in that in the unresolved 2097 keV/ 2084 keV - 1173 keV cascade at least a spin 0 for the level doublet 3257/70 keV can be excluded. Thus, from all 24 excited states established in this (n,γ) investigation, only six states could not be assigned spins.

If one compares the discussed (n,γ) level scheme with those found in inelastic scattering [2, 28 - 30] and stripping reactions [27, 29], as done in Fig. 5, an excellent agreement is revealed up to an excitation energy of about 4 MeV. There are significant, large level spacings from 1.2 to 2.0 MeV, from 2.3 to 2.9 MeV, and from 3.5 to 3.8 MeV (except a probably collective 3^{-} level at 3.7 MeV not observed in the (n,γ) reaction). For higher energies the comparison gets more difficult due to the increasing level density. In this region, of course, the (n,γ) scheme is not complete. Two levels (up to 3.5 MeV) are missing in our scheme compared with those of the (p,p') and (d,p) reactions, i.e. at 3175 keV [+)] and 3467 keV[+)]. Probably one has to assign spins heigher than 3 to these states. Due to the l = 3 value measured by Fulmer and McCarthy [27] for the level at 3175 keV, the spin assignment of 4^{+}, 5^{+} seems to be consistent. According to the deexcitation of this level to the first 2^{+} state, as observed in the decay of ^{62}Co [10], the spin 5^{+} can be excluded. - For the sake of completeness it may be noted, that two additional levels at 3275 keV and 4051 keV have been proposed by

+) Here the energy values of the MIT measurements [28] are cited, as they mostly agree best with our values.

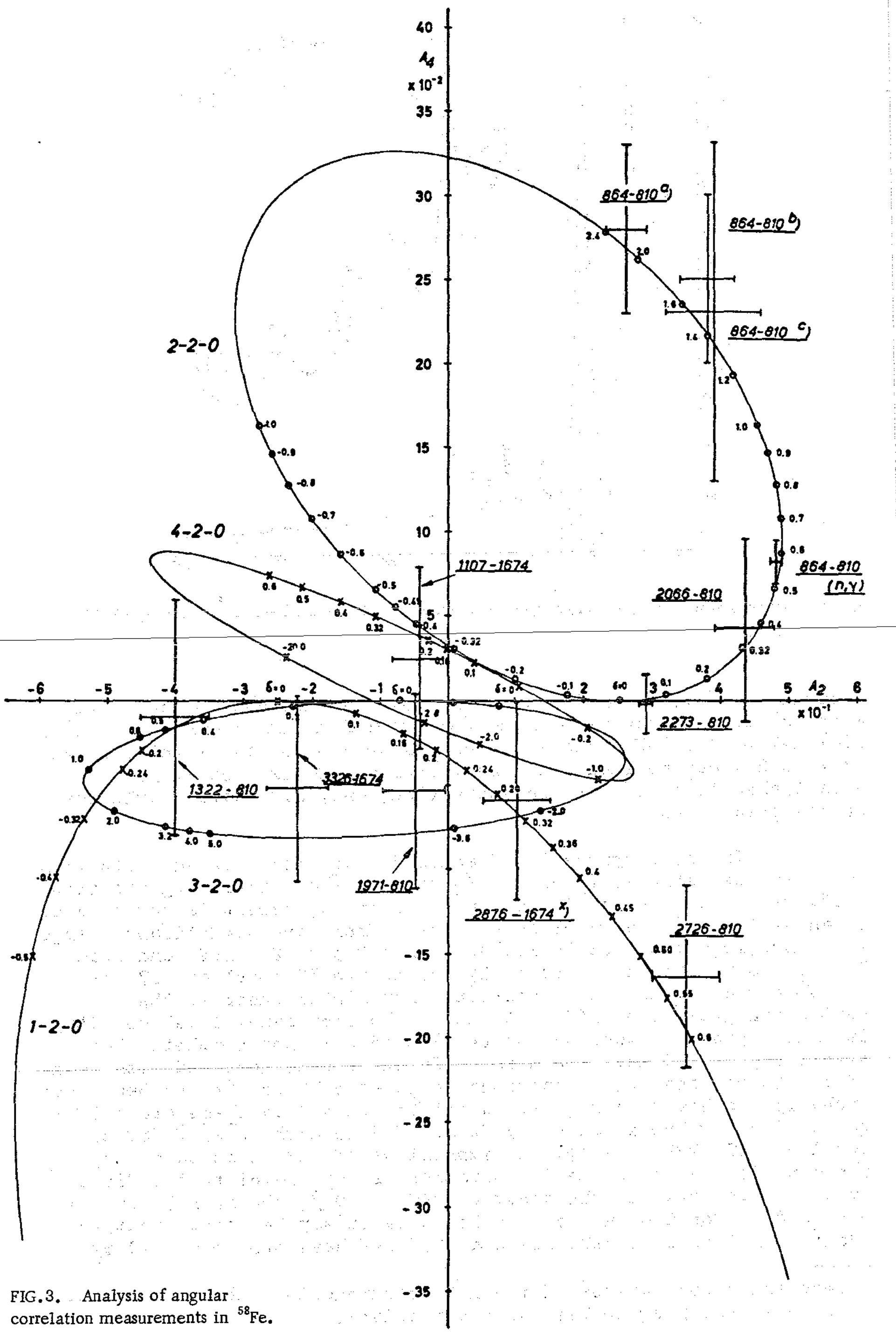


FIG. 3. Analysis of angular correlation measurements in ^{58}Fe.

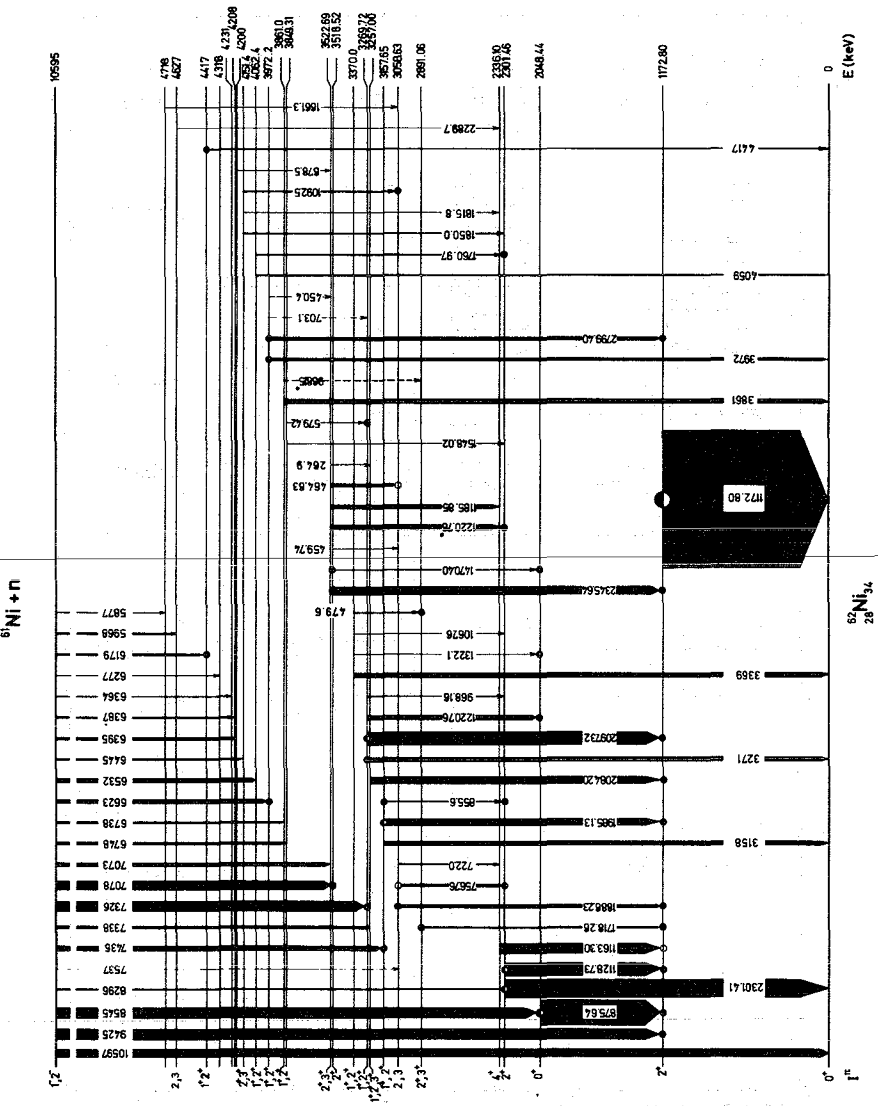


FIG.4. Level scheme of ^{62}Ni.

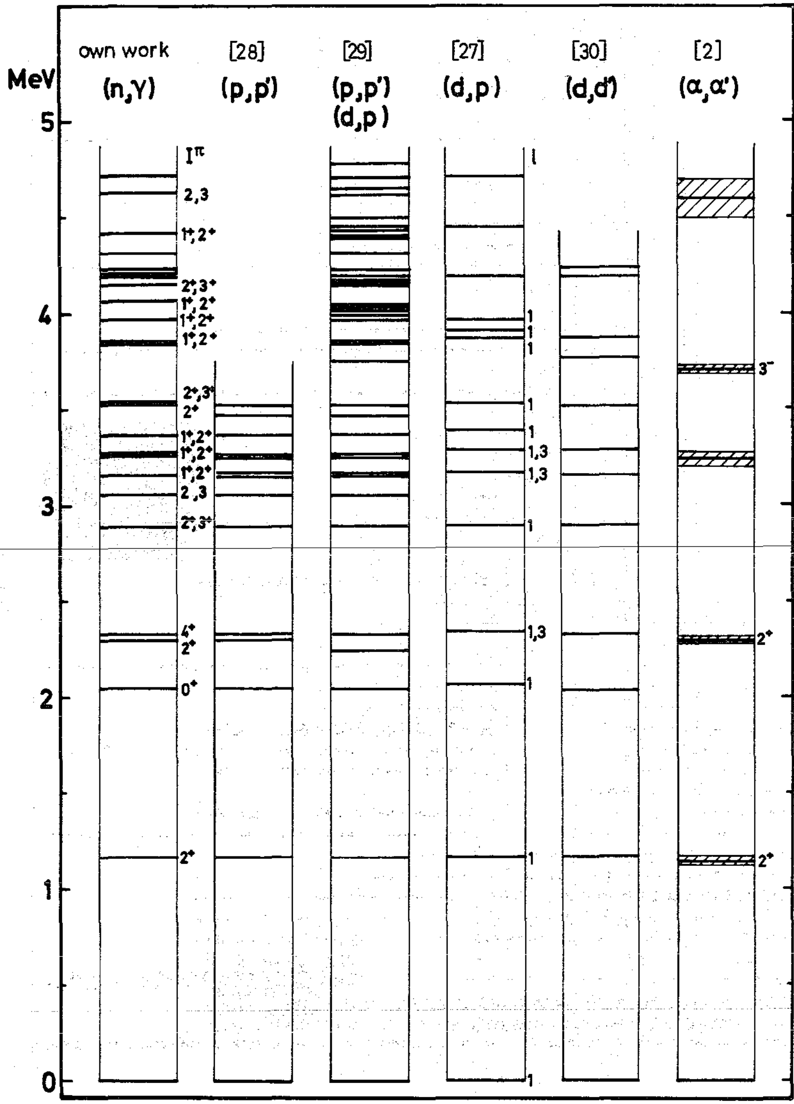


FIG. 5. Comparison of ^{62}Ni levels found by different reactions.

Mo et al. [10]. Because of the energy precision and of the spin assignment 4, the first of these cannot be identified with our 1^+, 2^+ state at 3270 keV. For the level at 4051 keV, too, no analogue can be seen in the (n,γ) scheme.

4. Comparison of Experimental Schemes with Theory

Out of those available data an "experimental" ^{62}Ni level scheme has been constructed for comparison with calculated states in Fig. 6. A similar procedure was done with the ^{58}Fe scheme in Fig. 7, also including experiments other than the (n,γ) investigation. In Fig. 6 there are shown four theoretical level schemes resulting from shell-model calculations taking into account effective interactions. The common basic assumptions are the following: In all Ni isotopes a ^{56}Ni core is treated as being inert, i.e. excitations of neutrons or protons from the completely filled 1 f 7/2 shell ("core excitations") are neglected. The low-lying states are due to the motion of neutrons around a doubly closed-shell core. These active neutrons are restricted to the shells 2 p 3/2, 1 f 5/2, 2 p 1/2.

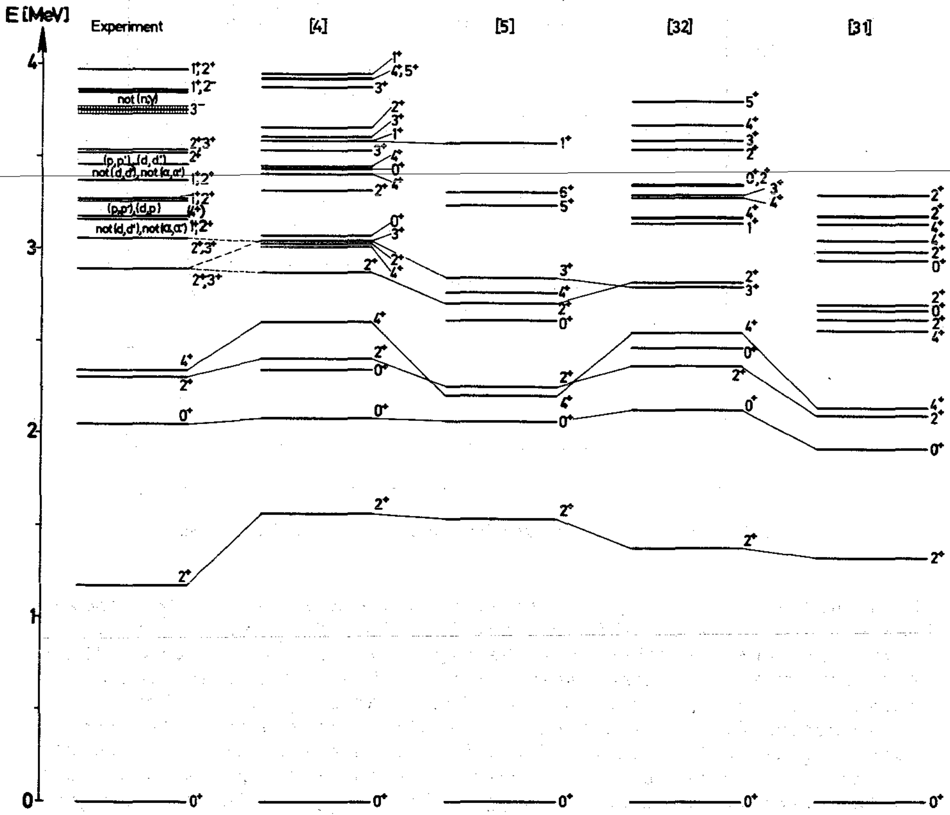


FIG.6. Experimental and calculated energy levels in ^{62}Ni.

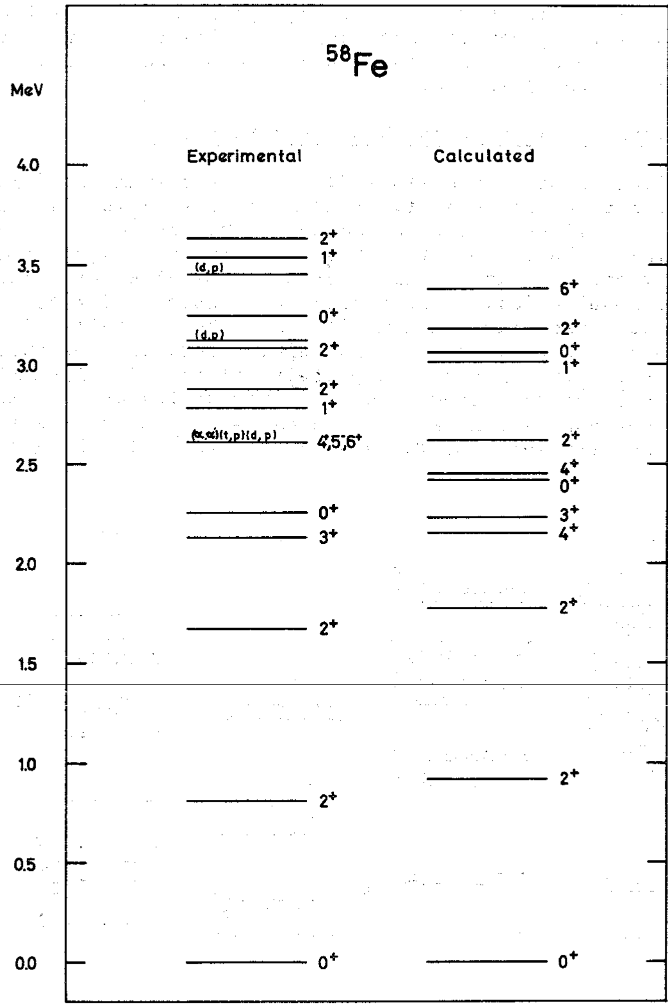


FIG.7. Comparison of the experimental and theoretical ^{58}Fe level scheme.

Contributions of the 1 g 9/2 shell (estimated at least 3 MeV above the 2 p 3/2 level in ^{57}Ni) are not included. The single particle level spacings are taken from the experimental ^{57}Ni spectrum. Within the configurations chosen there exist 30 two-body matrix elements between the antisymmetric two-particle states. As the number of experimental data is too small for a direct parametrization, the number of parameters is cut down. The calculations differ - roughly spoken - in the procedure of restricting and fitting the parameters to the experimental data. Looking at Fig. 6 again, in the right hand level scheme surface delta interaction [31] was applied with an attractive strength constant fitted to the odd-even mass difference. The agreement of the low-lying levels with experiment is surprisingly good. In the scheme of Hsu et al. [32] the nucleon-nucleon potential used was an s-state interaction with four radial matrix elements, as suggested by a least-squares fit to 27 experimental Ni-energy values. In one of the most refined calculations Cohen et al. [5] parametrized a two-body potential with central, tensor and two-body spin-orbit parts together with the four (already mentioned) radial matrix elements. This procedure yields 12 free parameters to be fitted to 24 experimental level energies in Ni. Finally Auerbach [4] fitted 17 of a total of 30 matrix elements to the body of available energy data, using the Kallio-Kolltveit potential for calculating the rest of them.

On the whole the agreement between calculations and experiment is quite satisfactory up to about 3.2 MeV. Generally the first 2^+ state is reproduced too high. There is a trend in these calculations to predict more 0^+ states than will probably ever be observed. Particularly 0^+ states should be fed strongly in the (n,γ) reaction, but there is no indication that such an experimental state exists between 2.1 and 3.8 MeV. The calculations would prefer the level at 3059 keV to be a 3^+ state, thus leaving the spin 2 for the level at 2891 keV. The experimental 3^- state, of course, cannot be reproduced within the configurations chosen. Taking another nucleus, ^{58}Fe, for a comparison between shell-model calculations and experimental states, the agreement seems to be even better (see Fig. 7). For each experimental level there exists a theoretical counterpart within about 250 keV (except one 4^+ level). The assumptions of these calculations performed by McGrory [7] had been (i) an inert ^{48}Ca core, (ii) the last six protons being restricted to the 1 f 7/2 shell and (iii) only (2 p 3/2, 1 f 5/2, 2 p $1/2)^n$ configurations for the four active neutrons. The Hamiltonian included p-p, n-n, and n-p interactions, the parameters of which were fitted to spectroscopic data in ^{54}Fe, in the Ni isotopes (as done by Cohen et al.) and in the N = 29 isotones from ^{49}Ca to ^{57}Ni (as done by Vervier [33]), respectively.

In the case of ^{58}Fe a comparison between experimental and theoretical transition rates is impossible because of a lack of such calculations. But for ^{62}Ni there were given some theoretical B(E2) ratios by Auerbach and by Cohen et al., presented in Table II. This table is a compilation of B(E2) ratios as predicted by the simple vibrational model (Col. 1)(with the phonon selection rule $|\Delta\nu| = 1$), as deduced from our experimental data in ^{58}Fe (Col. 2) and in ^{62}Ni (Col. 3), and as calculated in the shell model with effective interactions (Col. 4). The first experimental value has to be considered as an upper limit, as the $2_2^+ \rightarrow 2_1^+$ transition was assumed to be pure E2 radiation which is most probably not true. The same assumption holds for the other experimental values; there the deduced ratios express limits only if one of the transitions is below the detection threshold. One interesting feature should be pointed out that can be seen in the first line: The experimental fact of a strong inhibition of the crossover transition $2_2^+ \rightarrow 0_1^+$ in ^{62}Ni - as postulated by vibrational models - is also reproduced by shell-model calculations. This inhibition had been thought to be a good argument for the vibrational character of ^{62}Ni. As the position of the first 3^+ state in ^{62}Ni has not yet been definitely established, the experimental B(E2) value was calculated for both possible candidates, the levels at 2891 keV (c) and 3059 keV (d). The first one seems to agree better with the shell-model value. The corresponding ratio for ^{58}Fe is much

Table II

Comparison of reduced transition rates

Ratio	Vibrational model	^{58}Fe experiment	^{62}Ni experiment	^{62}Ni shell model
$\frac{B(E2;2_2^+\to 2_1^+)}{B(E2;2_2^+\to 0_1^+)}$	∞	10.5	≤ 23	1310 a) 33 b)
$\frac{B(E2;3_1^+\to 2_2^+)}{B(E2;3_1^+\to 2_1^+)}$	∞	≤ 350	≤ 10 c) 100 d)	1 b)
$\frac{B(E2;2_2^+\to 2_1^+)}{B(E2;2_2^+\to 0_2^+)}$	(∞)	-	≥ 0.1	29 a)

a) Ref. [4] b) Ref. [5] c), d) see text

higher (in the limit). - One cannot say that these few examples strongly support the shell-model calculations, but there are no serious discrepancies either. It is remarkable that the two shell-model values given for the cascade-crossover ratio of the second 2^+ state differ by a factor of 40. One would like to know how much the theoretical values for other transitions differ from each other. Finally, our decay scheme offers many more experimental γ-branching ratios waiting for a comparison with theory.

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