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STUDY OF THERMAL NEUTRON CAPTURE IN ^{58}Ni *

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ABSTRACT

The energies and intensities of the primary gamma-rays from $^{58}Ni(n,\gamma)^{59}Ni$ reaction have been measured with a Ge(Li) pair-spectrometer in the region of 3.7 to 9.3 MeV. The thermal neutron capture cross section of ^{58}Ni was determined to be 4.52 ± 0.10b by summing the primary transition intensities. The neutron separation energy was found to be 8999.93 ± 0.34 keV. It is shown that the decay of the capture state is non-statistical and that there is a strong correlation between the strengths of excitation of levels by the (n,γ) and (d,p) reactions. These results are discussed in terms of a direct neutron capture reaction mechanism.

ESTUDO DA CAPTURA DE NÊUTRONS TÉRMICOS NO ^{58}Ni

RESUMO

As energias e intensidades dos raios gama primários emitidos na reação $^{58}Ni(n,\gamma)^{59}Ni$ foram medidos na região de energia de 3,7 a 9,3 MeV utilizando-se um espectrômetro de pares. A secção de choque de captura de nêutrons térmicos do ^{58}Ni foi determinada somando-se as intensidades das transições primárias e o valor encontrado é de 4,52 ± 0,10 b. A energia de separação do nêutron foi calculada em 8999,93 ± 0,34 keV. Foi mostrado que o decaimento do estado de captura é não estatístico e que existe uma forte correlação entre os "strengths" de excitação dos níveis de energia pelas reações (n,γ) e (d,p). Esses resultados são então, discutidos em termos de um mecanismo de reação de captura direta do nêutron.

INTRODUCTION

The low energy neutron radiative capture reaction - or simply (n,γ) reaction - has been a very rich source of data on nuclear spectroscopy investigations for almost fifty years, not only at high excitation energies, but also for weakly excited nuclear systems. However, considerable uncertainty still exist in our actual understanding of the detailed mechanism of the reaction itself.

(*) Trabalho apresentado na International Conference on Nuclear Data for Science and Technology, realizada em Mito, Japão, de 30 de maio a 03 de junho de 1988.

In 1936, N. Bohr[1] formulated the statistical theory of the compound nucleus according to which the slow neutron capture followed by the emission of dipole radiation is dominated by compound nucleus formation and the decay mode of the compound state is independent of its method of formation. This theory has been applied to the most heavy nuclides not in the proximity of a closed shell.

However, it has been shown that, for a large number of light nuclei and nuclei near closed shell, there are other contributions to the total cross sections. These contributions manifest themselves in non-statistical effects. A good explanation of the off-resonance capture cross sections of primary E1 transitions to final states with a certain degree of single-particle character is given by a direct capture mechanism dominated by single particle transitions from the entrance channel.

Various simple neutron capture reaction mechanisms have been proposed to explain these non-statistical effects. Some of these simple processes, shown in fig. 1, may be described theoretically in the following models:

a) Direct or hard sphere capture model[2,3] in which the incident s-wave neutron is scattered directly by the nuclear surface into a low-lying p-state. In this process enhanced eletric dipole transition is emitted. (see fig. 1a).

b) Channel capture model[2,3] or valence neutron model[4,5] in which one can visualize the motion of a valence neutron orbiting an inert core with the emission of dipole radiation, when the s or p-wave neutron is scattered by the resonant state into a low-lying final single particle orbit. Specifically for p-wave capture, the important transitions are $p \rightarrow s$ and $p \rightarrow d$. (see fig. 1b).

c) Semi-direct process[6] or capture through a doorway state formation[7] in which the incident neutron scatters in the target nucleus creating an intermediate or doorway state, such as $2p - 1h$ state, with the subsequent emission of gamma-rays on the combination of a particle and a hole. (see fig. 1c).

The study of $^{58}Ni(n,\gamma)^{59}Ni$ reaction is of special interest because one expect correlation between (d,p) single-particle spectroscopic strengths and reduced radiative intensities for transitions to $\ell_n = 1$ final states following thermal neutron capture. Previous thermal neutron

capture data had been related (references [8] and [9] are the most recent) and are available in recent compilations of the Nuclear Data Sheets[10]. The present study was performed in an attempt to improve on the available thermal neutron capture cross section data and the accuracy of intensity and transition energy of primary gamma-rays.

In the present experiment we have measured the gamma-ray spectrum of thermal neutron capture on ^{58}Ni in the energy range of 3.7 to 9.3 MeV. We have determined the energies and transition intensities for nineteen primary gamma-rays. The partial cross section for these primary transitions have been calculated, and by summing all of them, we have determined the total thermal neutron capture cross section for the $^{58}Ni(n,\gamma)^{59}Ni$ reaction. We have also calculated the theoretical value of the partial cross sections for eleven primary E1 transitions based on the direct capture model and compared with the experimental results. The neutron binding energy of ^{59}Ni has also been determined.

EXPERIMENTAL PROCEDURE

The experiment was carried out at the tangential irradiation facility of the IEA-R1 reactor of the IPEN. The basic features of the internal target facility are described in more details elsewhere[11].

The target was a well-mixed sample of 4.2 g natural nickel and 11 g melamine ($C_3H_6N_6$) contained within a reactor grade graphite capsule. The sample was positioned close to the reactor core where the neutron flux is typically about 5.2×10^{11} n.cm^{-2}sec^{-1} at the target position. The target was counted for a period of 170 hours.

The gamma-rays emitted following thermal neutron capture in the experimental target were detected by a Ge(Li) NaI(Tl) pair spectrometer consisting of a 42.5 cc true coaxial Ge(Li) detector which fits into a cylindrical opening in the common housing of two optically separated 5" x 6" NaI(Tl) crystals facing the central Ge-crystal from opposite sides. The triple coincidence events were registered by a 8192 - channel analyser system. The ADC is stabilized against zero and gain drifts using precision pulse generaters and a spectrum stabilizer.

Calibration of efficiency of the detecting system

The efficiency of the detecting system to a certain energy value

is defined as the ratio between the number of gamma-rays which are registered by the detecting system and the total number of gamma-rays which reach the detector. The determination of the efficiency curve as a function of the gamma-ray energies was made experimentally, by measuring a set of gamma-rays with very well known energy and intensity values. For this purpose we used gamma-rays from $^{14}N(n,\gamma)^{15}N$ and $^{35}Cl(n,\gamma)^{36}Cl$ reactions in the region of 1.8 to 11 MeV. In order to make this calibration we have measured a mixed sample of melamine ($C_3H_6N_6$) and sodium chloride (NaCl).

An analytical form which was found to represent the observations is

$$\ln \text{ (peak area/intensity)} = \sum_{n=o}^{3} An \left[\ln(E\gamma)\right]^n \qquad (1)$$

where $E\gamma$ is the full gamma-ray energy (as the pair-spectrometer only detects the pair-production events, $E\gamma = Ed + 2moc^2$, with Ed = double-escape gamma-ray energy). A detailed description of the experimental procedure to determine the efficiency of the detecting system can be encountered in references {12} and {13}.

The energies and intensities values for differents gamma-rays were taken from reference {14} for ^{15}N and reference {15} for ^{36}Cl.

Figure 2 shows the natural logarithmic plot of the relative efficiencies for the double-escape peaks. The curve was obtained by fitting the experimental data points with a least-squares method given by the SAS code{16}.

Energy calibration

For a precision determination of gamma-ray transition energies we used the very well known energies of the $^{14}N(n,\gamma)\ ^{15}N$ reaction{14}. The channel-number to energy transformation function is based on a model of the form

$$E = \sum_{n=o}^{2} a_n\ k^n \qquad (2)$$

where k denotes the channel-number of the peak centroid.

However, in attempting to obtain accurate unknown gamma-ray energy

values, it is necessary to make corrections for the detecting system non-linearity. This non-linearity arises mainly in the analog - to - digital converter, and we have applied the general procedure in determining corrections for the double-escape mode operation of the system. We have used a spectrum of precisaly known gamma-rays appropriate to the range of energies of interest. Two well spaced energies - one near the beginning and the other near the end of the spectrum - was then taken to stablish a linear energy-channel number relantionship. The remainder of the gamma-ray energies were used to generate a correction curve of derivations from perfect linearity.

We found convenient to use the prompt gamma-ray spectrum from neutron capture in a mixed sample of melamine ($C_3H_6N_6$) and sodium chloride (NaCl). Energies of capture gama-rays from all three constituents of melamine and from chlorine are well known and extend from under 2 MeV to nearly 11 MeV.

Cross sections and intensities calculations

When ^{14}N and ^{58}Ni from the sample were irradiated with thermal neutrons simultaneously, the capture gamma-ray spectra for both nuclei were recorded. Using the thermal neutron cross section value of 77.2 mb from reference {17} as the cross section standard, the partial cross section of a primary gamma-ray with energy E_γ produced by neutron capture in nickel target can be simply calculated by the following equations.

$$\sigma_1 I_{i1} = \frac{N_2 \varepsilon_2(E_{\gamma j}) A_1}{N_1 \varepsilon_1(E_{\gamma i}) A_2} \cdot \sigma_2 I_{j2} \qquad (3)$$

where N is the total number of nuclei of the element, $\varepsilon(E_{\gamma i})$ is the relative efficiency of the detecting system for the $E_{\gamma i}$ energy and A is the area under the double-escape energy peak of the measured gamma-rays obtained by a gaussian fitting in the computer code; σ and I_i are the thermal neutron capture cross section and the transition intensity respectively. The subscripts 1 and 2 refer to nickel and nitrogen respectively.

The resultant spectrum was analysed by the GAUSSV computer code {18} which gives the area under the peaks and the - energies of the unknown primary gamma-rays of nickel after correction for non-linearity.

We used the 5297, 5592, 7298 and 8310 keV gamma-ray transitions from $^{14}N(n,\gamma)$ reaction as standards in order to evaluate the partial cross sections of the primary gamma-rays of the $^{58}Ni(n,\gamma)$ reaction. The total cross section was calculated by summing all the partial cross sections

$$\sigma = \sum_i \sigma I_i \qquad (4)$$

RESULTS

The energies and intensities of the ^{59}Ni primary gamma-ray transitions determined in the present work are listed in table I, and compared with the previously known values[8,10]. Following Ishaq[8], we have assumed that the 5459 and 5621 keV transitions are primary gamma-rays.

The total thermal neutron capture cross section determined here is 4.52 ± 0.10 barns which is in very good agreement with the 4.6 ± 0.3 barns value of the reference[19] and with a value of 4.5 barns reported by Ishaq[8].

The main sources of errors in the partial cross section measurements and, consequentely, in the primary gamma-ray intensities of the $^{58}Ni(n,\gamma)$ reaction are due to the uncertainties of the peak area, of the relative efficiencies of the detecting system and of the nitrogen gamma-ray intensities used as standard.

DISCUSSION

As has been said before the non-statistical effects are present in some nuclei, specially those with mass number A ~ 40 and A ~ 140. These effects can be described theoretically in various models.

Experimentally these effects may be seen by studying the behavior of the correlation coefficient ρ between $I_n = I\,(d,p)$ - spectroscopic strengths and EI primary (n,γ) intensities reduced by a factor E^n, where E is the primary gamma-ray energy.

We define the linear correlation coefficient of two variables as

$$\rho = \frac{\sum_{i}^{1}(G_{n\gamma} - \bar{G}_{n\gamma})\ \sum_{i}^{1}(G_{dp} - \bar{G}_{dp})}{\left[\sum_{1}^{1}(G_{n\gamma} - \bar{G}_{n\gamma})^2 \sum_{i}^{1}(G_{dp} - \bar{G}_{dp})^2\right]^{1/2}} \qquad (5)$$

where $G_{n\gamma}$ and G_{dp} are the strengths of transitions in (n,γ) and (d,p) reaction and are difined as

$$G_{n\gamma} = \frac{I_\gamma}{E_\gamma^n}$$

$$G_{dp} = (2J + 1)\, S_{dp}$$

where I_γ and E_γ are the intensity and energy of the primary capture gamma-ray, J is the spin of the final state and Sdp is the spectroscopic factor for the (d,p) reaction to that state. The sum in (5) is taken over all of the $l_n = 1$ states in question, and $\bar{G}_{n\gamma}$ and $\bar{G}_{dp}$ are the strengths for the two reactions averaged over all the final states.

For the largest value of the correlation coefficient ρ we have: for $n - 1$ indicating direct capture, for $n - 2 - 3$ indicating valence capture and for $n > 3$ indicating the formation of doorway states.

Figure 3 shows the correlation coefficient ρ as a function of the power of the ^{59}Ni gamma-ray energy. As can be seen, a value of $\rho = 0.987$ is obtained at maximum for $n = 0$ and this value remains quite constant in the range $0 < n < 3$, and for $n > 3$, the value of ρ decreases quickly. Thus it is not clear which of the process (direct capture or valence capture) is causing the observed non-statistical effect, however from the behavior of the curve we can discard the process of the formation of doorway states.

Mughabghab[20] has used the valence neutron model to predict the intensities of some transitions leading to the low-lying $P_{1/2}$ and $P_{3/2}$ states in ^{59}Ni, following s- wave thermal neutron capture in ^{58}Ni. This model has a simple procedure, which uses no adjustable parameters, and correctly predicts the intensities of the first three $l_n = 1$ transitions in ^{59}Ni.

Here, we compare the measured partial cross sections of the primary transitions with the theoretical predictions calculated by the direct capture model.

Based on the direct reaction theory of neutron capture,

Mughabghab[21] has given the full expression for the potential capture of an s - wave neutron with energy E_n by a target nucleus of spin I to a final state of the single particle p orbital with spin J_f :

$$\sigma_{POT} = \frac{0.062}{R\ E_n}\left(\frac{Z}{A}\right)^2 \mu \frac{(2Jf+1)Sdp}{6(2I+1)}\, Y^2 \left(\frac{Y+3}{Y+1}\right)^2 \left[1 + \frac{R\text{-}acoh}{R}\, Y\, \left(\frac{Y+2}{Y+3}\right)\right]^2 \qquad (6)$$

$$= \sigma_{HS}\left[1 + \frac{R\text{-}acoh}{R}\, Y\, \left(\frac{Y+2}{Y+3}\right)\right]^2$$

where σ_{HS} denotes the hard sphere capture, Sdp is the spectroscopic factor of the (d,p) reaction where the neutrons carryng angular momentum ln = 1; acoh is the coherent scattering lenght; Y = KR, where K is neutron wave number and μ is the weighting factor, related to the entrance neutron channel:

$I = 0$, $\mu = 1$

$I \neq 0$, $\mu = 1$ for $J_f = I \pm 3/2$ and

$\mu = 2$ for $J_f = I + 1/2$

R is the nuclear radius in fm, here taken as $R = 1.45\ A^{1/3}$, A e Z are the number of nucleons and number of protons.

The second term within the brackets represents the resonance channel contribution which takes into account the interference between hard sphere and channel capture. One can note that for R = acoh, potential capture is equivalent to hard sphere capture; for R > acoh and R < acoh, there is respectively constructive or destructive interference between hard sphere and channel resonance capture.

The calculated values for the partial direct capture cross sections are given in the table II. As can be seen the calculation yields result of the correct order of magnitude, although the experimental results are not so well reproduced as in other cases[21].

THE NEUTRON SEPARATION ENERGY

In the courses of this experiment we also determined a value of the neutron separation energy of the ^{59}Ni. From the earlier measured values of the 465, 878, 1301 and 3181 keV levels[8] toghether with the

energies of the measured primary gamma-rays to these levels, we have obtained an average value for the separation energy as 8999.61 ± 0.33keV. In the table III we show the energy sums of two-step transitions and their average value. The energy values of the primary transitions have been corrected for recoil. The value of the neutron separation energy for ^{59}Ni is in complete agreement with the energy of the gamma-ray of the direct transition between the capture state and the ground state. Therefore, we have adopted the neutron separation energy for ^{59}Ni as 8999.93 ± 0.34 keV this value agrees well with the known values of 8999.91 ± 0.20 keV[8] and 9000.1 ± 0.4[10].

REFERENCES

01. ANDERSON, P.; EKSTRÖM, L.P.; LYTTKENS, L. Nuclear data sheets for A = 59. Nucl. Data Sheets, 39(4):641, 1983.

02. AJZENBER - SELOVE, F. Energy levels of leght nuclei A = 13 - 15. Nucl. Phys., A, 449:1, 1986.

03. BARR, A.J.; GOODNIGHT, S.H.; SALL, J.P. Computer program SAS. In: RAY, A.A., ed. SAS user's guide: statistics, 1982 edition. Cary, North Caroline, SAS Institute, 1982.

04. BOHR, N. Neutron capture and nuclear constitution. Nature, 137: 344, 1936.

05. BROWN, G.E. Direct and semi-direct (p,γ) and (n,γ) reactions. Nucl. Phys., 57:339, 1964.

06. CARBONARI, A.W. Determinação do conteúdo de proteínas em grãos pela análise de raios gama prontos de captura radioativa. São Paulo, 1983. (Dissertação de mestrado, Instituto de Pesquisas Energéticas e Nucleares).

07. COSMAN, E.R.; PARIS, C.H.; SPERDUTO, A.; ENGE, H.A. Nuclear - reaction studies in the nickel isotopes: the Ni^{58} (p', p') Ni^{58} and Ni^{58} (d,p)^{59} Ni reactions. Phys. Rev., 142:673, 1966.

08. ESTRADA, E.L. & FESHBACK, H. Resonance and direct gamma ray interactions. Ann. Phys., 23:123, 1963.

09. FULMER, R.H.; MCCARTHY, A.L.; COHEN, B.L.; MIDDLETON, R. Deuteron stripping studies in the light isotopes of nickel. Phys. Rev., B, 955:133, 1964.

10. HELMER, R.G. & PUTNAM, M.H. Gauss V: a computer program for the analysis gamma-rays spectra from Ge(Li) spectrometer. 1972. Idaho, Falls, Aerojet Nuclear Co., 1972. (ANCR-1043).

11. HOFMEYR, C. The ^{58}Ni $(n,\gamma)^{59}Ni$ reaction. In: Neutron capture gamma rays spectroscopy and related topics: proceedings of the 2nd International conference... held in Petten, the Netherlands. 1974. p. 537.

12. ISHAQ, A.F.M.; ROBERTSON, A.; PRESTWICH, W.V.; KENNETT, T.J. Thermal neutron capture in isotopes of nickel. Z. Phys., A, 281:365, 1977.

13. ISLAM, M.A.; PRESTWITCH, W.V.; KENNETT, T.J. Determination of the thermal radiative capture cross section of ^{14}N. Nucl. Instrum. Methods, 188:243, 1981.

14. KRUSCHE, B.; LIEB, K.P.; DANIEL, H.; VON EGIDY, T.; BARREAU, G.; BÖRNER, H.G.; BRISSOT, R.; HOFMEYR, C. Gamma rays energies and ^{36}Cl level scheme from the reaction $^{35}Cl(n,\gamma)$. Nucl. Phys., A, 386:245, 1982.

15. LANE, A.M. & LYNN, J.E. Anomalous radioactive capture in the neutron resonance region: analysis of the experimental data on electric dipole transitions. Nucl. Phys., 17:586, 1960.

16. LANE, A.M. & LYNN, J.E. Theory of radioactive capture in the resonance region. Nucl. Phys., 17:563, 1960.

17. LANE, A.M. & MUGHABGHAB, S.F. Relation between the optical model and the valence model of F-1 neutron capture at and between resonances. Phys. Rev., C, 10:412, 1974.

18. LYNN, J.E. The theory of neutron resonance reactions. Oxford, Clarendon Press, 1968. p.326.

19. MUGHABGHAB, S.F. Breakdown of the extreme statistical model in neutron capture. Phys. Lett., B, 35:469, 1971.

20. MUGHABGHAB, S.F. Verifications of the Lane - Lynn theory of direct neutron capture. Phys. Lett., B, 81:93, 1979.

21. MUGHABGHAB, S.F.; DIVADEENAM, M.; HOLDEN, N.E. Neutron cross sections. New York, Academic Press, 1981. v.1. Pt.A.

22. PECEQUILO, B.R.S. Nova técnica para a determinação de impurezas em compostos de urânio e de tório pela análise dos raios gama pron tos de captura. São Paulo, Instituto de Energia Atômica, 1978. (IEA - DT - 078).

23. PECEQUILO, B.R.S.; VENTURINI, L. and CARBONARI, A.W. Calibração em eficiência de um espectrômetro de pares para fotons na região de 1.9 a 11 MeV. Aplicação na determinação das intensidades dos isó topos no níquel. In: Física nuclear no Brasil: 6º reunião de tra balhos... realizada em Itatiaia, 1983.

TABLE I - The observed primary transitions and intensities in ^{59}Ni

Transition Energy (keV)		Intensity Photons/100 CAPTURES	
Present	Ref. {8}	Present	Ref. {8}
3931.21 ± 0.61	3930.46 ± 0.66	0.42 ± 0.01	0.40 ± 0.05
4031.35 ± 0.56	4030.79 ± 0.55	0.53 ± 0.01	0.46 ± 0.06
4284.49 ± 0.46	4284.21 ± 0.69	0.46 ± 0.01	0.39 ± 0.05
4858.85 ± 0.28	4859.18 ± 0.28	1.53 ± 0.04	1.53 ± 0.11
4977.18 ± 0.28	4977.48 ± 0.72	0.30 ± 0.01	0.26 ± 0.04
5270.06 ± 0.23	5269.58 ± 0.74	0.43 ± 0.04	0.29 ± 0.04
5312.59 ± 0.23	5313.18 ± 0.20	1.83 ± 0.04	1.74 ± 0.10
5435.75 ± 0.24	5436.72 ± 0.33	0.73 ± 0.02	0.72 ± 0.05
5459.06 ± 0.48	5459.10 ± 1.50	0.10 ± 0.01	0.09 ± 0.03
5620.74 ± 0.40	5621.00 ± 1.00	0.17 ± 0.02	0.16 ± 0.03
5817.08 ± 0.26	5817.99 ± 0.25	3.54 ± 0.08	3.70 ± 0.24
5972.84 ± 0.28	5974.40 ± 0.47	0.92 ± 0.03	0.87 ± 0.08
6105.13 ± 0.29	6106.03 ± 0.31	2.35 ± 0.05	2.39 ± 0.17
6583.65 ± 0.31	6584.61 ± 0.20	2.63 ± 0.06	2.74 ± 0.16
7263.56 ± 0.35	7265.75 ± 0.71	0.33 ± 0.01	0.31 ± 0.04
7697.43 ± 0.28	7698.40 ± 0.41	1.33 ± 0.03	1.28 ± 0.09
8121.09 ± 0.25	8121.76 ± 0.24	4.56 ± 0.10	4.65 ± 0.25
8534.21 ± 0.26	8534.14 ± 0.26	25.14 ± 0.56	25.6 ± 1.4
8999.18 ± 0.34	8999.91 ± 0.30	52.71 ± 1.16	52.7 ± 3.5

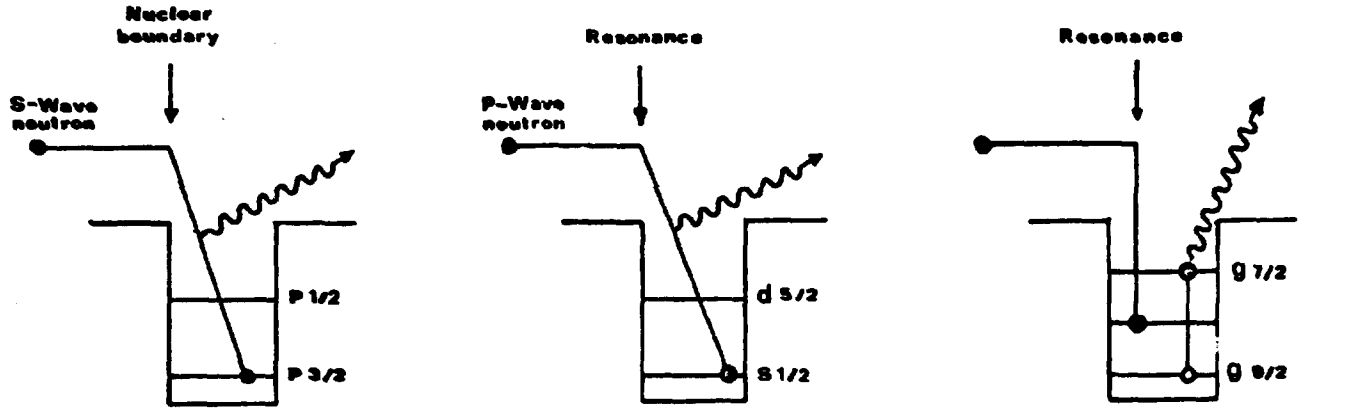
TABLE II - Theoretical and experimental partial cross-sections for some E1 primary transitions in ^{59}Ni

Transition Energy E_γ (keV)	Intensity I_γ per 100n	Level Energy Ex (keV)	J_f^π	$(2J_f+1)Sdp$ [a]	Partial cross sections Theory	Experiment
8999.18	52.71	0	$3/2^-$	2.740	2.714	2.381 ± 0.045
8534.21	25.14	465.06	$1/2^-$	1.260	1.112	1.136 ± 0.022
8121.09	4.56	878.09	$3/2^-$	0.324	0.257	0.206 ± 0.004
7697.43	1.33	1301.52	$1/2^-$	0.519	0.366	0.060 ± 0.001
7263.56	0.33	1734.78	$3/2^-$	0.031 [b]	0.019	0.015 ± 0.001
6583.65	2.63	2414.91	$3/2^-$	0.104	0.052	0.119 ± 0.002
6105.13	2.35	2893.8	$3/2^-$	0.025	0.011	0.106 ± 0.002
5972.84	0.92	3025.7	?	0.070	0.028	0.041 ± 0.001
5817.08	3.54	3181.81	?	0.065	0.025	0.160 ± 0.003
4977.18	0.30	4035	$1/2^-$, $3/2^-$	0.053	0.014	0.014 ± 0.001
4031.35	0.53	4968	$1/2^-$	0.032	0.005	0.024 ± 0.001

a) Reference {22}
b) Reference {23}

TABLE III - Neutron separation energy for ^{59}Ni (in keV) obtained from two-step sucessive transitions.

8534.89 ± 0.26	+	465.06 ± 0.07	=	8999.95 ± 0.27
8121.70 ± 0.25	+	878.09 ± 0.10	=	8999.79 ± 0.27
7697.98 ± 0.28	+	1301.52 ± 0.08	=	8999.50 ± 0.29
5817.39 ± 0.26	+	3181.81 ± 0.24	=	8999.20 ± 0.35
average value			=	8999.61 ± 0.15



a. Direct capture

b. Valence capture

c. Semi-direct capture

Fig.1. Description of simple reaction mechanisms of neutron radiative capture in terms of direct capture, valence neutron model and doorway state formation

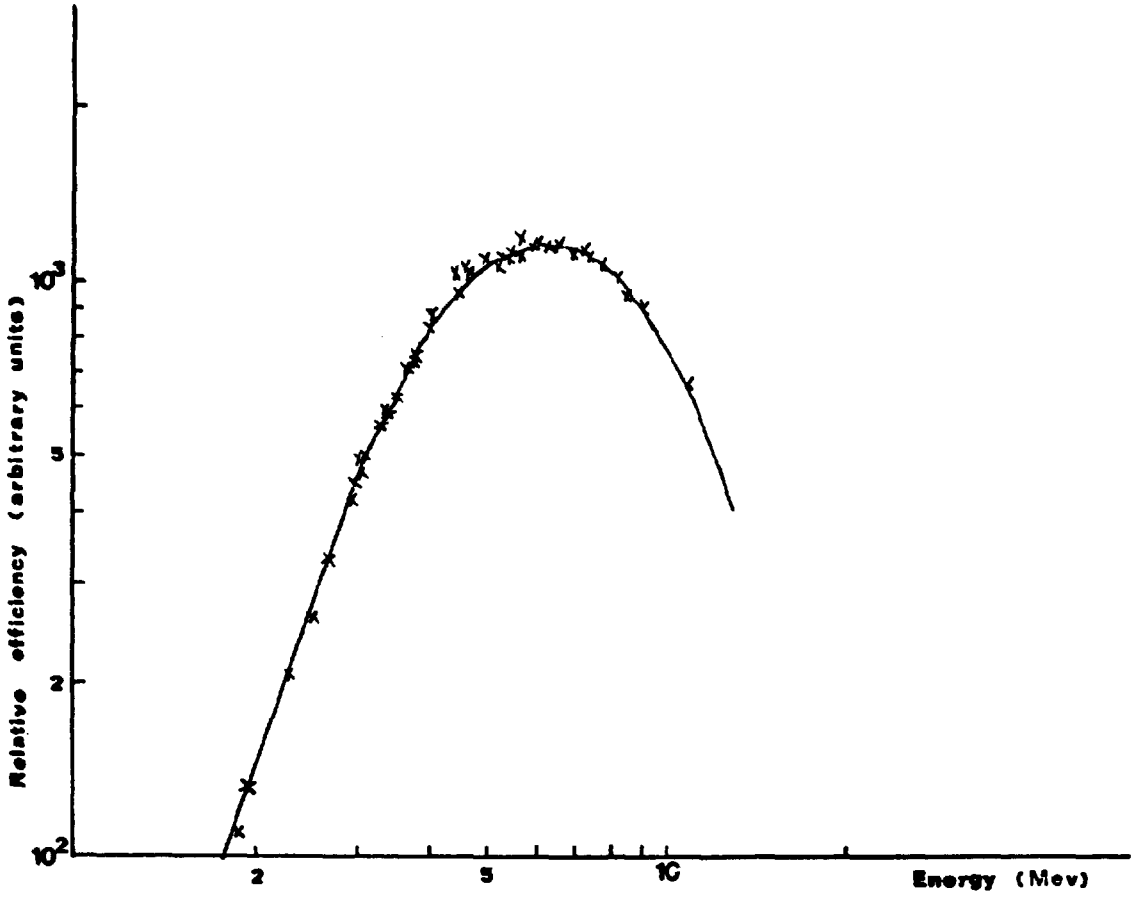


Fig. 2. Relative efficiency curve for detecting system

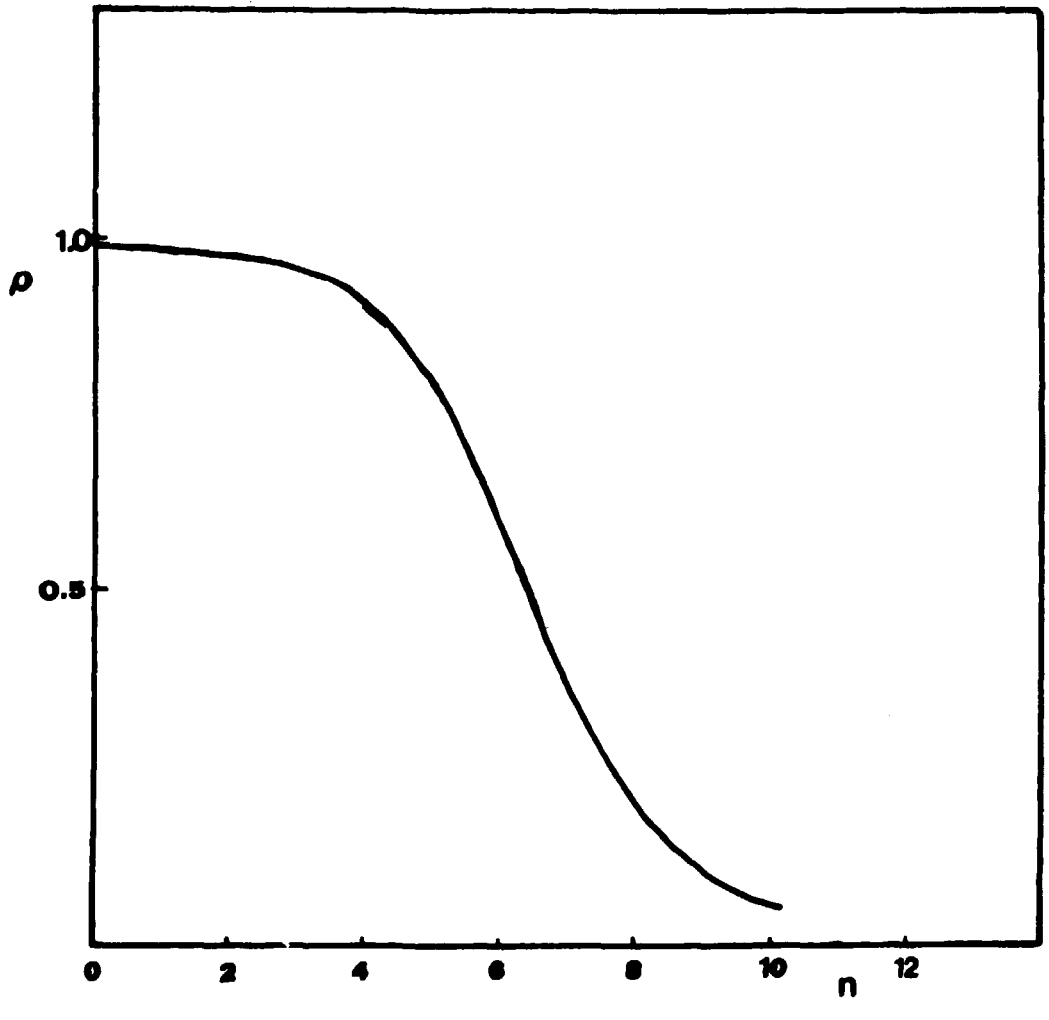


Fig.3. The correlation coefficient ρ as a function of n between $(2J+1)S_{dp}$ and I_γ/E_γ^n for ^{59}Ni