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(n,α) REACTION - A NEW CHANNEL FOR STUDYING THE NATURE OF NEUTRON RESONANCES

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1. Introduction

In thirty years since its begining, neutron spectroscopy has provided a large amount of information on the properties of resonance states of many atomic nuclei. For nonfissionable nuclei such characteristics of resonances as E_0, Γ, Γ_n, Γ_γ, more rarely spin J, were determined. However, the nature of resonance states is, as a rule, very complicated; therefore starting from so scarce qualitative (not quantitative) experimental material one cannot hope to understand the properties of highly excited nuclear states better than the nuclear statistical model can claim to do. In this connection, it seems of great interest to concentrate neutron spectroscopy studies on acquisition of the largest possible number of parameters of individual excited states and investigation of the behaviour of these parameters during transition from resonance to resonance.

From this point of view, the study of the spectra of secondary particles emitted after the resonance neutron capture is by far a perspective trend. The studies of γ -ray spectra using germanium detectors have already drawn our attention to a number of peculiarities which cannot be accounted for in the framework of the rough statistical model.

New information on nuclear resonance states can be obtained by studying the (n , α) reaction. The comparative "simplicity" of the α -particle and the advanced theory of α decay make it possible in a number of cases to hope for a more complete analysis of experimental data than in the case of the (n, γ) reaction. Unfortunately, because of the large Coulomb barrier for α particles in medium and heavy nuclei, the cross sections of this reaction are very small; therefore its study requires powerful neutron sources and it has been started only in recent years.

The investigations of the (n , α) reaction on thermal neutrons were begun 10 years ago /1/ and to the present in a number of laboratories of the world spectra of α particles after the thermal neutron capture were studied on 5 nuclei /1-7/ and the ^{143}Nd (n, γ α) reaction was discovered /8/.

Of course, more extensive and unambiguous data can be obtained from studies of α decay of individual resonance states of atomic nuclei. Such experiments were started in our Laboratory on the IBR reactor. In 1965 the first results on total α widths for ^{147}Sm and ^{149}Sm resonances were obtained /9/ and in 1967 the first measurements of α -particle spectra in individual resonances (^{147}Sm (n, α) /10/) were performed.

The studies of the (n, α) reaction on the two lines mentioned above are now being continued in the Laboratory. Some results of these investigations are discussed in this paper.

II. Installations for Studying the (n , α ...) Reaction on Resonance Neutrons

The creation of modern powerful neutron spectrometers, say such as the IBR reactor, and large α -particle detectors made it possible to begin studies in the new region of neutron spectroscopy, that is the studies of the (n , α) reaction. Such peculiarities of the (n , α) reaction as

a) very small cross sections (for medium and heavy nuclei $\sigma(n,\alpha)/\sigma(n,\gamma) < 10^{-5}$);

b) a very small range of the α particle to be recorded in the target substance;

c) a strong γ -ray background exceeding the α -particle intensity by 6 to 8 orders of magnitude -

called for creation of special detecting equipment.

In a number of years several types of detectors for α - particles registration and measurement of their spectra were tested. In measurements of total α widths (for counting particles in individual resonances) a gaseous scintillation detector with a multilayer target with a working area of 0.7 m^2 was used. The presence of an electric field of 800 v/cm in which there was a scintillator (xenon) was a typical peculiarity of the detector; this permitted the light flash to be increased by 2 orders of magnitude. The detector construction made it possible to measure the effect and the background simultaneously /11/ (see Fig.1). Alpha-particle spectra were measured by grid ionization chambers. A double ionization chamber in which the plane of targets was inclined towards the neutron beam at an angle of 15° proved to be good on the neutron beam from the IBR reactor. This permitted, using a slit neutron collimator, only a small part of the sensitive volume of the chamber (out of the space between the grid and the collector) to be irradiated by the reactor beam and thus the sources of amplitude distortions to be considerably attenuated.[12] (Fig 1).

For neutrons, the time-of-flight spectrometry method was used. The flight path varied from 30 to 100 m and the resolution varied from 600 to 30 nsec/m. For measurements of the (n, α) reaction cross sections, α particles were recorded by 4096-channel time analyzers. For studies of the α-particle spectra in individual resonances, a multi-dimensional magnetic tape analyzer developed in our Laboratory [13] was used which recorded the time of flight (2048 channels), the pulse height (512 channels) and the number of the detector (2-6). Targets consisted of layers of the sample, as a rule, from separated isotopes from 0.2 mg/cm^2 (for measurements of the α-particle spectra) to $5 \div 10$ mg/cm^2 (for registration of α particles) thick on an aluminium backing. The energy resolution of ionization chambers in operating conditions, on the reactor beam, accounted for $\approx$ 200 keV for $E_\alpha \approx 8 \div 10$ MeV.

As an example of our measurements, in Fig. 2 and 3 you can see the dependence of the α-particle yield in the $^{147}Sm(n, \alpha)^{144}Nd$ reaction on the neutron time of flight and the α-particle spectra in individual resonances of this reaction. It is of interest that in the time spectrum in the region of a sufficient resolution all resonances known from measurements of other cross sections [14] showed up. In the α-particle spectra attention is drawn by noticeable fluctuations of individual α transitions from resonance to resonance and no distinct predominance of the intensities of α transitions to the ground state as it is the case in the usual α decay of the ground states of even-even nuclei.

In conclusion of the description of the experimental technique, I would like to note that difficult background conditions often demand considerable improvements in the equipment when beginning measurements with another isotope with a lower cross section. This noticeably affects the progress of investigations.

III. Discussion of the Results

After resonance neutron with zero orbital moment get captured by the nuclei under study, even-even nuclei in excited states with two possible values of spin and parity, which coincides with the parity of the target-nucleus, are formed. For example, in the case of the Sm and Nd isotopes $J^{\pi} = 3^{-}$ or 4^{-}. In the overwhelming majority of cases, excited state decays by emission of γ rays; and only with a relative probability of $< 10^{-5}$ α decay takes place (Fig. 4). According to the rule of summation of angular momenta and the law of conservation of parity, α decay to the ground state $(I^{\pi} = 0+)$ is possible only for resonances with one of the possible spin values, say $J^{\pi} = 3^{-}$. On one hand, this fact makes the analysis of the total α- width distribution more complicated, on the other hand it provides the experimentalist with a new method of spin identification of resonances.

So far we have obtained about fifty values of total α-width of the ^{149}Sm, ^{147}Sm, ^{145}Nd, ^{143}Nd, /9,15/, ^{95}Mo ^{123}Tc /16/ resonances; spectra of α particles of the decay of 13 resonance states of ^{147}Sm and ^{145}Nd have been measured.

1) Partial α widths

Alpha-particle spectra shown in Fig. 3 permit us to observe a two-dimensional picture of α decay by changing initial (i) and final (j) nuclear states. The partial α widths measured experimentally are determined by the probability of the α -particle formation at the surface of the compound nucleus (reduced partial) α widths $\gamma^2_{\alpha ij\ell}$) and by the factor of the nuclear Coulomb and centrifugal barrier penetrability ($P_{j\ell}$):

$$\Gamma_{\alpha ij} = 2 \sum_{\ell} \gamma^2_{\alpha ij\ell} P_{j\ell} = 2\gamma^2_{\alpha ij} \sum_{\ell} P_{j\ell} \quad . \qquad (1)$$

Due to the fact that in experiment the contributions of α particles with different orbital moments ℓ to the $i \to j$ transition cannot be measured separately, we have to use value of $\gamma^2_{\alpha ij}$ averaged over ℓ omitting index ℓ (formula (1)).

When analyzing partial reduced α widths in the ^{147}Sm (n , α) reaction it should be noted that:

a) Resonances with E_0 = 3.4; 29.7; 83.7; 123.4; 184 eV have α transitions to the ground state, consequently, their spins and particles $J^{\pi} = 3^-$.

b) For the 184 eV resonance, the widths of the partial α transition to the ground state is 30 times as large as the value averaged over other resonances with the same value of spin (and exceeds the maximal value by an order of magnitude). This is probably an indication of the fact that resonance wave function contains a substantial persentage of the admixture of the two-quasi-particle component of the particle-particle type, see paper /17/ by V.G. Soloviev.

c) For the other resonances with $J^{\pi} = 3^-$, the average reduced partial α widths for transitions to the ground state are 3 times less than those for transitions to the first excited state of the daughter nucleus; this is apparently a manifestation of the noticeable contribution of one-phonon types of excitation in resonance states /17/.

d) The reduced partial α -widths distribution is described better by the Proter-Thomas distribution with the number of degrees of freedom $\nu = 2$ than $\nu = 1$ (Fig. 5). This can be associated with the fact that in our case $\gamma^2_{\alpha i j}$ is averaged over ℓ . For example, for $3^- \to 2^+$ transitions (see formula (5) with $j = 1$) this gives us $\nu_{ef} = 1.9$.

e) It is of interest to compare reduced neutron and α widths for the nuclei studied; some time ago Bethe proposed to use experimental values of reduced neutron widths for the estimation of α widths /18/. The data given in Table permit apparently a preliminary conclusion that for some nuclei the ratio of the mentioned widths can be in the order of unity to be drawn.

2) Total α widths

By recording the α -particle yield in individual resonances we are able to measure total α widths

$$\Gamma_{\alpha i} = \sum_j \Gamma_{\alpha i j} = 2 < \gamma^2_{\alpha i} > \sum P_{j\ell} . \qquad (2)$$

Since now the value of $< \gamma^2_{\alpha i} >$ is averaged not only over ℓ but also over the final states of α decay (with weight determined by the relative quantity $P_{j\ell}$), the distribution of total $\Gamma_{\alpha i}$ widths can also be approximated by analogy with partial widths to the Porter-Thomas distribution with the average value

$$< \Gamma_\alpha > = 2 < \gamma^2_\alpha > \sum_{j\ell} P_{j\ell} \qquad (3)$$

and dispersion

$$D(\Gamma_a) = \sum_{j\ell} D(\Gamma_{\alpha ij}) = 8 <\gamma_a^2>^2 \sum_{j\ell} P_{j\ell}^2 , \qquad (4)$$

this gives

$$\nu_{ef} = \frac{2<\Gamma_{ai}>^2}{D(\Gamma_{ai})} = \frac{(\sum_{j\ell} P_{j\ell})^2}{\sum_{j\ell} P_{j\ell}^2} . \qquad (5)$$

Fig. 6 presents: a) the experimental distribution of total a widths for resonances of the ^{147}Sm (n, a) reaction and the theoretical one taking account of two possible spin values; b) the probability for the resonance with a given value of Γ_{ai} to have $J^\pi = 3^-$. The widths lying to the left from the dashed line belong with the probability of $\eta > 99\%$ to resonances with $J^\pi = 3^-$ (for more details see /19/).

If we assume that the statistical theory is valid for the description of a decay of resonance states, then we can calculate the average value of the total a width:

$$<\Gamma_a> = \frac{D}{2\pi} \sum_{j\ell} P_{j\ell} , \qquad (6)$$

where D is the average distance between resonances with a given value of spin and parity. When calculating $P_{j\ell}$ in the quasi-classical approximation (for example /20/) we obtain the theoretical values $<\Gamma_a>_{st} \gtrsim <\Gamma_a>_{exp}$ /16/. Somewhat better agreement with experiment is achieved by the penetrability calculations using the optical model /19,21/ (see Fig. 7).

This is a brief account of the first results of the investigation of the (n, a) reaction in the resonance neutron region.

IV. Problems and Perspectives

The studies of α decay of neutron resonances have actually been just begun, but perspectives of the development of the new branch of neutron spectroscopy are beyond any doubt. This would permit neutron spectroscopy and conventional nuclear spectroscopy, which has long been successfully dealing with the study of low-lying states of atomic nuclei, to be still more closely connected, progressive experimental and theoretical approaches to be borrowed, new information on the very process of α decay to be obtained etc.

Certainly, small cross sections of the (n, α) reaction present great difficulties to experimentalists: production of high fluxes of resonance neutrons with a sufficient energy resolution creation of detectors and spectorometers capable of preserving their characteristics in high neutron and γ -ray fields; development of spectrometric electronics which can accept an overload condition etc. However, when one overcomes these difficulties it will be possible to extend considerably the range of nuclei under study and to proceed to the solution of a number of interesting physical problems.

We have already started the searches for the (n, α) reaction in the region of deformed nuclei in order to be able to study α decay of resonance states to the levels of the rotational band. Here even the value of ν_{ef} for total α widths can give information on the admixture of rotational type excitations in nuclear resonance states. If the magnitude of this admixture determines, in general, the probability of transition to the levels of the rotational band, then the values of $\gamma^2_{\alpha ij}$ for different j -states of one band will be correlated and will fluctuate with $\nu_{ef} = 1$. In the absence of such a correlation for some nuclei (for example, osmium), probably $\nu_{ef} \approx 4$.

Attention should be drawn to the fact that in future when measuring α -particle spectra in a wider range of E_α it will probably be possible to assess the shape of the nuclear potential and to notice irregularities weaker than those which are now supposed to explain fission from isomer states.

The questions of the influence of the orbital moment of the emitted α particle on the magnitude of reduced α widths and also pair correlations (so far there have been contradictory opinions on this question) /17,22/ are to be solved.

The study of the α -particle interaction with nuclei using the optical model is gaining in importance not only for nuclear physics but also for astrophysics. Here the (n, α) reaction can yield unique information on the imaginary part of the optical potential especially for medium and heavy nuclei, to verify the presence of giant resonances in the strength function for α particles. Now the available experimental data lie in the region of minimum of the α -particle strength function /21/. The presence of giant resonances shifted along the scale of atomic weights for even and odd values of ℓ will make it possible in a number of cases to judge about the parity of the state of the daugther nucleus resulting from α decay.

Some nuclei after the capture of resonance neutrons have sufficient energy to emit more complicated nuclei than α particle; thus in the $^{147}Sm(n, ^{8}Be)^{140}Ce$ reaction beryllium nuclei can emerge with the energy of $\approx$ 12 MeV. Heretofore our measurements in the 3.4 eV resonance have only given the upper estimate: $\Gamma_{Be} < 1$ nanoelectronvolt.

More complete analysis of experimental data, can, certainly, be made by studying simultaneously α -particle and γ -ray spectra and by investigating correlations of different partial widths in individual resonances and resonance groups.

In conclusion, the author would like to express his sincere gratitude to I.M. Frank, F.L. Shapiro and V.G. Soloviev for useful discussions and also to co-workers of the Laboratory of Neutron Physics J. Kvitek, M. Stempinski, M. Florek, M. Pshitula, R.F. Rumi, V.G. Semionov, I. Wilhelm and V.I. Furman whose results are used in this paper.

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Table

Comparison of reduced neutron and partial α widths

Widths \ Target-nucleus	^{95}Mo	^{123}Te	^{143}Nd	^{145}Nd	^{147}Sm	^{149}Sm	^{155}Gd [6]
$\langle \gamma_n^2 \rangle$	4.3	1.9	5.0	1.9	1.9	1.2	0.23
$\langle \gamma_\alpha^2 \rangle (N)$	0.21(5)	0.5(4)	0.8(5)	1.15(4)	0.08(9)	0.007 (6)	0.005 (2)
$\langle \gamma_\alpha^2 \rangle / \langle \gamma_n^2 \rangle$	0.05	0.26	0.16	0.6	0.042	0.006	0.02

*) In brackets you can see the number of widths over which the averaging was made.

16

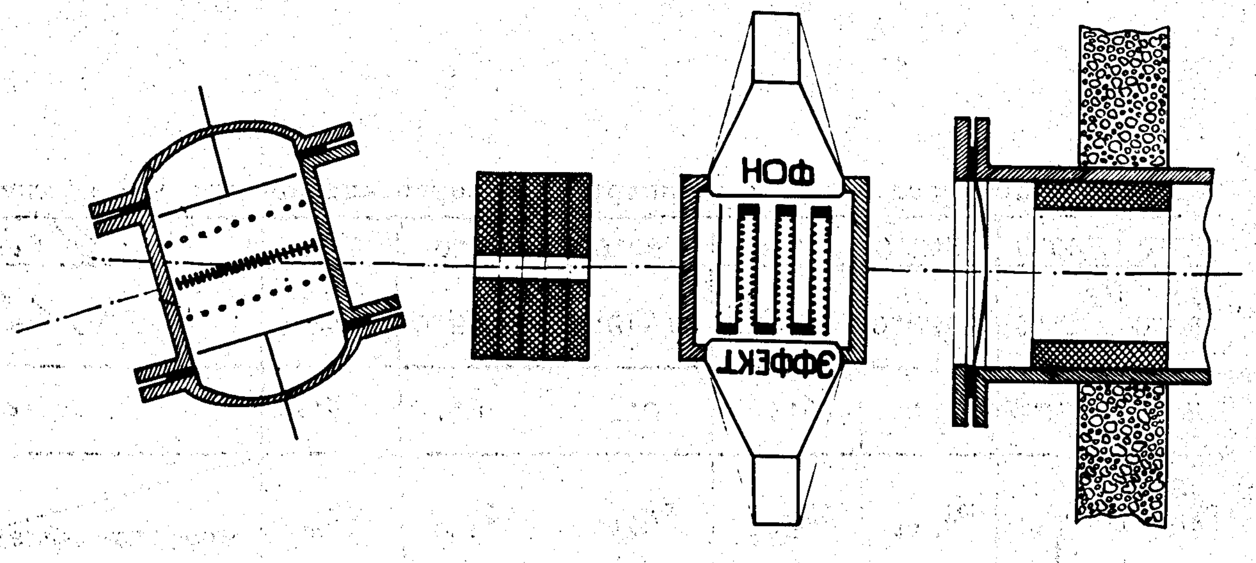
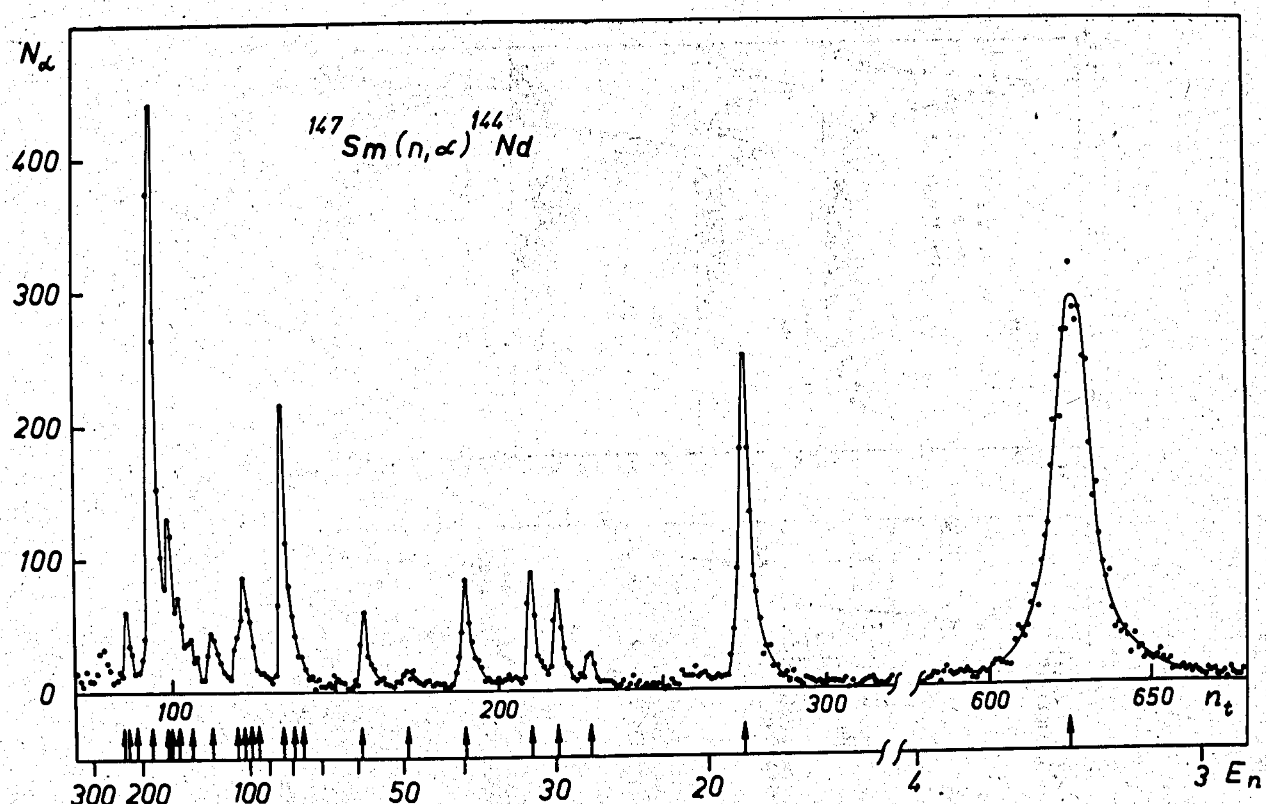
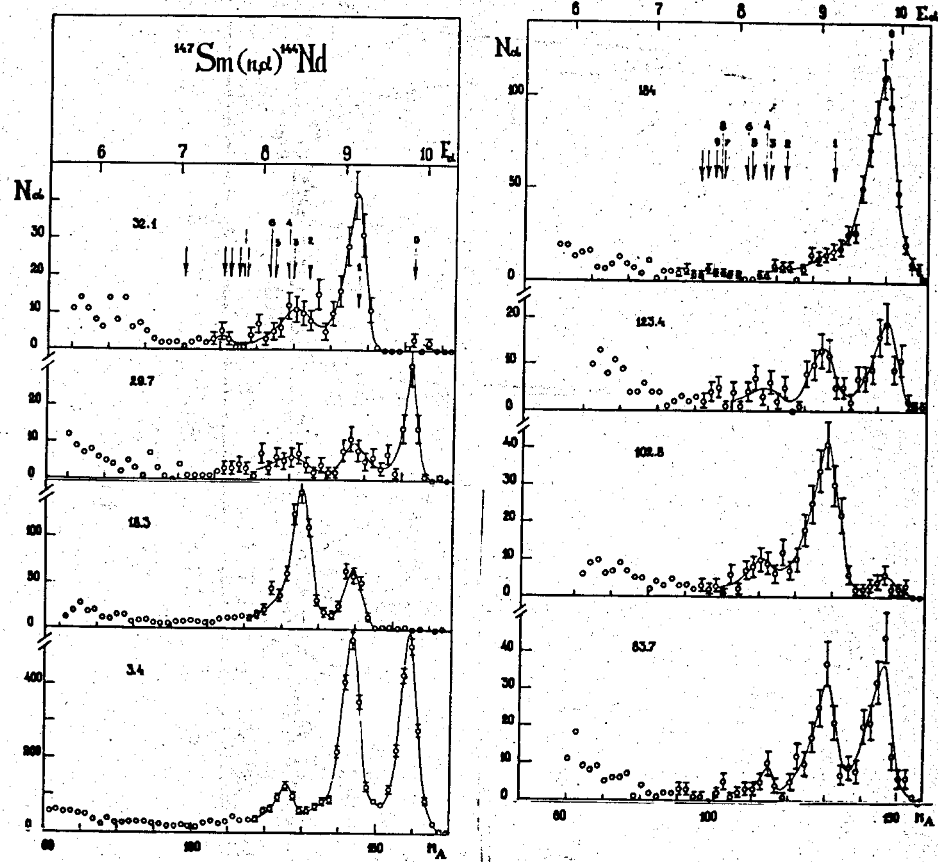

ФОН
ЭФФЕКТ

Fig. 1.

17


N_α
$^{147}Sm(n,\alpha)^{144}Nd$
400
300
200
100
0
100
200
300
600
650
n_t
300
200
100
50
30
20
4
3
E_n



$^{147}Sm(n,\alpha)^{144}Nd$
E_α
N_α
32.1
29.7
18.3
3.4
184
123.4
102.8
83.7
M_A

Fig 3.

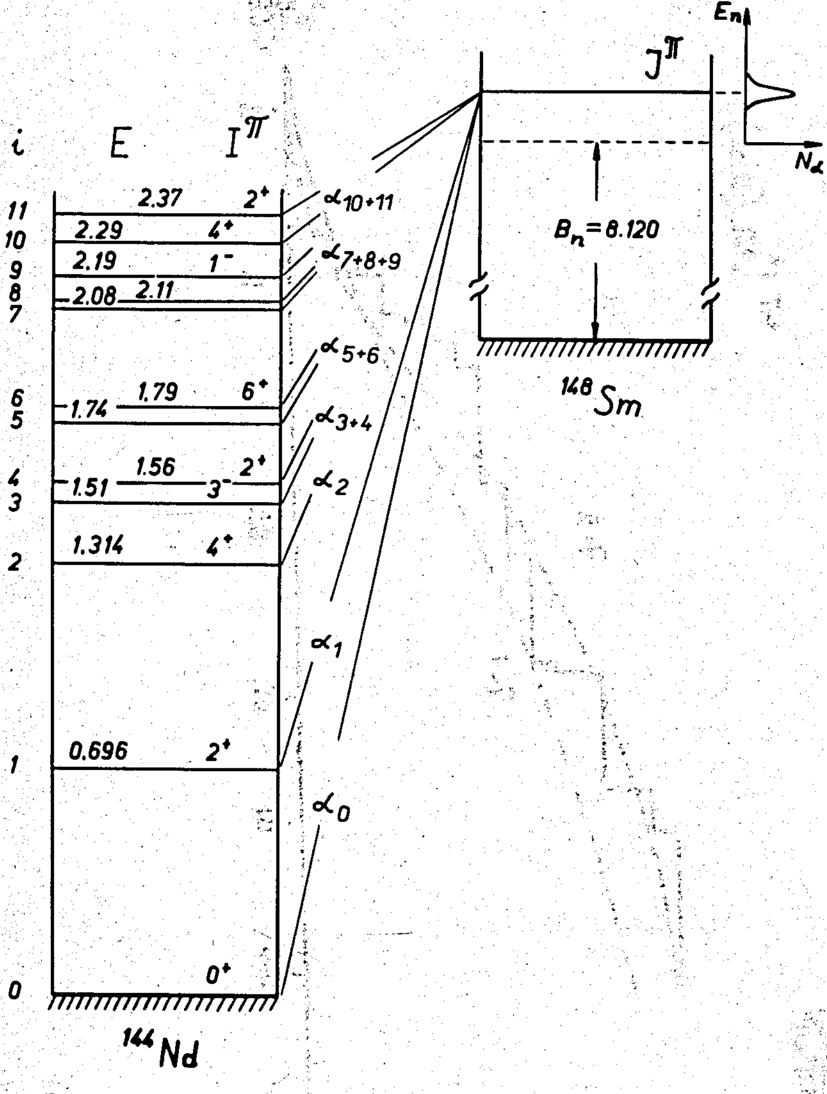

i
E
I^{π}
11
10
9
8
7
6
5
4
3
2
1
0
2.37
2^+
2.29
4^+
2.19
1^-
2.08
2.11
1.74
1.79
6^+
1.51
1.56
2^+
3^-
1.314
4^+
0.696
2^+
0^+
^{144}Nd
α_{10+11}
α_{7+8+9}
α_{5+6}
α_{3+4}
α_2
α_1
α_0
J^{π}
E_n
N_α
$B_n = 8.120$
^{148}Sm

Fig 4.

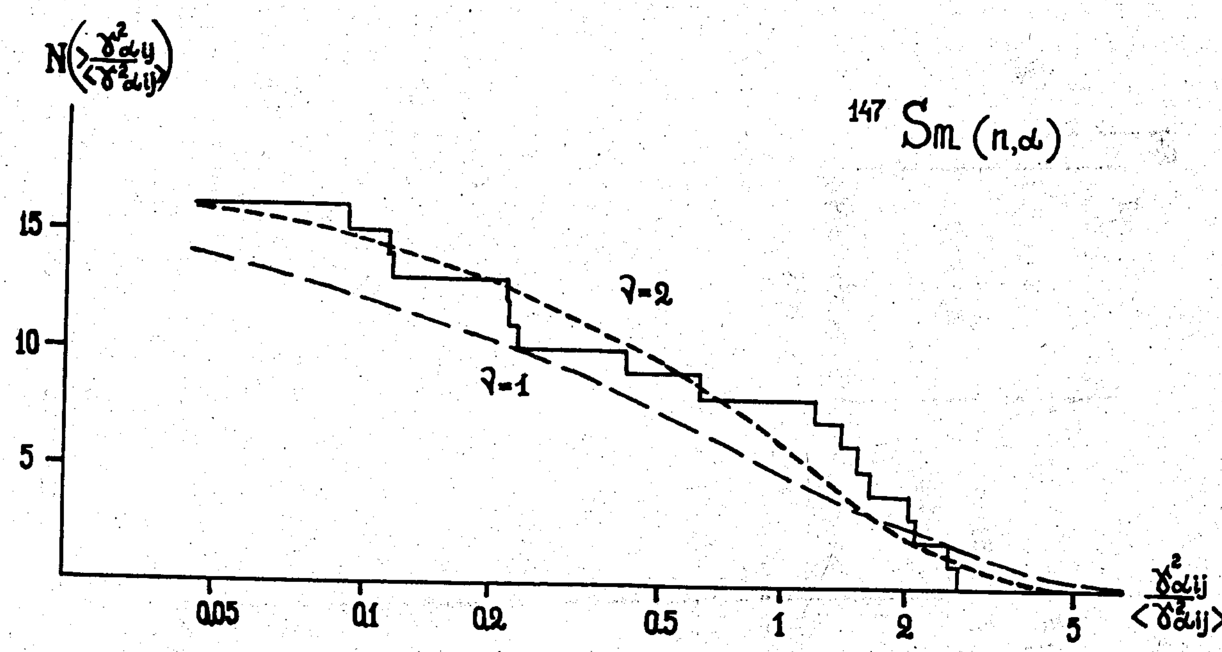

$^{147}Sm\ (n,\alpha)$
$N\left(>\frac{\gamma^2_{\alpha ij}}{\langle\gamma^2_{\alpha ij}\rangle}\right)$
15
10
5
ν=2
ν=1
0.05
0.1
0.2
0.5
1
2
5
$\frac{\gamma^2_{\alpha ij}}{\langle\gamma^2_{\alpha ij}\rangle}$

Fig 5.

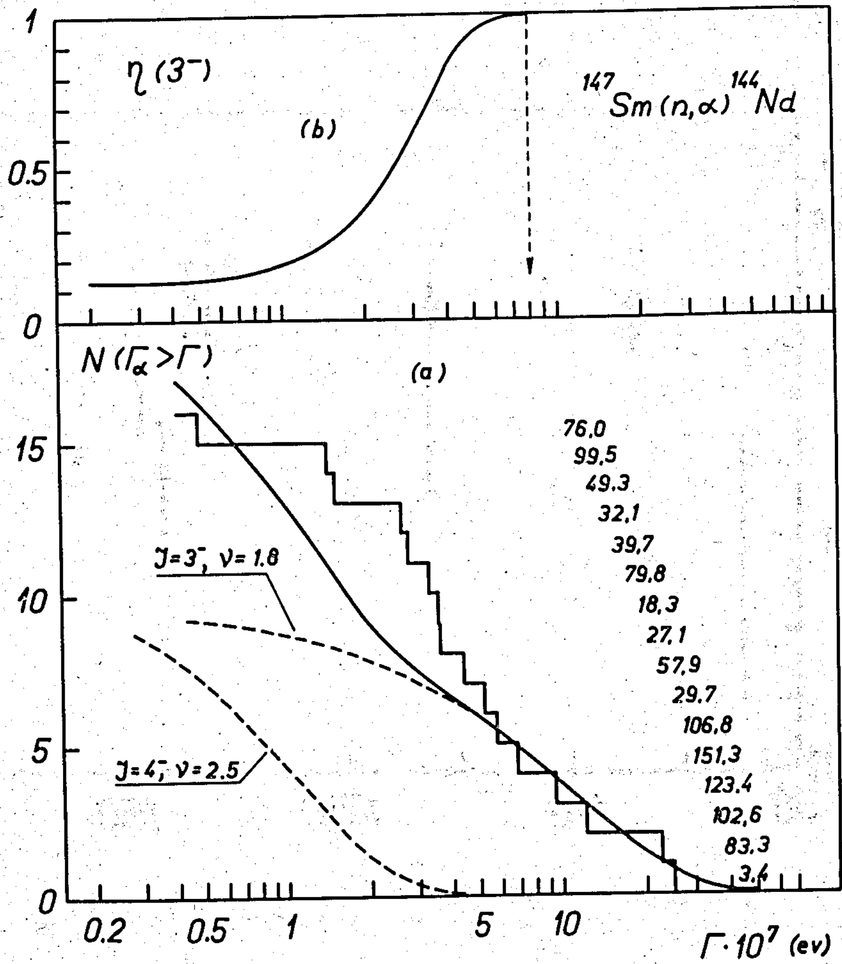

1
0.5
0
η (3⁻)
(b)
147 Sm (n,α) 144 Nd
N (Γα > Γ)
(a)
15
10
5
0
J = 3⁻, ν = 1.8
J = 4⁻, ν = 2.5
76,0
99,5
49.3
32,1
39,7
79,8
18,3
27,1
57,9
29.7
106,8
151,3
123.4
102,6
83.3
3,4
0.2
0.5
1
5
10
Γ·10⁷ (ev)

Fig. 6.

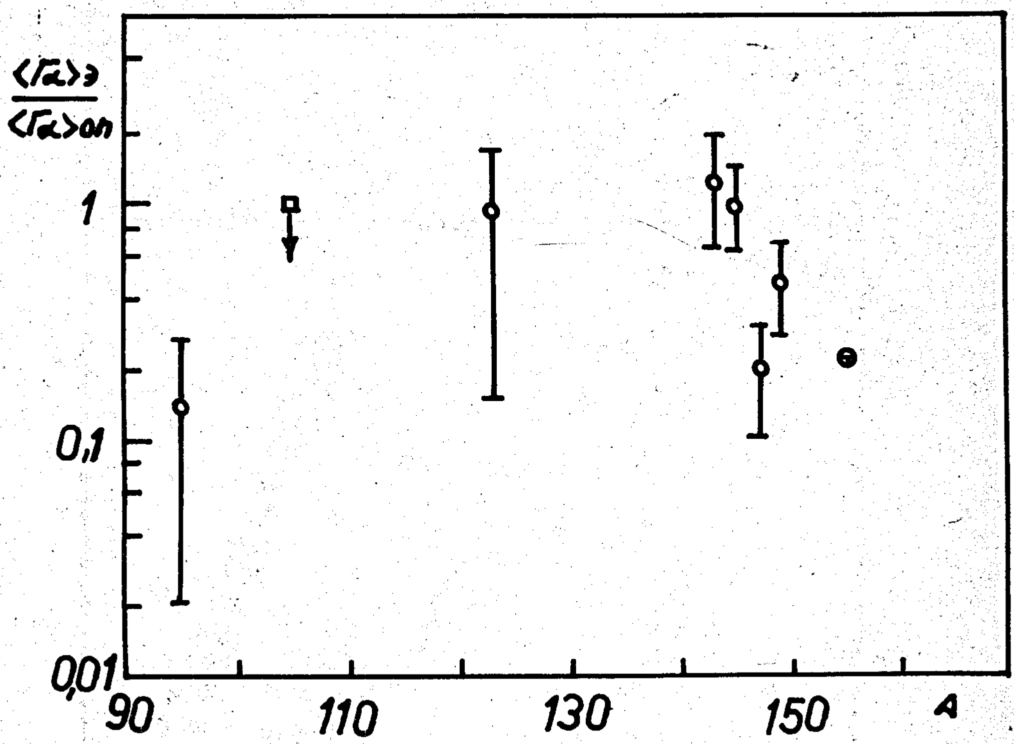


Fig. 7.