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THE RADIATIVE CAPTURE OF FAST NEUTRONS

Joint report, Institute "Jožef Stefan", Ljubljana and Institute "Rudjer Bošković", Zagreb, Yugoslavia.

Compiled by N. Cindro, Institute "Rudjer Bošković", Zagreb, Yugoslavia.

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An outstanding problem in neutron physics is the capture of fast neutrons and, in particular, 14 MeV neutrons. There are two reasons for this statement. First, the mechanism of fast neutron capture is not well known. Second, there appears to be an anomaly possibly connected to nuclear structure. We shall give a brief review of both problems, pointing at the efforts in the two Yugoslav Institutions.

The total cross section for (n,γ) capture has so far been measured by two physically different techniques: the activation technique and the integration technique. The cross section σ_{act} obtained by activation measurements comprises the deexcitation through the photon emission of the complex system (target + neutron) via the bound and unbound states of the final nucleus. The integration method (σ_{int}) measuring the prompt gamma spectra gives, in practice, the decay to bound states only. In fact, the usual procedure in integrating prompt gamma spectra is to count gamma rays from $E_\gamma = E_n + Q$ *) to $E_\gamma = E_n$. Thus only decays to bound states are counted, and $\sigma_{act} \geq \sigma_{int}$ due to the omission of cascade deexcitation through the unbound states of the final nucleus.

1. <u>The capture mechanism at MeV energies.</u> The capture mechanism for energies below a few MeV should be well described by the statistical model. Above, no model gives satisfactory agreement for the energy dependence and gamma spectra. The so-called direct - semidirect model, proposed by several

*) The Q value of an $A(n,\gamma)$ B reaction is the neutron binding energy in the nucleus B.

authors[1-3] is currently the most used one, but with variable success. It should be noted that the pure direct capture model yields total cross sections smaller by an order of magnitude than the experimental ones[4].

The direct - semidirect (DSD) model emphasizes the role of the giant resonance. It assumes that giant resonance states are excited in the process of fast neutron capture. Thus the neutron - nucleon interaction in this model is described by the common optical potential (present in the direct capture model) plus the residual interaction of the incident nucleon with the target nucleons. It is this part of the interaction which allows the dipole resonance states to be excited as intermediate states in the reaction process. Now, the giant resonance states are the well-known collective states with high probability of radiative decay; hence, their excitation would greatly enhance the (n,y) capture cross section.

The DSD models have so far considered only the radiative capture to bound signale particle states. Also, electric dipole transitions have only been considered. The usual procedure is to add coherently the direct and the semidirect amplitudes. The strength of the residual interaction, responsible for the semidirect mechanism was estimated by Brown[1] using a schematic model. On the other hand, Lushnikov and Zaretski[2] deduced their formula following the general Migdal theory[5]. Clement, Lane and Rook[3] excited the collective vibrational states of nuclei by the interaction of the incident particle with the target nucleus through a potential containing a spherical part (optical potential) and a deformed (particle - vibration coupling) part. A typical fit of an experimental spectrum by the three variants of the model is seen in Fig. 1. The gamma ray spectra exhibit a gross structure similar to that predicted by Lane, Thomas and Wigner[7] (the so-called primary structure) modulated by the resonance-like enhancement reflecting the effect of the dipole giant resonance. The primary structure depends on the strength of radiative transitions to particular single particle levels and on the way the spectroscopic factors of these states are distributed over real nuclear states[8]. Due to the well--known phase space considerations (factors (2j + 1) in the direct capture cross section) the transitions to levels having high j values are considerably enhanced. The modulating effect of the semidirect capture, on the other hand, is governed by the parameters of the giant dipole resonance, which is seen from the fact that the peak of the energy distribution appears in the gamma ray energy scale about 1 MeV higher than the peak of the corresponding giant dipole resonance.[8] The effect of the modulation depends on whether the primary structure is very pronounced and, in particular, on the presence of high spin single particle levels (f and g levels). These levels cause bumps in the gamma ray energy spectrum which can be distinguished from the primary structure only by their position[8].

It appears that the calculations of Lushnikov and Zeretski[2] give an overall fit to the data which is comewhat superior to that of Refs. (1) and (2). Typically, the agreement is quite satisfactory for low excitation energies (high outgoing gamma energies), while it becomes worse at excitation energies above 4-5 MeV[6]. This is mainly due to the destructive interference between the direct and semidirect contributions to the matrix element in this region.

The DSD models, however, present several difficulties and inconsistencies. This is in particular the case of 6-8 MeV neutron capture studied by Bergquist et al.[9] which could not be explained in terms of the DSD models. In some cases (such as Ni(n,y) theory and experiment agree within 40%[9], while in some others (e.g. ^{206}Pb(n,y)) the calculated spectral intensity was by an order of magnitude lower than the experimental one[10].

Extensive calculations and good overall fit for the low excitation energy region for 14 MeV neutron radiative capture was obtained by the Ljubljana group[11].

2. <u>The comparison $\sigma_{act}/\sigma_{int}$.</u> Perhaps the most outstanding problem in 14 MeV neutron capture is the difference in σ_{act} and σ_{int}. The problem is the following: As stated before, the measured σ_{act} should in principle be larger than σ_{int}, since the former includes decays to all, bound and unbound, states, while the latter comprises the decay only to bound states. It is expected, however, that this difference should not be too large, since the decay to unbound states would favour the emission of particles, in particular the (n,n'y) reaction. Moreover, high energy gamma rays (corresponding to the decay to bound states) are favoured

by the E^{2L+1} factor in the multipole expansion. There is, of course, the bordering region just around the binding energy, where the available neutron energy might be too small to overcome the centripetal barrier, and gamma rays compete favourably with particle emission. It is difficult to estimate this contribution, since no present theory deals with this region.

The present experimental status of the measured σ_{act} vs σ_{int} is given in Fig. 2, taken from Ref. 13. It appears from the figure that the integrated cross sections follow a smooth path in the somewhat thicker shaded line. The calculated cross sections of Ref. 12 also fall on this line. On the contrary, the activation cross section varies greatly. Sometimes the difference between σ_{act} and σ_{int} is of an order of magnitude. Moreover, a trend might be perceived in this difference: σ_{act} is largest inbetween the closed neutron shells; σ_{act} σ_{int} around the closed neutron shells. This trend is made more visible by a different shading of the region. The possible systematics in the σ_{act} vs σ_{int} difference was first pointed out by Cvelbar et al.[13].

The interpretation of the data in Fig. 2 is full of unanswered questions. First of all, the reliability of both the activation and integration data presents some open problems. In particular, the activation data are unreliable, since measurements of the same cross sections at nominally the same energies yield results which differ by more than a factor of two. Several sources of error - aside of the trivial ones - might contribute to scatter the experimental data. In the first place the influence of slow and thermal neutrons is to be subtracted. Because of the enormous difference in cross sections for thermal and fast neutron capture (sometimes of more than 1000) even a small amount of slow neutrons might change the measured cross section appreciably. A second effect is the difference in bombarding energy. The bombarding energy dependence of the activation cross section for the radiative neutron capture was investigated by Wille and Fink[14]. They found only a very slight energy dependence for bombarding energies from 8 to 18 MeV. Thus the possible bombarding energy difference could not account for the difference in experimental results.

A third possible source of error is the effect of secondary neutrons stemming from (n, 2n) reactions on the target. The energy of these neutron has a maximum around 1 MeV. Now, the capture cross section for 1 MeV neutrons is very small for closed shell nuclei and becoming larger outside the closed shells. Thus in a finite target neutrons from the (n, 2n) reactions could be absorbed giving rise to (n,) processes indistinguishible from processes coming from the neutron beam. The amount of this process can be estimated by a Monte Carlo calculation. A reasonable preliminary estimate would be around 0.5 mb,[15] unsufficient to explain the difference.

The integrated cross sections, although showing a smooth tendency, might nevertheless be subject to a systematic error. Some of the integrated cross sections were obtained by measuring gamma rays at a given angle and assuming the angular distribution to be isotropic. It is not clear whether this assumption was justified experimentally.

The importance of precise activation measurements was already emphasized at the 14th Summer Meeting on Fast Neutrons and Nuclear Structure in Duilovo, in 1969. A group in Zagreb has started a systematic survey of 14 MeV (n,y) reactions. The preliminary results are presented in Table 1.

Table 1

(n,y) cross sections at 14 MeV (Ref. 16)

Element	Activation cross section (mb) this paper	others
^{55}Mn	1.4 ± 0.2	1.2 ± 0.3
^{41}K	2. ± 0.3	3.7 ± 1
^{37}Cl	1.8 ± 0.2	
^{27}Al		
^{23}Na	0.25 ± 0.04	0.29 ± 0.1
^{137}I	7 ± 0.5	7.2 ± 1.2

On the supposition that the differences in σ_{act} and σ_{int} exist and that they are largest inbetween the closed shells, the mechanism giving such a difference is still to be explained.

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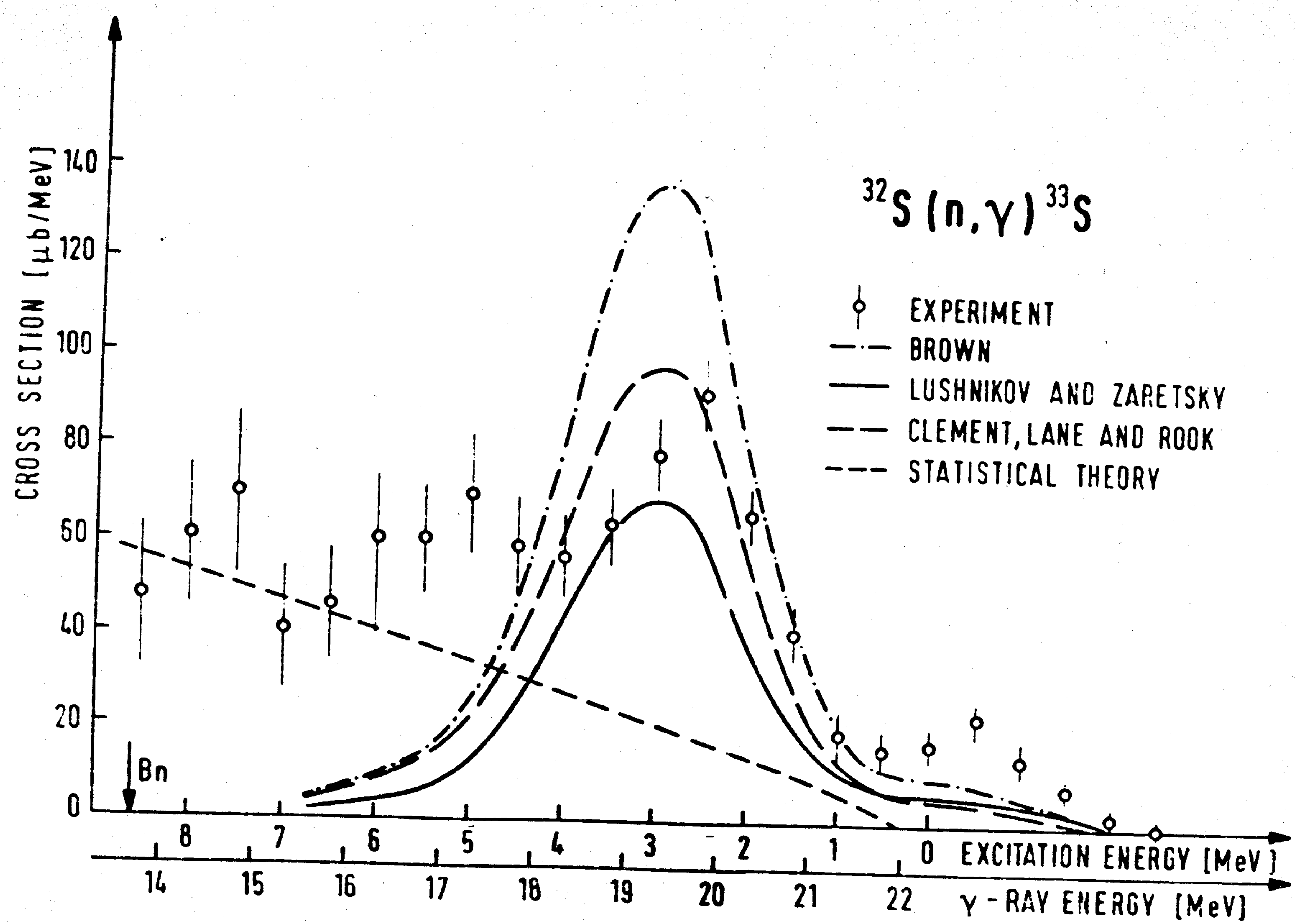
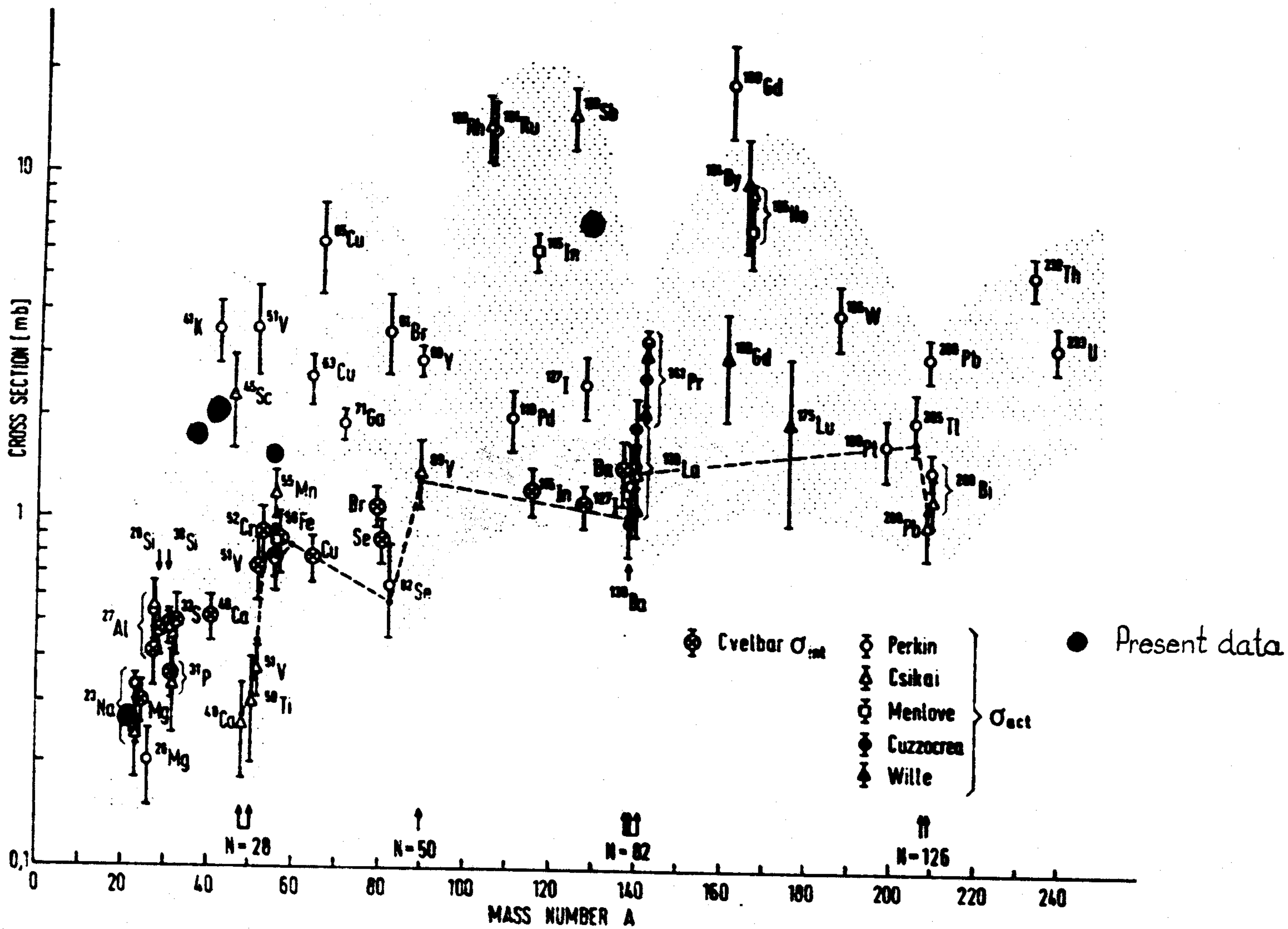

$^{32}S(n,\gamma)^{33}S$
EXPERIMENT
BROWN
LUSHNIKOV AND ZARETSKY
CLEMENT, LANE AND ROOK
STATISTICAL THEORY
CROSS SECTION [μb/MeV]
140
120
100
80
60
40
20
0
Bn
8
7
6
5
4
3
2
1
0
EXCITATION ENERGY [MeV]
14
15
16
17
18
19
20
21
22
γ - RAY ENERGY [MeV]

Fig. 1. Comparison of the experimental spectrum and the models for the 14 MeV (n,γ) reaction on ^{32}S.

(Ref. 8)



CROSS SECTION [mb]
MASS NUMBER A
N=28
N=50
N=82
N=126
Cvelbar σint
Perkin
Csikai
Menlove
Cuzzocrea
Wille
σact
Present data

Fig. 2. Mass dependence of the activation cross section (σ_{act}) and integrated cross section (σ_{int}) for the radiative capture of 14 MeV neutrons. The broken line connects the theoretical integrated cross section values taken from Ref. 12. (from Ref. 13).