INDC(CCP)-313
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International Atomic Energy Agency

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IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

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Reproduced by the IAEA in Austria
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90-02347

# NEUTRON CROSS-SECTION EVALUATION FOR $^{15}N$

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Natural nitrogen contains only 0.37% $^{15}N$. However, the neutron data for this nucleus have various characteristics which justify attention being paid to it despite its rareness. The neutron binding energy in the $^{16}N$ compound nucleus is anomalously small at 2.5 MeV. There are only three levels below the binding energy. These two related factors result in an exceptionally small radiative capture cross-section with a thermal value of $\sigma_{n\gamma}$ = 24 ± 8 μb. Relative neutron overloading inhibits the emission of charged particles during absorption of a neutron by a $^{15}N$ nucleus. Therefore, even in a hard reactor spectrum this isotope seems to be an almost pure scatterer with a low charged particle yield.

Few experimental data are available on $^{15}N$ neutron cross-sections. There are some studies which measure the total cross-section [2-4] covering the 0.5-30 MeV range; there are individual measurements of the total cross-section and radiative capture cross-section at the thermal point [5-6]; and there are results on differential elastic scattering cross-sections over a fairly narrow energy range [7-8]. The characteristics of the $^{16}N$ compound nucleus levels corresponding to neutron resonances have been thoroughly studied in reactions with charged particles, and they are collected together in Ref. [9]. The resonance parameters are contained in Ref. [1]. A $^{15}N$ file has been created in the ENDF/B-V library, but only a short description of it has been published [10].

The evaluation of the total cross-section in the resonance region given in this paper is based on the data from Ref. [4] which are the most detailed and accurate available. In the 0.891-20.0 MeV range they have been smoothed using the rational functions approximation program PADE2 [11], employing the method described in detail in Ref. [12]. The range was broken down into

19 intervals in each of which the cross-section was described using the resonance expansion

$$\sigma_t(E) = C + \sum_{i=1}^{I} \frac{\alpha_i (E - \varepsilon_i) + \beta_i}{(E - \varepsilon_i^2) + \gamma_i^2} . \qquad (1)$$

Continuity of the cross-section at the point where the intervals meet is ensured (but not smoothness!). If $\beta_i = \gamma_i = 0$, then the resonance component assumes the polar form $\alpha_i/(E-\varepsilon_i)$. The approximant here has a discontinuity where $E = \varepsilon_i$ and, of course, it is essential that the value of $\varepsilon_i$ lie beyond the boundaries of the next approximation interval. The resulting parameter values are given in Table 1. They enable one to compute, where necessary, the value of the total cross-section at any point using formula (1). The cross-section energy dependence obtained is shown in Fig. 1.

The constants in formula (1) can be related in the resolved resonance region to resonance parameter values in the generally accepted sense for the purposes of comparison with available data. This is most easily done for the parameters $\lambda_i$ and $\varepsilon_i$. Here the ratios $\varepsilon_i = E_{0i}$ (resonance energy) and $\gamma_i = \Gamma/2$ ($\Gamma$ is the total resonance width) apply. Comparison of the data in Table 1 with the data in Ref. [1] shows that the resonance and energy values tally in all cases to three decimal places, but for the $2\gamma_i$ and $\Gamma_i$ values (though the qualitative agreement is satisfactory) there are quantitative differences. The divergence is greatest for the narrowest resonance - width 2 keV - since the energy resolution in this case is comparable to $\Gamma$, and a correction for it is not introduced in the present paper. The value obtained was $2\gamma_i = 4.3$ keV.

When processing by interval the two widest resonances ($E_0 = 2650$ keV, $\Gamma = 1100$ keV and $E_0 = 2840$ keV, $\Gamma = 714$ keV) were omitted or, more precisely, their contribution in each interval was taken to be a suitably smooth background described by the "polar" component and not the "resonance" component in expression (1). This situation is illustrated in Fig. 2 where

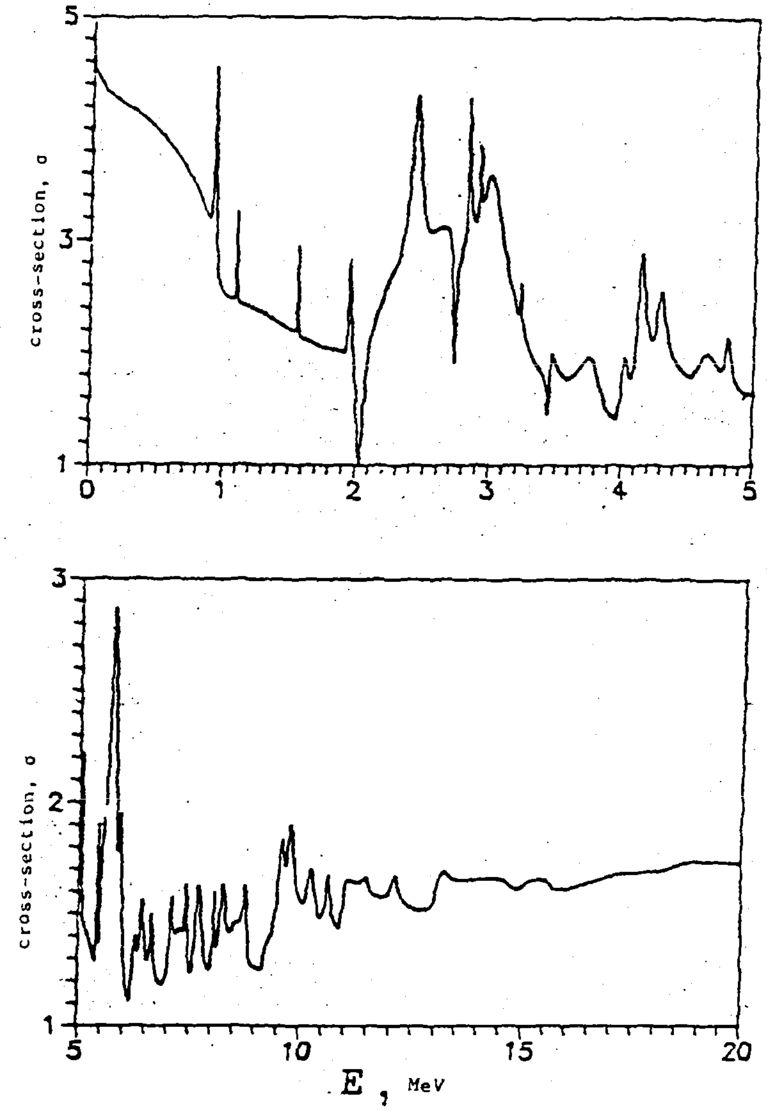


Fig. 1:

*Energy dependence of the evaluated total cross-section for* $^{15}N$.
The curve shows the values of $\sigma_{tot}(E)$ calculated using formula (1) with the parameters from Table 1.

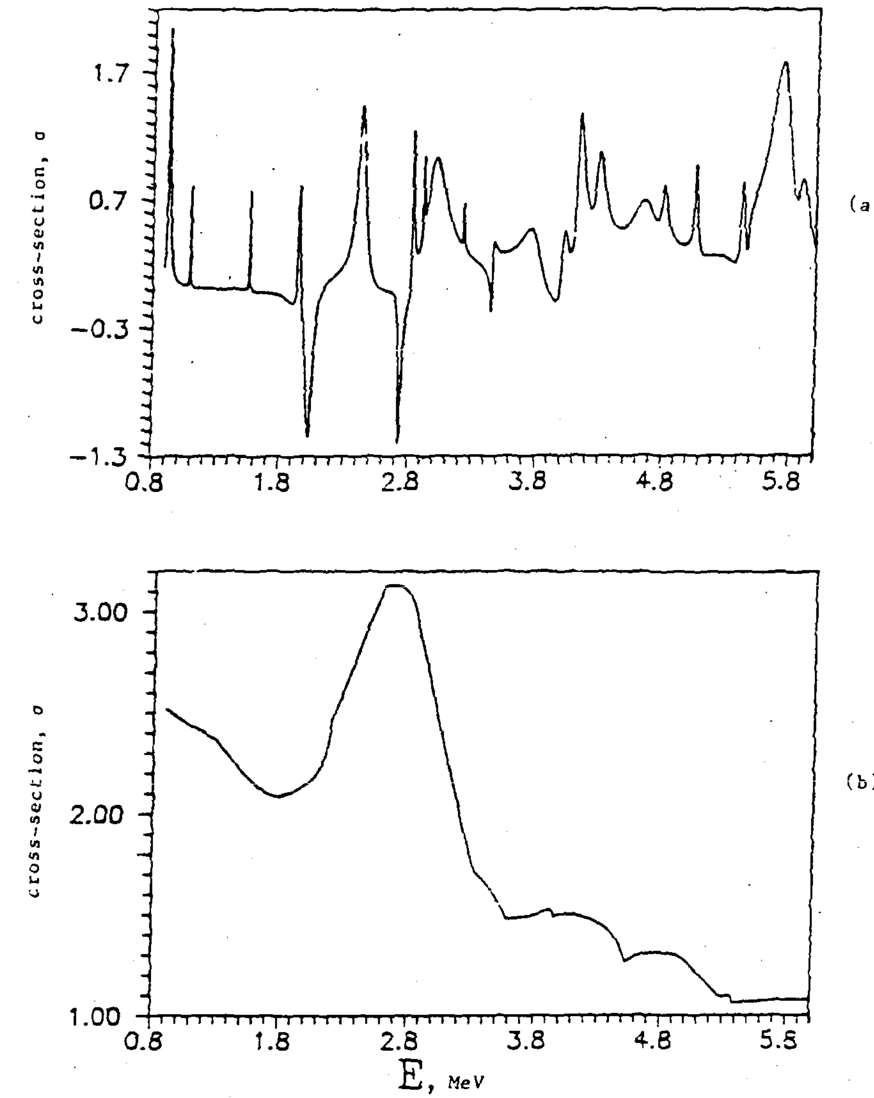


Fig. 2:

*Contributions of the "resonance components"* (a) and the *"fitted curve"* (b) to the total cross-section. One can see how the two widest overlapping resonances in the 3 MeV region, on processing by interval, appear as a contribution to the background.

Table 1

Parameters of the analytical description of the energy dependence for the total $^{15}N$ cross-section (see expression (1))

| No. | $E_{min}$ <br> $E_{max}$ <br> C | $\alpha$ | $\bar{\beta}$ | $\gamma$ | $\varepsilon$ |
|---|---|---|---|---|---|
| 1*) | 0.0000 | 1.8572E+03 | 0 | 0 | -4.0542E+02 |
| | 0.8910 | 2.2287E-01 | 0 | 0 | 6.1046E+00 |
| | 0.0000 | -2.6294E-04 | 2.3783E-05 | 3.9799E-03 | 5.9644E+00 |
| 2 | 0.8910 | 1.5280E+01 | 0 | 0 | -5.1739E+00 |
| | 1.3020 | 1.8688E-03 | 1.8682E-04 | 9.4825E-03 | 0.9224E+00 |
| | 0.0000 | -1.4624E-04 | 3.2781E-06 | 1.7044E-03 | 1.0956E+00 |
| 3 | 1.3020 | 2.1261E+00 | 0 | 0 | -2.4618E-01 |
| | 1.7500 | -2.3546E-04 | 4.4118E-06 | 2.1612E-03 | 1.5636E-00 |
| | 0.9860 | | | | |
| 4 | 1.7500 | -4.6370E-02 | 0 | 0 | 2.2873E+00 |
| | 2.2000 | 3.0102E-03 | 1.2235E-04 | 1.1057E-02 | 1.9483E+00 |
| | 2.0170 | 6.6741E-03 | -1.5133E-03 | 3.4994E-02 | 2.0362E+00 |
| 5 | 2.2000 | -6.1582E+01 | 0 | 0 | -3.6641E+00 |
| | 2.6000 | -1.3404E-02 | 2.0023E-03 | 3.7554E 02 | 2.4339E+00 |
| | 12.959 | | | | |
| 6 | 2.6000 | 3.6609E-03 | 8.8538E-05 | 8.5098E-03 | 2.8286E+00 |
| | 2.8800 | -4.8958E-03 | -2.5048F-04 | 1.4785E-02 | 2.7312E+00 |
| | 3.1120 | | | | |
| 7 | 2.8800 | 1.2954E+01 | 0 | 0 | 9.1215E-01 |
| | 3.3310 | 6.5411E-05 | 7.4833E-06 | 4.5799E-03 | 3.2256E+00 |
| | -3.6190 | -5.8421E-05 | 1.6325E-05 | 4.8167E-03 | 2.9147E+00 |
| | | 4.2260E-02 | 8.5110E-03 | 9.4548E-02 | 2.9882E+00 |
| 8 | 3.3310 | 3.8381E+00 | 0 | 0 | 1.3719E+00 |
| | 3.5870 | 4.6838E-03 | -2.1267E-05 | 9.3636E-03 | 3.4491E+00 |
| | 0.0000 | | | | |
| 9 | 3.5870 | 6.7172E+00 | 0 | 0 | -7.0303E-01 |
| | 3.9620 | -2.9917E-02 | 3.9163E-03 | 9.8535E-02 | 3.7853E+00 |
| | 0.0000 | | | | |
| 10 | 3.9620 | 1.4342E-02 | 4.9709E-04 | 3.3741E-02 | 4.0063E+00 |
| | 4.5240 | 1.4491E-02 | 1.2058E-03 | 4.2970E-02 | 4.2815E+00 |
| | 1.5970 | 2.7022E-02 | 1.3233E-03 | 3.5190E-02 | 4.1260E+00 |
| 11 | 4.5240 | 5.3206E-04 | 0 | 0 | 4.4597E+00 |
| | 4.9320 | -1.9332E-03 | 6.9915E-03 | 1.2255E-01 | 4.6478E+00 |
| | 1.5390 | 3.5532E-03 | 2.9929E-04 | 2.6724E-02 | 4.7996E+00 |
| 12 | 4.9320 | 2.9759E+00 | 0 | 0 | 3.0990E+00 |
| | 5.3850 | -2.3693E-03 | 1.2906E-04 | 1.3542E-02 | 5.0590E+00 |
| | 0.0000 | | | | |
| 13 | 5.3850 | -1.4639E-02 | -2.5660E-04 | 2.1601E-02 | 5.4454E+00 |
| | 6.1420 | 2.8566E-02 | 1.0871E-04 | 3.3575E-02 | 5.4164E+00 |
| | 1.1460 | 4.1995E-02 | 3.9498E-03 | 6.8542E-02 | 5.8891E+00 |
| | | -1.4320E-01 | 1.4590E-02 | 9.9270E-02 | 5.7738E+00 |
| 14 | 6.1420 | -3.4527E-03 | 0 | 0 | 7.0431E+00 |
| | 6.9260 | 1.8521E-02 | 0 | 0 | 5.9586E-00 |
| | 0.0000 | -1.1569E+01 | 0 | 0 | 1.7647E+01 |
| | | 1.6153E-03 | 5.0546E-04 | 4.1014E-02 | 6.6498E+00 |
| | | 1.5651E-02 | 1.0355E-03 | 5.8132E-02 | 6.4004E+00 |
| | | 8.2963E-03 | 1.9959E-03 | 7.4336E-02 | 6.2536E+00 |
| 15 | 6.9260 | -1.9347E+01 | 0 | 0 | 2.4685E+01 |
| | 7.8500 | 3.0835E-03 | 4.6485E-04 | 3.9612E-02 | 7.0906E+00 |
| | 0.0000 | -3.1625E-03 | 4.1266E-04 | 3.2760E-02 | 7.4427E+00 |
| | | -3.2050E-02 | 5.5603E-03 | 1.6340E-01 | 7.3390E+00 |
| | | 7.3588E-03 | 5.2532E-03 | 1.0073E-01 | 7,7102E+00 |
| 16 | 7.8500 | -7.1801E-04 | 9.6107E-05 | 1.7143E-02 | 8.0701E+00 |
| | 9.0120 | -8.8809E-03 | 8.6635E-04 | 5.3986E-02 | 8.7978E+00 |
| | 1.3320 | -9.3566E-03 | 2.0435E-03 | 7.8648E-02 | 8.2879E+00 |
| | | -4.1534E-03 | 6.9214E-03 | 1.9795E-01 | 8.5554E+00 |
| | | -8.1249E-02 | 4.1476E-03 | 1.6980E-01 | 7.7669E+00 |
| 17 | 9.0120 | -3.8775E-02 | 0 | 0 | 1.1135E+01 |
| | 10.7200 | 8.4785E-03 | -9.7823E-05 | 8.6184E-02 | 9.2189E+00 |
| | 1.2780 | -2.9819E-03 | 1.1146E-03 | 6.5336E-02 | 1.0643E+01 |
| | | -3.8159E-03 | 3.2805E-03 | 1.0845E-01 | 1.0261E+01 |
| | | -9.0466E-03 | 4.5584E-03 | 9.4094E-02 | 9.5928E+00 |
| | | 3.2657E-02 | 4.5999E-03 | 1.0238E-01 | 9.7511E+00 |
| 18 | 10.7200 | 5.6038E+01 | 0 | 0 | -2.4562E+01 |
| | 12.6200 | -2.7447E-03 | 5.5077E-04 | 9.0817E-02 | 1.1486E+01 |
| | 0.0000 | -1.2628E-03 | 1.2153E-03 | 9.7286E-02 | 1.2115E+01 |
| | | 2.1672E-02 | -8.7274E-04 | 1.0440E-01 | 1.0946E+01 |
| 19 | 12.6200 | 8.4145E-02 | 0 | 0 | 1.6157E+01 |
| | 15.7200 | -3.7197E+01 | 0 | 0 | 3.6315E+01 |
| | 0.0000 | -7.2261E-03 | -4.1999E-03 | 2.4742E-01 | 1.4819E+01 |
| | | 2.0963E-02 | 1.9990E-03 | 1.6591E-01 | 1.3076E+01 |
| 20 | 15.7200 | -6.2721E-02 | 0 | 0 | 1.4925E+01 |
| | 20.0000 | 2.4418E-03 | 5.5418E-02 | 8.2542E-01 | 1.9559E+01 |
| | 1.6860 | | | | |

*/ Independent variable of the approximant in the first interval = ln(E,eV); in all the rest E,MeV.

the contributions of these two groups of components are presented separately. In the lower part of the figure the broad peak corresponding to the two resonances indicated stands out clearly.

In the $10^{-5}$ eV ≤ E ≤ 0.91 MeV range, the cross-section was calculated using the Reich-Moore model taking the resonance parameters from Ref. [1] and normalizing to the thermal value. In this region it is difficult to approximate the cross-section using a rational energy function since the drop in the values for the independent variable is too great. Since it is desirable to have analytical approximation formulae for the total cross-section over the whole evaluation range, in the interval $10^{-5}$ eV-0.91 MeV a rational approximation was set up taking the form of the function x = ln(E) where E is expressed in eV. The parameters obtained using this method are also given in Table 1 and the relevant (first) interval is marked with an asterisk. The lower limit of this interval is conventionally given as zero in Table 1, although in fact the approximation was carried out from the lower limit of the evaluation range $10^{-5}$ eV.

Below 10 eV our processing of the experimental data indicates the existence of two new resonances ($E_0$ = 8555 keV, 2γ = 396 keV and $E_0$ = 9218.9 keV, 2γ = 172 keV) regarding which there are no data in the literature. For several resonances with energies $E_0$ = 9610, 9770, 10 250, 10 640, 11 090, and 11 410 keV, evaluations of their widths were obtained which are not given in Ref. [1].

There are no direct experimental data on the fast neutron radiative capture cross-section for $^{15}N$. In the resolved resonance region there are individual data on the radiation width for s-neutrons for the level where $E_0$ = 2.038 MeV and $\Gamma_{\gamma 0}$ = 0.234 eV; these are given in Ref. [1]. At the thermal point a cross-section value of $\sigma_{n\gamma}$ = 0.024 ± 0.008 mb is taken to apply. Therefore the cross-section $\sigma_{n\gamma}$ was evaluated in the following way:

(a) In the $E_n = 10^{-5}$ eV–0.891 MeV neutron energy region, the fast neutron radiative capture cross-section was described using the formula

$$\sigma_{n\gamma} = 3.817 \cdot 10^{-9} \quad E_n^{-1/2} \ \sigma , \qquad (2)$$

where $E_n$ is expressed in MeV. Formula (2) gives an energy dependence for $\sigma_{n\gamma}$ of type I/v, where v is the velocity of the neutrons and is normalized to the thermal value 0.024 mb. The resonance integral is $I_\gamma = 0.011$ mb;

(b) In the $E_n = 0.891$–20 MeV neutron energy region, the radiative capture cross-section was calculated using the Breit-Wigner formula. For the total neutron widths and the positions of the neutron resonances the values for $\gamma_i$ and $\varepsilon_i$ from Table 1 were used. For the resonance $E_n = 2.038$ MeV the experimental value for the radiation width $\Gamma_\gamma = 0.234$ eV was used. For other resonances a mean value of $\Gamma_\gamma$ was used derived from the condition that the values of $\sigma_{n\gamma}$ are the same when $E_n = 0.891$ MeV, those values having been obtained from formula (2) and from the description using the Breit-Wigner model.

In the $E_n = 10^{-5}$ eV–0.891 MeV neutron energy range, the elastic scattering cross-section was calculated using the Reich-Moore model with the resolved resonance parameters from Ref. [1] and normalizing to the thermal value $\sigma_s = 4.57$ b. For energies of $E_n > 0.891$ MeV, the elastic scattering cross-section was obtained by deducting the cross-sections of all the other processes described above from the total cross-section.

The inelastic neutron scattering cross-sections with excitation of discrete levels in the $^{15}N$ nucleus were evaluated using the Hauser-Feshbach-Moldauer model within the SMT-80 program [13]. The parameters of the optical model for neutrons were derived from the description of the total cross-sections given in Ref. [4] for the neutron energy region $E_n = 5$–30 MeV. The parameters were fitted using the ABAREX program [14]. Table 2 gives the

Table 2

Parameters of the optical model of $^{15}N$ for neutrons

| $V_0$, MeV | $W_s$, MeV | $V_{so}$, MeV | $r_0$, fm | $r_s$, fm | $r_{so}$, fm | $a_0$, fm | $a_s$, fm | $a_{so}$, fm |
|---|---|---|---|---|---|---|---|---|
| 45.6 | 3.78 | 5.70 | 1.16 | 1.25 | 1.01 | 0.68 | 0.60 | 0.48 |

1. $^{15}N(n,p)^{15}C$ - reaction. The calculation for the (n,p) reaction cross-section takes into account excitation of three discrete levels in the $^{15}C$ nucleus.
2. $^{15}N(n,d)^{14}C$ - reaction. The calculation for the (n,d) reaction cross-section takes into account excitation of four levels in the $^{14}C$ nucleus.
3. $^{15}N(n,t)^{13}C$ - reaction. The calculation for the (n,t) cross-sections takes into account excitation of four discrete levels in the $^{13}C$ nucleus.
4. $^{15}N(n,\alpha)^{12}B$ - reaction. The calculation for the cross-sections of this reaction takes into account excitation of seven discrete levels in the $^{12}B$ nucleus.

values for the parameters of the optical model for neutrons for $^{15}N$. The first eleven levels, whose characteristics were taken from Ref. [9], were used as discrete excited levels in the $^{15}N$ nucleus. The continuous spectrum energy limit was taken to be 9.25 MeV which is 100 keV higher than the last resolved level. The following reactions were taken into account as competing processes: (n,p), (n,α), (n,t) and (n,d). Figure 3 shows the evaluated excitation functions obtained for the process (n,n'), and Fig. 4 the cross-sections of the threshold reactions where one or two particles are emitted.

The excitation functions for reactions with charged particle emission (protons, deutons, tritons, α-particles) were calculated using the Hauser-Feshbach-Moldauer model within program SMT-80 [13]. The systematics

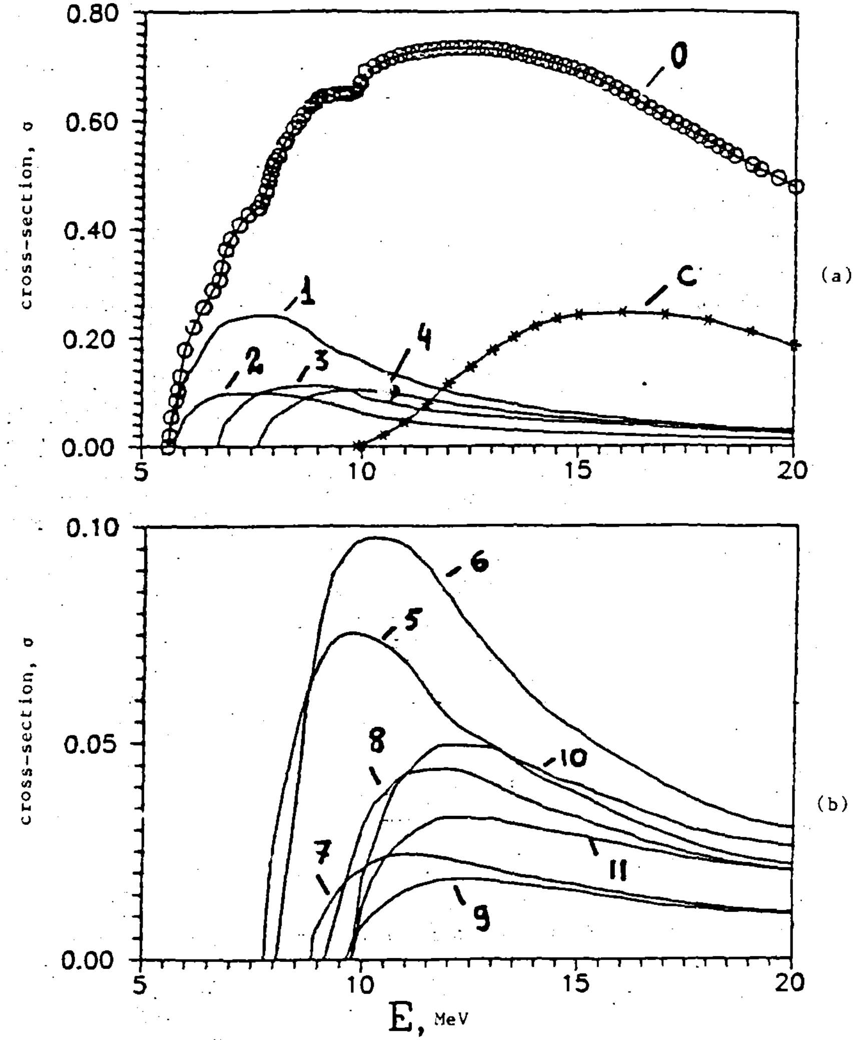


Fig. 3: Evaluated inelastic scattering cross-sections:

(a) 0 - Total inelastic scattering cross-section;

1-4 - Inelastic scattering cross-sections with excitation of 1-4 levels;

(b) 5-11 - The same with excitation of 5-11 levels;

12 - With excitation of the levels of the continuum.

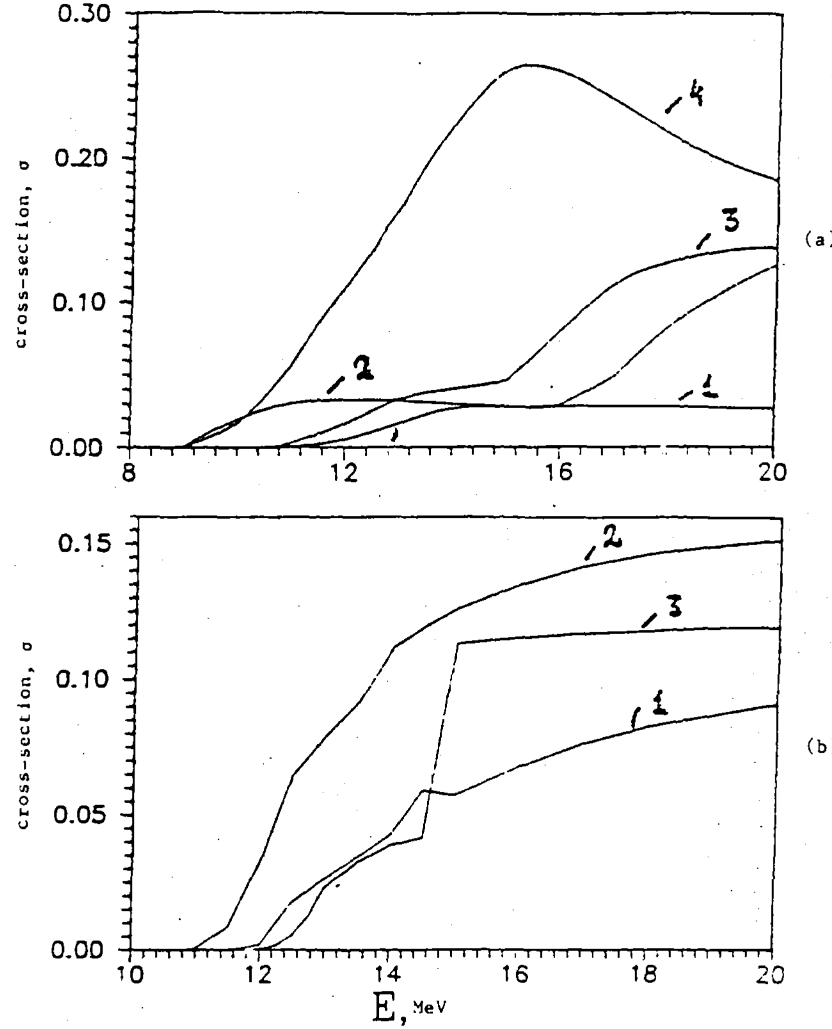


Fig. 4: Evaluated threshold reaction cross-sections:

(a) 1 - $\sigma_{np}$, 2 - $\sigma_{nd}$, 3 - $\sigma_{nt}$, 4 - $\sigma_{n\alpha}$;

(b) 1 - $\sigma_{n2n}$, 2 - $\sigma_{nnp}$, 3 - $\sigma_{nn\alpha}$.

obtained in Ref. [15] were used as the parameters of the optical model for charged particles. The diagrams of the discrete levels for residual nuclei are taken from Ref. [16].

The following multi-particle reactions which are accessible in the neutron energy region up to 20 MeV were examined: $^{15}N(n,np)^{14}C$; $^{15}N(n,n\alpha)^{11}B$; $^{15}N(n,2n)^{14}N$. The cross-sections of these reactions were calculated using the evaporation model with residual nucleus level density parameters obtained from the description of the total level density in the neutron binding energy region. The data from Ref. [1] were used as experimental data on neutron resonance density.

The angular distributions for the gamma rays accompanying all the processes examined were taken to be isotropic. The angular distributions of charged particles and neutrons emitted in all threshold reactions were assumed to be isotropic in the centre-of-mass system.

The angular distributions for inelastic neutron scattering processes with excitation of discrete levels were calculated using the ABAREX program [14] and then presented in the laboratory system of co-ordinates as Legendre polynomial expansion coefficients.

The angular distributions of elastically scattered neutrons were also calculated using the optical model for the neutron energy regions $E_n = 10^{-5}$ eV-192 MeV and $E_n > 3.46$ MeV. In the interval 1.92-3.46 MeV the experimental data from Ref. [8] were used.

The secondary neutron energy spectra were obtained for the processes (n,np), (n,nα), (n,2n) and (n,n') across the continuum. The evaporation model was used to obtain energy distributions, the main parameter of the model being the thermodynamic temperature of the *residual nucleus in relation to* the energy of the incident neutron. For the (n,n') process the energy dependence of the temperature T was determined using the equation:

$$aT^2 = U = E_n - 2T, \qquad (3)$$

where a is the level density parameter for $^{15}N$;

2T is the mean energy removed by the secondary neutron;

$E_n$ is the initial energy of the neutron.

The level density parameters a for residual nuclei were determined from the resolved resonance data in Ref. [1]. For instance, for the isotope $^{15}N$ (target nucleus $^{14}N$), within the framework of the simplest Fermi-gas model we get the value a = 1.542 $MeV^{-1}$ from Ref. [1]. Then, using expression (3), the dependence $T(E_n)$ is set up. A similar dependence $T(E_n)$ was used for the (n,np), (n,nα) and (n,2n) processes.

For all the reactions looked at which involve excitation of discrete levels in the residual nuclei, the standardized gamma transport probabilities were evaluated. The data compiled in Ref. [9] were those mainly used to evaluate these quantities.

This nuclear data evaluation for the isotope $^{15}N$ is presented in the form of a file of evaluated data in the ENDF/B-5 format. The $^{15}N$ file is included in the working version of the BROND-1 library (MAT = 720), and can be accessed for analysis and use via the Nuclear Data Centre of the State Committee on the Utilization of Atomic Energy.

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