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INTEGRAL HIGH-ENERGY NUCLON-NUCLEUS CROSS SECTIONS FOR MATHEMATICAL EXPERIMENTS WITH ELECTRONUCLEAR FACILITIES

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Интегральные высокоэнергетические нуклон-ядерные сечения для математических экспериментов с электроядерными установками

Найдена параметризация интегральных сечений σ_{nonel}, σ_{tl}, σ_{tot} для неупругих, упругих и полных протон- и нейтрон-ядерных взаимодействий при средних и высоких энергиях. На основе найденной параметризации создана программа для интерполяционных расчетов интегральных сечений взаимодействия с произвольными ядрами-мишенями при энергиях протонов $E = 1$ МэВ — 1 ТэВ и при энергиях нейтронов $E = 12{,}5$ МэВ — 1 ТэВ.

Работа выполнена в Лаборатории вычислительной техники и автоматизации ОИЯИ.

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Integral High-Energy Nuclon-Nucleus Cross Sections for Mathematical Experiments with Electronuclear Facilities

A parametrization of the integral cross sections σ_{nonel}, σ_{tl}, σ_{tot} for the elastic, nonelastic and total proton- and neutron-nucleus interactions is considered at medium and high energies. On the basis of this parametrization a code is created for the interpolational calculations of the integral cross sections for arbitrary target nuclei at proton energies $E = 1$ MeV — 1 TeV and neutron energies $E = 12.5$ MeV — 1 TeV.

The investigation has been performed at the Laboratory of Computing Techniques and Automation, JINR.

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Introduction

Complexity and high rate of experiments with Accelerator Driven Systems force to replace real physical experiments by mathematical ones. Results of such an approach depend essentially on exactness of the integral cross-sections of nuclon-nucleus interactions. In the low-energy region $E \leq 14 - 20$ MeV there are quite precise neutron cross-sections for the majority nuclei of practical interest, for example, the 26-group library [1]. One can also use more detailed libraries, thought comparative calculations have shown that such an improvement is important for the study of transmutation processes. However, it is usually unnecessary for modeling radiation damage, neutron yield and spatial distributions of produced heat in targets, etc.

The situation is worse significantly at higher energies where there are no measured data at all for some nuclei and we must use rather rough interpolations, especially in the case of the elastic and total proton-nucleus cross-sections where there are only a few experimental points [2,3].

We have composed the tables of the estimated integral proton and neutron cross-sections

$$\sigma_{el} = \int \sigma_{el}(\theta) d\Omega, \quad \sigma_{nonel} = \sum_j \sigma_{in}^{(j)}, \quad \sigma_{tot} = \sigma_{el} + \sigma_{nonel}$$

for the most frequently encountered nuclei (natural mixtures of isotopes)

$$H, D, He, Li, Be, C, N, O, Na, Al, S, Ca, Ti, Fe, Cu$$

$$Br, Mo, Cd, Sn, Ba, W, Pb, U, Cf$$

using all known now experimental values as well as a paranetrization and theoretical models in intermediate intervals. These tables are incorporated into a new version of the Code CROSEC providing by means of an interpolation the cross-sections for nuclei with arbitrary values of the mass and charge numbers A, Z at various energies E [1]. The CROSEC can be used as a quick-operating subroutine inside the Codes modeling particle transport in media.

Tables of cross-sections

To calculate the dependence of cross-sections vs energy at energies where the projectile de Brogle wave length is significantly smaller than the size of the target nucleus, the optical model based on a solution of the Schrödinger equation with a phenomenological complex potential was used [4—6]:

$$\sigma_{el} = \pi\lambda^2 \sum_{\ell}(2\ell+1)\left|1-\exp(2i\eta_{[}\ell])\right|^2,$$

$$\sigma_{nonel} = 2\pi\lambda^2 \sum_{\ell}(2\ell+1)\left(1-\exp(-4\chi_\ell)\right),$$

$$\eta_\ell = \delta_\ell + i\chi_\ell \simeq (1/2)\int_{\lambda\ell}^{\infty} \frac{rn(r)\,dr}{\sqrt{r^2+(\lambda\ell)^2}},$$

$$Re\, n(r,E) = A\xi_1(E)\left[\frac{Z}{A}\alpha_p(E)\sigma_p(E)+\right.$$
$$\left.\left(1-\frac{Z}{A}\right)\alpha_n(E)\sigma_n(E)\right]d(r),$$

$$Im\, n(r,E) = A\xi_2(E)\left[\frac{Z}{A}\sigma_p(E)+\left(1-\frac{Z}{A}\right)\sigma_n(E)\right]d(r)..$$

[1]Note that the tables in CROSEC correspond to the mass numbers of natural mixture of isotopes: e. g. $A = 118.7$ for antimony, $A = 207.2$ for lead and so on.

Here λ is the divided by 2π de Broglie wave length in the center of mass system, σ_p and σ_n are total p-p and n-n cross-sections, α_p and α_n are corresponding rations of the real and the imaginary parts of the elastic amplitude at zero scattering angle calculated by means of dispersion relations, $d(r)$ is the intranuclear density determined in the experiments with electron scattering, ξ_i are weakly energy dependent adjusting parameters. Their values have been fitted to obtain the best agreement of calculated and experimental data simultaneously for several neighboring nuclei. (The experimental data are taken from the compilation [2]). At high energies where one must take into account large number of waves ($\ell \gg 1$) the sums is replaced by integrals [6].

In the region $E > 1\,GeV$ we also used the Glauber approximation with the amplitude of the nuclon-nuclon interaction containing adjusting factors. The obtained cross-sections coincide with those estimated by means of the optical formula presented above.

At energies $E \geq 100\,MeV$ the proton-nucleus cross-sections have been approximated by the simple expression

$$\sigma_p = \sigma_n(\alpha - \beta E)$$

and at $E > 1\,GeV$ by the formulae

$$\sigma_p = \sigma_n(1 - \gamma \ln E)$$

with parameters α, β and a small factor γ determined by a comparision with the optical and Glauber's cross-sections at the boundary energies.

When the projectile energy is smaller several tens MeV, particularly, in the case of light nuclei where the de Brougie wave length is only few times smaller than the nuclear sizes, we used the phenomenological expression

$$\sigma(E,A,Z) = \pi\left[r_o A^{1/3} + \lambda(E,A)\right]^2 \times$$
$$[1 - V(A,Z)/E_c]\, f(E)\varphi(A)^{\gamma(E)}$$

where V is the Coulomb barrier (for neutrons V=0), λ is the de Brodgle wave length of the projectile, (E_c is its kinetic energy in center of mass system. The functions $f(E)$, $\varphi(A)$ and $\gamma(E)$ are determined by the sums

$$\sum_i u_i E^{s_i}, \quad \sum_i v_i A^{t_i}$$

with constant adjusting parameters (different for protons and neutrons). When energy $E \gg 1\,GeV$ the function $\varphi(A) \to A$ and $\gamma(E) \to$ const.

Our tables contain the neutron cross-sections for energies from $E = 12.5$ up to $10^6\,MeV$. In the case of protons the low energy $E = 1\,MeV$.

Comparison to experimental data

The neutron cross-sections obtained by the interpolational procedure are in the limits of the best experimental data and are close to the values presented in the figures of the atlas [?]. As an example, in Fig. 1 the cross-section for lead are shown. It should be noted that our interpolated curves are smoothly sewed together with the data taken from the compilation EB6.

At very high energies $E \gg 10\,GeV$ an encreasing in cross sections is observed. This is due to the increasing of the total p-n and p-p cross-sections.

In Figs. 2 and 3 the calculated and experimental data for protons are compared in the case of a light, medium and heavy nucleus. Since at high energies the proton cross-sections are close to the neutron ones, the data in Figs are shown only for $E < 35\,MeV$. Up to now measurements have been done only for σ_{nonel} and the experimental points are in good agreement with the approximation curves. There are no experimental data for the low-energy proton cross-sections σ_{el} where they differ from the neutron ones, therefore one cannot estimate the precision of the approximation.

Presently several approximations for σ_{el} are known (see, e.g., [8,9], however, without experimental information it is difficult to prefer one to another.

Conclusion

We conclude that the method of the parametrization described above allows one to create a Code which is an effective tool to predict various integral nuclon-nucleus cross-sections. The Code can be used in the particle transport Codes FLUKA,LAHET, MCNPX and in the Code CASCAD developed in Dubna for mathematical modelling of electronuclear facilities.

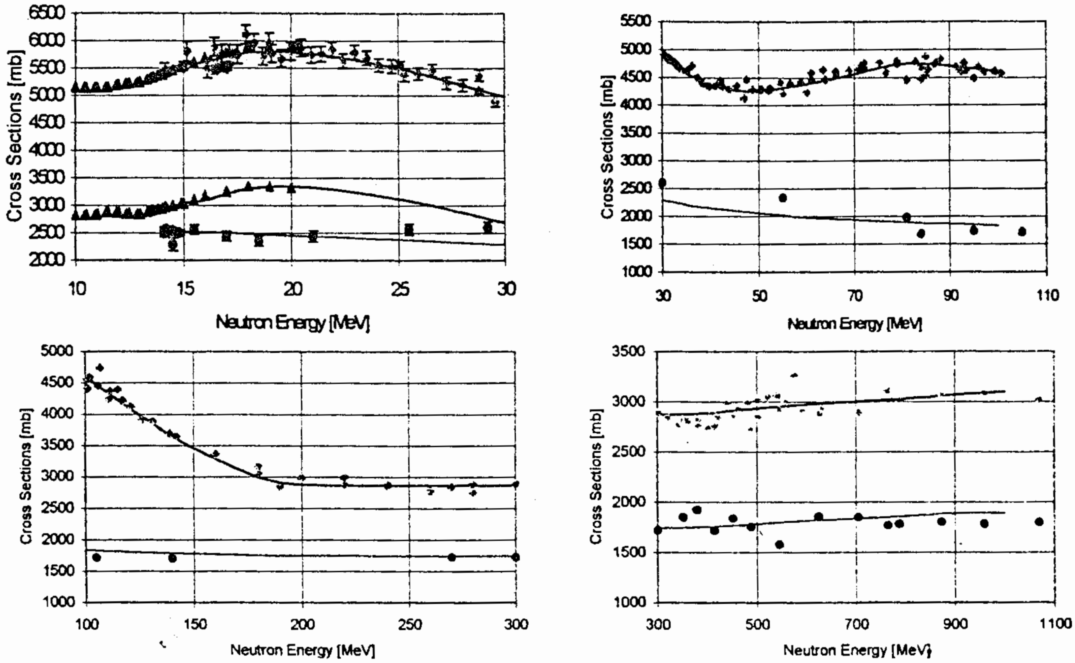

Fig. 1. Cross-sections for $n +^{207.2} Pb$. In the first fig. the upper, intermediate and low curves are the calculated σ_{tot}, σ_{el}, σ_{nonel}. In other figs the upper and low curves are σ_{tot}, and σ_{nonel} The triangles at low energies are the data EB6. The other marks are the experimental points from the compilation [2].

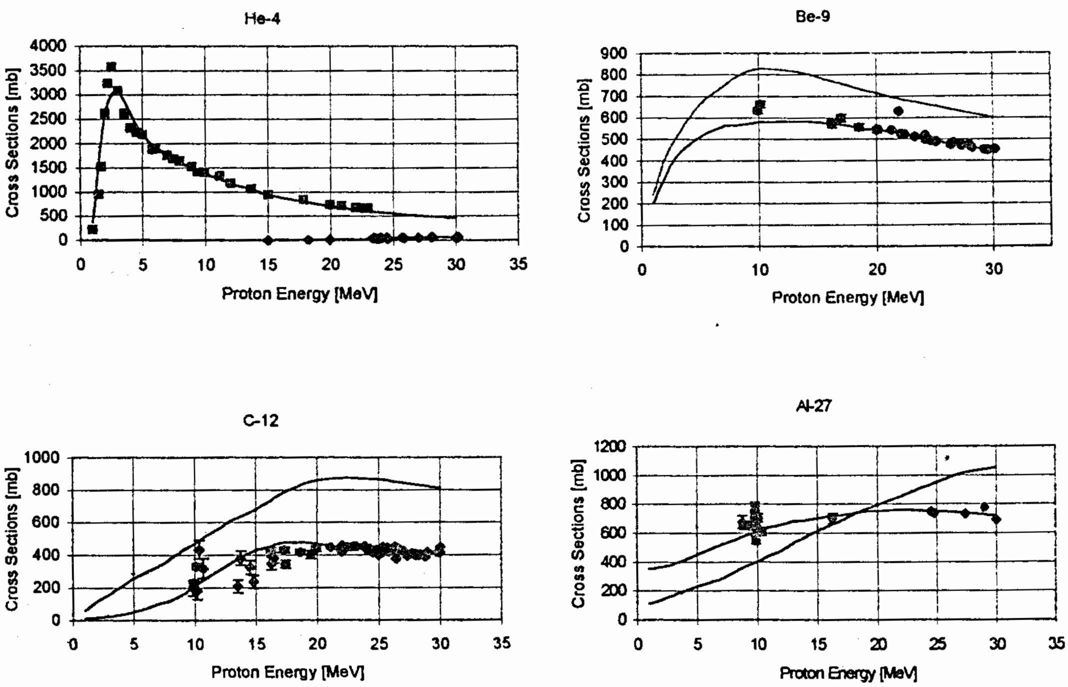

Fig. 2. Proton cross-sections. The upper and low curves are the calculated σ_{el} and σ_{nonel}. For light nuclei $\sigma_{el} > \sigma_{nonel}$, for medium elements σ_{nonel} grows up and becomes greater than σ_{el}. Experimental points from the compilation [2].

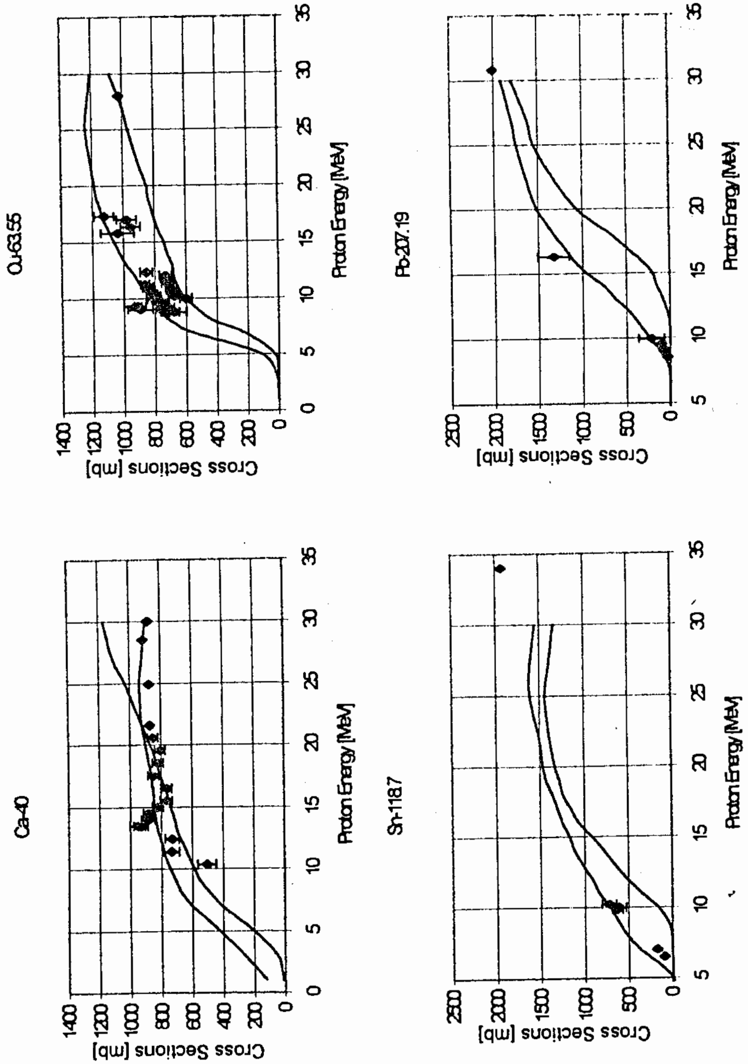

Fig. 3. Proton cross-sections σ_{el} *and* σ_{nonel}*. All details are as in Fig. 2.*

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