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GAMMA-RAY PRODUCTION DATA AND RELATED NUCLEAR STRUCTURE CALCULATIONS

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Abstract: Calculations of photon production cross sections and spectra, arising from neutron capture and inelastic scattering reactions, are performed for some structural materials in the incident neutron energy range 1.0 MeV < E_n < 20 MeV, of interest for applied purposes. The role played by nuclear structure effects is investigated as far as both discrete and continuum levels and relevant electromagnetic transitions are concerned. Properties of the giant dipole resonance are discussed as regards the validity of Brink-Axel hypothesis.

(neutron induced reactions, photon production cross sections and spectra, nuclear level density, giant dipole resonance, interacting boson model)

Introduction

Production cross sections and spectra of photons emitted in neutron-induced reactions are basic data for radiation shielding analysis and gamma-heating estimate in both fission and fusion reactors. Since experimental information over a broad incident-neutron energy range (in the MeV region) and for a large number of nuclides is not easily obtainable owing to the difficulties inherent in measurements of this kind, model calculations have to supply it.

Thus it is important to check the reliability of commonly-adopted models of nuclear reactions, namely Hauser-Feshbach statistical model[1] and, as for high-energy tails of emitted-particle and photon spectra, direct and preequilibrium models[2], in predicting gamma-ray production data. From a theoretical point of view, this investigation is of some interest in elucidating the mechanisms underlying nuclear reactions and de-excitation processes induced by MeV-neutrons. As an example, discrete gamma-rays emitted in (n,n'xγ)reactions provide unique signature of the final nucleus involved in the process and, consequently, information on the relevant tertiary-reaction cross section, which becomes important for E_n > 10 MeV in the A ≅ 50-60 mass region.

Moreover, correlation-type experiments in which neutron spectra are measured for the $^{A}X(n,n'\gamma)$ reaction represent the only available method for the experimental determination[3] of the mean radiation width of the unbound states in the ^{A-1}X nucleus, if unstable. Discrete gamma-ray production cross sections, $\sigma(n,x\gamma)$, for incident neutron energies below 20 MeV are of basic concern in nuclear geophysics[4]; unfortunately, a lot of measurements and evaluations still remains to be done, in order to create an appropriate data base for applied purposes.

Due to the importance of the above-mentioned applications, it deserves interest to investigate carefully some common hypotheses underlying many facets in photon-nucleus interaction at low energy (just up to the giant dipole resonance region, E_n < 20 MeV) and the relevant calculations.

In particular, three main sources of information on nuclear structure are required in both statistical and preequilibrium models[2] of photon emission at low energy : i) scheme of discrete levels and electromagnetic branching ratios between them ; ii) nuclear level densities versus excitation energy, angular momentum, parity and, as for preequilibrium rate emission, particle-hole or quasiparticle number ; iii) giant-resonance parameters since both statistical and preequilibrium models generally assume that the GR response of a nucleus to electromagnetic radiation and the gamma-ray strength function are related together by means of the following equation :

$$\frac{\langle \Gamma_\gamma(E) \rangle}{D_J} = \frac{1}{\pi^2 \lambda\!\!\!^{-2}} \cdot \frac{1}{(2\Lambda+1)} \langle \sigma^{\Lambda}_{\gamma\,abs}(E) \rangle, \quad (1)$$

where D_J is the spacing of radiating states with spin J, $\lambda\!\!\!^{-}$ is the absorbed-photon wavelength and $\sigma^{\Lambda}_{\gamma\,abs}$ the absorption cross section for an incident photon with multipolarity Λ. The Brink-Axel hypothesis then assumes that $\sigma_{\gamma abs}$ has the form of the photoabsorption cross section built on the ground-state, by associating an identical resonance behaviour to each excited nuclear state.

In the following two sections, we shall present some preliminary results of analyses carried out in order to check the influence of nuclear structure effects on photon production data and the approximate validity of Brink-Axel hypothesis for the giant dipole resonance (GDR).

Photon production cross sections

For many applications such as those previously mentioned, one is concerned with a number of cross section calculations over a broad range of excitation energies, involving several different nuclei as final products or intermediate steps in reaction channels. Therefore, in order to save computing time, one is forced to adopt simple closed-form expressions for level densities and avoid complete microscopic calculations which can be performed, for instance, within the shell-model plus BCS approximation framework[5]. Many semiempirical formulae have been proposed up to today; here, we follow the approach discussed in ref.[6] with only slight modifications. In particular, we have found that the following expressions :

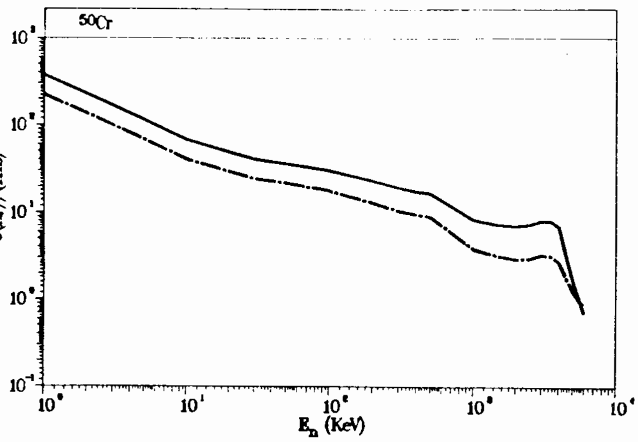
$$\rho(E,\pi,M) = \frac{\exp\left[2\sqrt{a(E-\Delta)}\,\right]}{12\sqrt{2}\,\sigma\, a^{1/4}(E-\Delta)^{5/4}}\exp(-M^2/(2\sigma^2))\times F_{par}(E,\pi)\ , \quad (2)$$

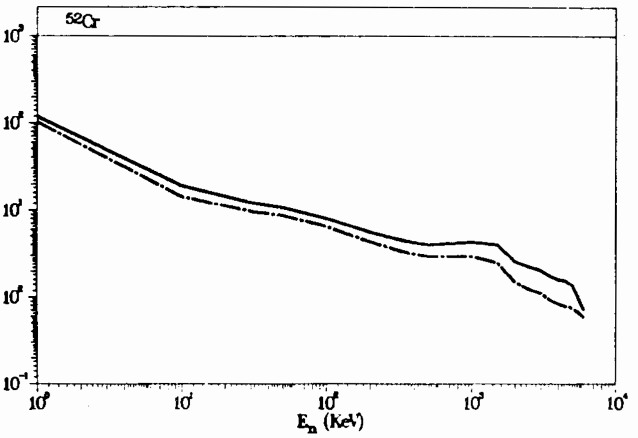
$$a(E) = \tilde{a}(1+e^{-\beta E})\ , \quad (3)$$

$$F_{par}(E,\pi) = \frac{1}{2}\mathrm{tgh}(\alpha E/2)\ , \quad (4)$$

with E excitation energy, M projection of the angular momentum on a given axis, π parity and σ spin cutoff factor, can reproduce satisfactorily all kind of experimental information such as cumulative numbers of levels of both parities at low energy, s- and p-wave average level spacings at the neutron binding energy, by means of four adjustable parameters, namely $\tilde{a}$, β, Δ and α. In particular, α is determined by requiring that eq. (4) reproduces the theoretical parity distribution of excited levels, estimated within a Nilsson plus BCS model[7]. Inclusion of parity effects in level density formalism has a great influence on statistical calculations of neutron capture cross sections[6], of the order of 30-50% over the whole energy range up to several MeV, and increases the average radiative widths, which are roughly proportional to the total neutron capture rate.

In figs. 1 and 2 for ^{50}Cr and ^{52}Cr, respectively, comparisons are shown between neutron capture cross sections calculated with level densities given by eqs.(2-4) or with usual Fermi-gas like formula, assuming equiprobability of the parity distribution. Moreover, we have performed some calculations of photon production cross sections and spectra in order to verify if the present approach to nuclear level densities is reliable and able to reproduce the experimental data. Thus we have considered neutron induced reactions on ^{56}Fe and used standard optical model and GR parameters for this mass region. The level density parameters (eqs.(2-4)) have been determined on the basis of experimental information and microscopic BCS calculations. Therefore, no more adjustable





Figs. 1 and 2. Neutron capture cross sections for ^{50}Cr (upper, fig.1) and ^{52}Cr (lower, fig.2), calculated by adopting for level densities eqs. (2-4) (solid lines) or usual Fermi-gas formalism.

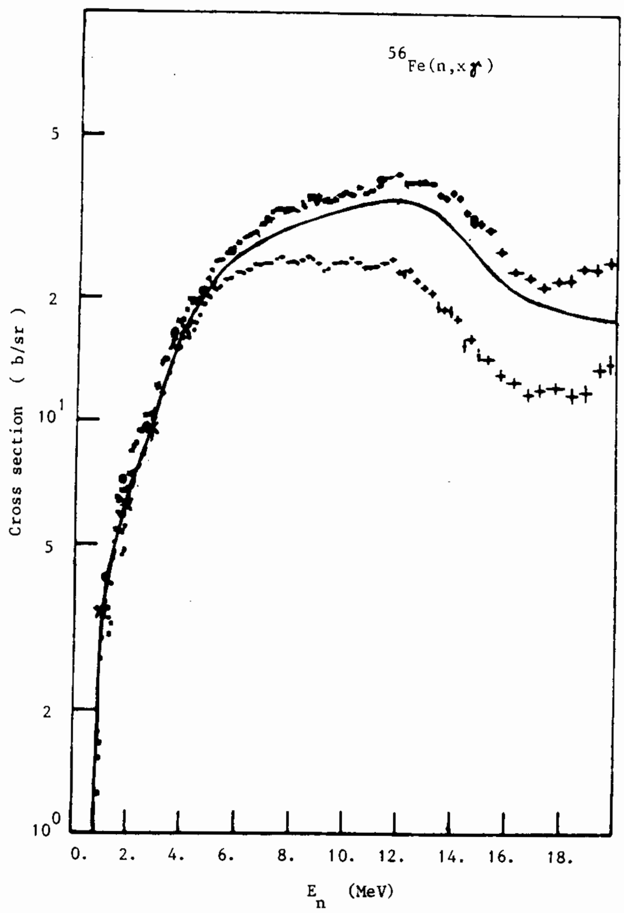


Fig. 3. Total photon production cross section for ^{56}Fe versus incident-neutron energy, at the scattering angle ϑ=125°. Experimental data are taken from ref.[10]; solid line : present calculations.

parameters are left free. Calculations have then been performed with a modified version of the PENELOPE code[8]. Neutron inelastic scattering, (n,2n), (n,p) and (n,α) cross sections, so obtained, compare well with the corresponding experimental data and will be presented in a forthcoming publication[9]. Figs. 3 and 4 show, respectively, the ^{56}Fe photon production cross section as a function of incident-neutron energy and the total gamma-ray spectrum, following 14.1 MeV neutron reactions.

As for fig.3, it has to be outlined that the difference between the two sets of measurements can be partly removed as due to an error in the flux measurement[10]; however, uncertainties on the absolute values of the cross section still remain and only the spectral shape (well reproduced by our calculations up to E_n = 18 MeV) is clearly determined. Moreover, it is worth noting that experimental data[10] refer to natural iron.

For a detailed analysis about the influence of discrete level schemes and related electromagnetic transitions on neutron capture cross sections and subsequent photon spectra, we refer to Koeling's paper[12], where a suitable model is presented and applied to ^{149}Sm. In this case low-lying collective states and e.m. transitions are taken from IBA[13] calculations, then dealt with a master equation technique to obtain gamma-ray spectra and multiplicity distribution. Owing to its feasibility, the IBA model is particularly suitable to calculate nuclear spectra and e.m. properties at low excitation energy, even for light-mass nuclei such as those in the s-d shell, by introducing further degrees of freedom (spin and isospin)[14]. Moreover, IBA calculations can supply to level density information ; recent IBA results for N=79 isotones are in remarkable agreement with experimental level densities for selected spin values up to ~5 MeV[15].

Giant dipole resonance and Brink-Axel hypothesis

Recently, the IBA model has been extended to the description of giant resonances too, by introducing suitable boson excitations in the model Hamiltonian (see ref.[16] and papers quoted therein for a review of the formalism and its applications). Therefore, it would be interesting to perform the analysis of ref.[12] again by including IBA calculations for the GDR, in addition to those for the low-lying spectrum.

Figs. 5 and 6 show IBA calculations of total photoabsorption cross sections in the GDR energy region, performed for ^{148}Sm and ^{154}Sm, respectively. The former nucleus has a spherical equilibrium shape, while the latter is an axially-symmetric rotor with the characteristic two-peaked photoabsorption cross section. The GDR built on the 0^+_1 ground-state is compared for both isotopes with the experimental data obtained by the Saclay group ; moreover, theoretical IBA results are shown with GDRs built on excited 0^+_n states. Essentially, the mean resonance energies and

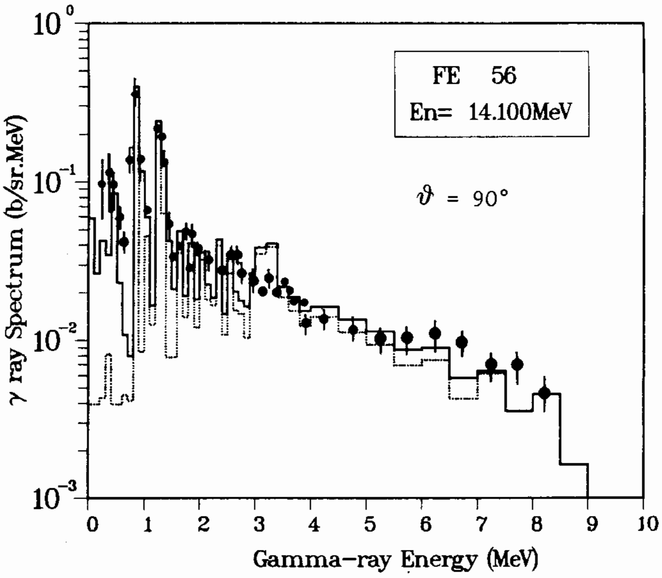


Fig. 4. Total gamma-ray spectrum of ^{56}Fe; solid line: present calculation; dashed line: (n,n'γ) contribution; • experimental data from ref.[11].

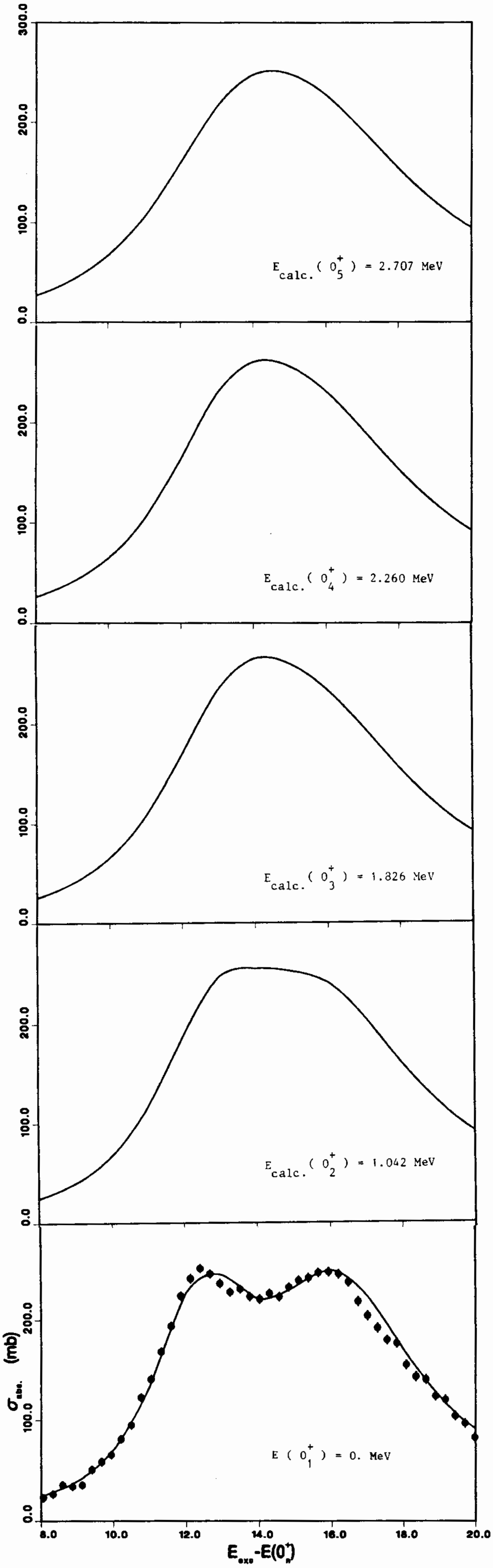
strengths are not much affected by temperature effects, even if the ^{154}Sm double-humped structure is washed out due to the increased spreading width associated with each GDR state according to the following semiempirical power law :

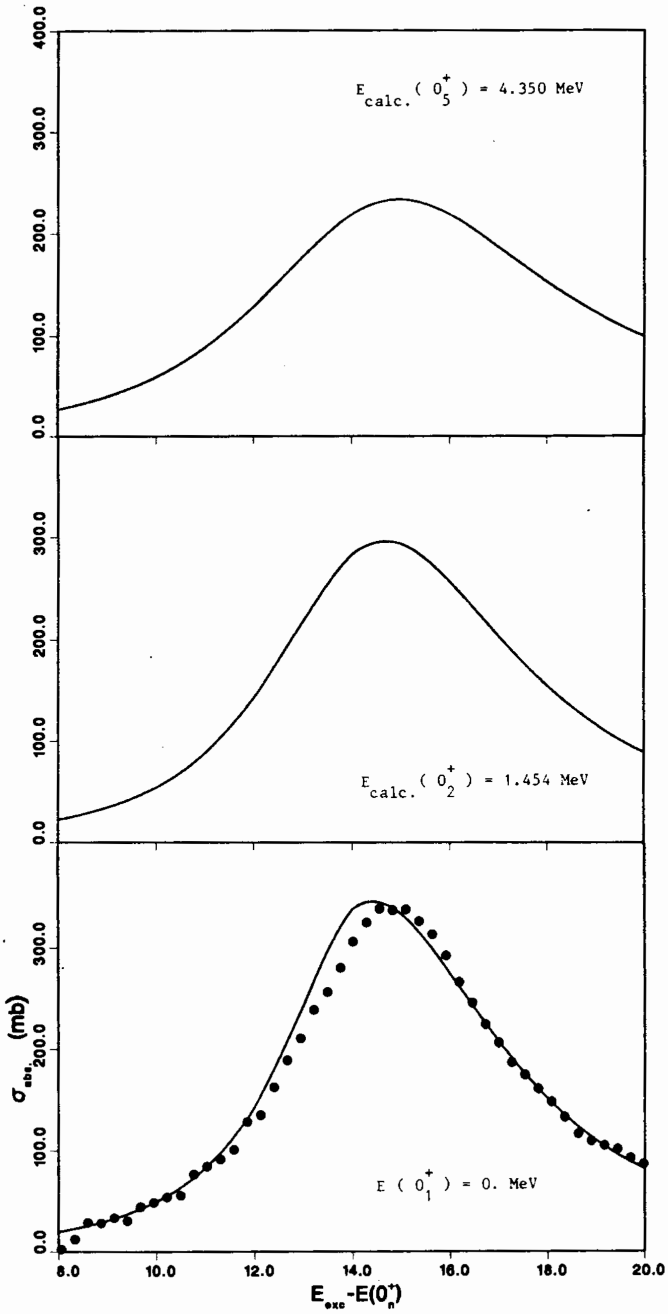
$$\Gamma(E) = k\,E^{c} \quad , \qquad (5)$$

with k = 0.035 MeV^{1-c} and c = 1.8. The IBA model is not suitable for evaluating the spreading widths, which depend on the coupling between GDR states and low-energy n particle-n hole configurations with n=2,3,... The results shown in figs. 5 and 6 seem to support the validity of Brink-Axel assumption, at least in the low-energy part of the GDR region. An analogous conclusion has been drawn by a recent analysis of isoscalar giant resonances at temperatures up to 8 MeV, based on a semiclassical Thomas-Fermi approach to RPA moments[17]. According to the authors of ref.[17], this result is still valid for the GDR.

Furthermore, experimental studies[18] of the statistical decay of GDR components built on excited nuclear levels at temperatures around 1-2 MeV and spins J ≅ 10-25 ħ suggest that mean resonance energies and strengths change smoothly compared to the properties of the ground-state GDR.

On the other hand, a phenomenological analysis of photon strength functions deduced from (n,γ) measurements[19] show that the apparent failure of Brink-Axel hypothesis for E1 transitions can be obviated by means of a proper introduction of energy-dependent spreading widths, just like in IBA calculations (see eq.(5)). However, experimental deviations of the E1 strengths below the particle-emission threshold from the simple GDR model must be handled with great care : Montecarlo calculations, quoted in ref.[20], show a pronounced structure of the photoabsorption cross section and, in some cases, an increase with decreasing





Figs. 5 and 6. Total photoabsorption cross sections from the ground states and 0^+_n excited levels of ^{148}Sm (above, fig.5) and ^{154}Sm (on the left, fig.6), respectively. Solid lines refer to IBA calculations described in the text.

energy, according to the adopted averaging procedure even if the extrapolated ground-state GDR Lorentzian is associated, as usual, with each level.

Therefore, further studies are demanded in order to elucidate this problem and, possibly, to develop alternative well-grounded approaches. We mention, for instance, the formula for the gamma-ray strength function proposed in ref.[21] which fulfils the dispersion properties of the dipole polarization operator, but the usual Brink-Axel formula does not.

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