ISTITUTO NAZIONALE DI FISICA NUCLEARE
Laboratori Nazionali di Frascati

LNF-78/34(R)
28 Luglio 1978

R. Caloi, L. Casano, L. Federici, S. Frullani, G. Giordano, G. Matone, M. Mattioli, G. Pasquariello, P. Picozza, D. Prosperi, P. Pelfer and C. Schaerf: RESONANT NUCLEAR SCATTERING OF $\gamma$-RAYS AS A TOOL TO INVESTIGATE THE LADON BEAM CHARACTERISTICS.

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R. Caloi[(x)], L. Casano[(x)], L. Federici, S. Frullani[(o)], G. Giordano, G. Matone, M. Mattioli[(x)], G. Pasquariello, P. Picozza, D. Prosperi[(+)], P. Pelfer[(+)] and C. Schaerf[(x)] : RESONANT NUCLEAR SCATTERING OF $\gamma$-RAYS AS A TOOL TO INVESTIGATE THE LADON BEAM CHARACTERISTICS.

## 1. - INTRODUCTION.

The characteristics of the LADON monochromatic and polarized photon beam[(1)] can be easily explored in the low energy region by resonant scattering experiments on single nuclear levels.

According to this, we will discuss in details how the 15.11 MeV ($1^+$) level in $^{12}C$ could be a good candidate for an accurate determination of the beam energy spread together with its polarization degree.

Typical counting rates and running time are deduced for a good significance of the suggested measurement.

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## 2. - CROSS SECTIONS AND COUNTING RATES.

As shown in Fig. 1, the scattered photons are supposed to be determined at an angle $\theta$ with respect to the direction of the incident pho

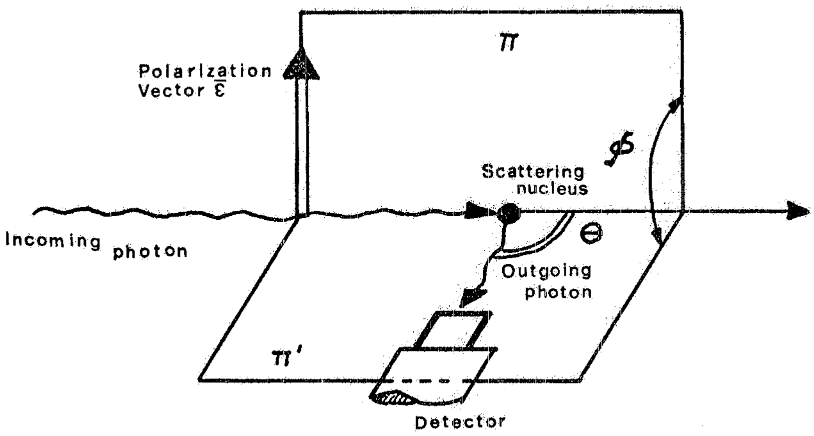


FIG. 1 - Sketch of a typical experiment employing a single $\gamma$-ray detector.

tons. Moreover, let be $\phi$ the angle between the scattering plane ($\pi'$) and the plane ($\pi$) containing both the flight direction of the incident photon and its polarization vector $\bar{\varepsilon}$. For dipole scattering on even-even nuclei, the resonant scattering differential cross section is dominated by the scalar contribution(2) and can be written as :

$$\frac{d\sigma_{rs}(\theta,\varphi)}{d\Omega} = \sigma_{rs}(E - E_r)\, g(\theta, \varphi) \quad , \tag{1}$$

where $\int g(\theta,\varphi)\, d\Omega = 1$. Therefore, in a single detector experiment, the counting rate of the scattered photons is given approximatively as follows :

$$I^{rs}(X, \theta, \varphi, \Delta\Omega) = \varepsilon_\gamma n_r \phi_\gamma \int_{\Delta\Omega} g(\theta, \varphi)\, d\Omega \int_0^\infty dE\, f(E - E_o) \cdot \cdot \int_0^X dx \left\{ e^{-n_r x \left[\sigma_{ra}(E) + \sigma_{aa}(E)\right]} \sigma_{rs}(E) \right\} , \tag{2}$$

where :

$\phi_\gamma$ = total $\gamma$-ray flux in photons/sec ;

$\varepsilon_\gamma$ = detector efficiency ;

$n_r$ = number of nuclei/cm$^3$ ($= \mathcal{N}\varrho/A$) ;

$\mathcal{A}$ = Avogadro number ;

$\varrho$ = monoisotopic target density ;

A = mass number ;

X = target thickness ;

$\Delta\Omega$ = detection solid angle ;

$\sigma_{ra}(E)$, $\sigma_{rs}(E)$ = resonant absorption and scattering cross section ;

$\sigma_{aa}(E)$ = atomic absorption cross section.

Moreover $E_o$ indicates the averaged value of the beam energy distribution and $f(E - E_o)$ is its spectral function normalized to the unity:

$$\int_0^\infty dE\, f(E - E_o) = 1 \, .$$

As shown in Appendix A, non resonant scattering processes can be neglected since they introduce only small and irrelevant corrections.

For the resonant scattering and resonant absorption cross sections we assume the usual Lorentz expressions ($J_o = 0$, $J_r = 1$; $\hbar = c = 1$) :

$$\sigma_{rs}(E) = 6\pi \left(\frac{E}{E_r}\right)^4 \frac{\Gamma_{\gamma o}^2}{(E^2 - E_r^2)^2 + \Gamma^2 E^2} \, , \qquad (3)$$

$$\sigma_{ra}(E) = \sigma_{rs} \left(\frac{\Gamma}{\Gamma_{\gamma o}}\right) \left(\frac{E_r}{E}\right)^2 \, , \qquad (4)$$

where $E_r$ is the resonant energy, $\Gamma$ is the total width of the resonant state and $\Gamma_{\gamma o}$ is its partial width for radiative decay to the ground state.

For the 15.11 MeV level of $^{12}C$, $\Gamma = 69$ eV and $\Gamma_{\gamma o} = 54$ eV, and consequently, the range where expression (3) is essentially different from zero

$$(E_r - \frac{\Gamma}{2}) \leq E \leq E_r + \frac{\Gamma}{2} \qquad (5)$$

turns out to be much narrower of the expected energy resolution of the LADON beam at 15 MeV ($\sim$100 keV). Thus the beam spectral function and the atomic cross section $\sigma_{aa}(E)$ can be considered to be practically constant in the energy range (5) and expression (2) can be simplified as follows :

$$I^{rs}(X, \theta, \varphi, \Delta\Omega) \simeq \varepsilon_\gamma n_r \phi_\gamma \int_{\Delta\Omega} g(\theta, \varphi)\, d\Omega \;\; f(E_r - E_o) \; \cdot$$
$$\cdot \int_0^X dx\, e^{-n_r \sigma_{aa}(E_r)\, x} \int_0^\infty dE \left[ e^{-n_r \sigma_{ra}(E)\, x} \; \sigma_{rs}(E) \right] \; . \qquad (6)$$

The thin target approximation, defined by the two conditions :

$$n_r X \sigma_{aa}(E_r) \ll 1 \qquad\qquad \sigma_{aa}(E_r) = 0.34 \text{ barn}$$
$$\text{with :} \qquad \sigma_{ra}(E_r) \simeq 25 \text{ barn}$$
$$n_r X \sigma_{ra}(E_r) \ll 1 \qquad\qquad n_r = 0.75 \times 10^{23} \text{ at/cm}^3$$

gives for the upper limit of the target thickness, the value $X \ll 0.5$ cm. Under this condition we can drop both exponentials in eq. (6) and by putting

$$\int_0^\infty dE\, \sigma_{rs}(E) \simeq \int_{-\infty}^{+\infty} dE\, \sigma_{rs}(E) \simeq 3\pi^2 \left(\frac{\Gamma^2_{\gamma o}}{\Gamma}\right) \frac{1}{E_r^2} \qquad (7)$$

we finally obtain :

$$I^{rs}(X, \theta, \varphi, \Delta\Omega) \simeq \varepsilon_\gamma \; n_r X \phi_\gamma \;\; g(\theta, \varphi)\, \Delta\Omega \;\; f(E_r - E_o) \frac{3\pi^2}{E_r^2} \frac{\Gamma^2_{\gamma o}}{\Gamma} \; . \qquad (8)$$

A more precise calculation including the target absorption effect is reported in Appendix B.

In conclusion, by means of a precise energy scan, eq. (8) enables to obtain a good determination of the beam energy distribution $f(E_r - E_o)$.

## 3. - DETERMINATION OF THE BEAM ENERGY DISTRIBUTION.

The angular distribution function $g(\theta, \varphi)$ is obtained by standard theoretical methods. In particular for $M_1$ transitions it can be obtained from that for $E_1$ transitions(2) by the substitution $\varphi \rightarrow \pi/2 - \varphi$.

For fully polarized photons, one has :

$$\frac{d\sigma_{rs}}{d\Omega}(\theta, 0) = \frac{d\sigma''(\theta)}{d\Omega} = \sigma_{rs}\, g''(\theta) \; , \qquad\qquad g''(\theta) = \frac{3}{8\pi} \; , \qquad (9)$$

$$\frac{d\sigma_{rs}}{d\Omega}(\theta, \frac{\pi}{2}) = \frac{d\sigma^{\perp}(\theta)}{d\Omega} = \sigma_{rs}\, g^{\perp}(\theta) \quad , \qquad g^{\perp}(\theta) = \frac{3}{8\pi}\cos^2\theta \quad , \tag{9}$$

whereas for unpolarized photons one obtains:

$$\left[\frac{d\sigma_{rs}}{d\Omega}\right]_{unp} = \frac{1}{2}\left[\frac{d\sigma''(\theta)}{d\Omega} + \frac{d\sigma^{\perp}(\theta)}{d\Omega}\right] = \sigma_{rs}(E - E_r)\,\bar{g}(\theta) \quad ,$$

being:

$$\bar{g}(\theta) = \frac{1}{2}\left[g''(\theta) + g^{\perp}(\theta)\right] = \frac{3}{16\pi}(1 + \cos^2\theta) \quad . \tag{10}$$

A preliminary estimate of the beam energy distribution of $(E_r - E_o)$ can be obtained by a previously developed Monte Carlo program[3] and is reported in Figs. 2a and 2b for two different experimental set-up.

Let us consider the first case where the electron ring is operated in its actual mode and the "Quadrupole-out" configuration is adopted (see reference (3) for details). We also assume the beam characteristics to be determined by a collimator of 8 mm radius placed at 50 meters from the center of the straigth section of the electron machine (ADONE). By operating at an electron energy of 630 MeV, we have[3]:

$$E_o = 15.11 \text{ MeV} \quad , \qquad \phi_\gamma = 2.9 \times 10^6 \ \gamma/s \quad ,$$

$$R = \frac{\Delta E_\gamma}{E_\gamma} = 1.9\,\% \quad , \qquad f(0) = 4.2 \text{ MeV}^{-1} \ .$$

By assuming:

$$\varepsilon_\gamma \simeq 80\,\% \quad , \qquad \Delta\Omega \sim 10^{-1} \text{ ster} \quad , \qquad \phi_\gamma X \sim 10^6 \ \gamma\, cm/s \quad ,$$

we obtain for unpolarized photons and at the maximum overlap condition $(E_o = E_r)$:

$$I^{rs} \sim 3.2 \ \gamma/s \ (\theta = 90^o) \ ; \qquad 4.8 \ \gamma/s \ (\theta = 135^o) \quad ,$$

that is a quite resonable prevision. A typical experiment allowing for a good determination of the shape $f(E - E_o)$ around 15.11 MeV could require effective running times of the order of a few hours.

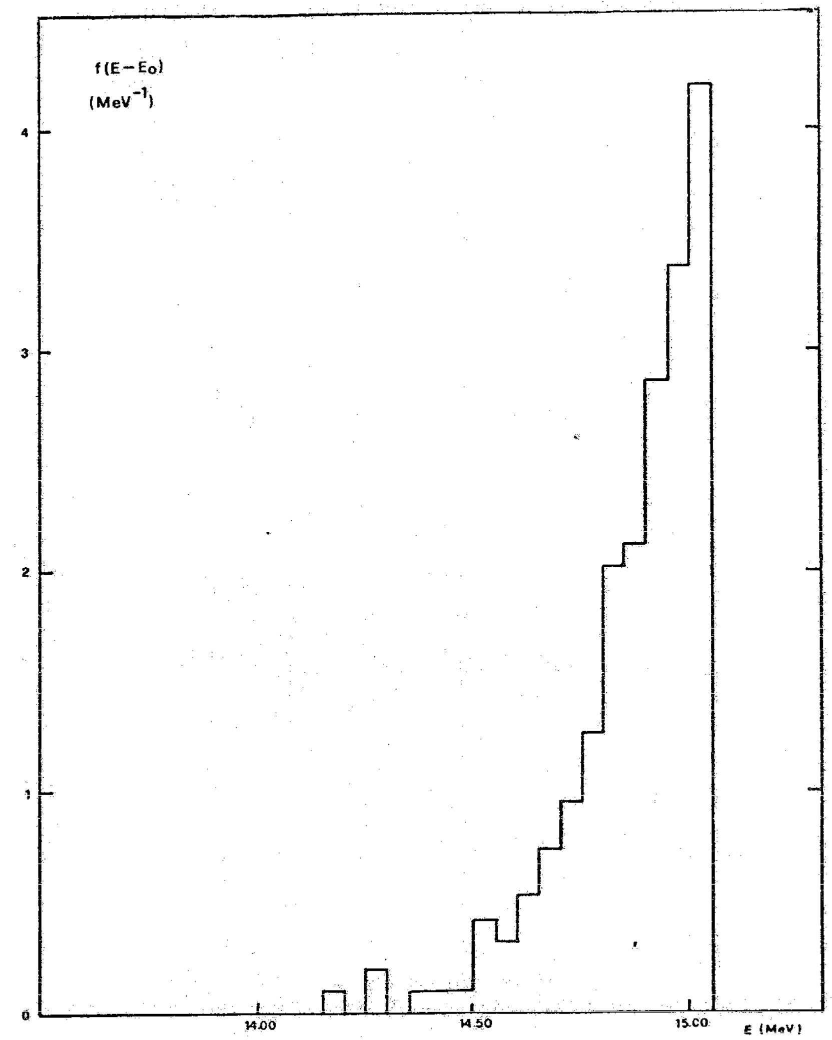


FIG. 2a - Beam energy distribution for $E_o$ = 15.11 MeV. Collimator distance = 50 m; collimator radius = 8.0 mm; $E_{ADONE}$ = 630 MeV; energy resolution = 1.9 %; photon intensity = 2.9 x $10^6$ $\gamma$/s.

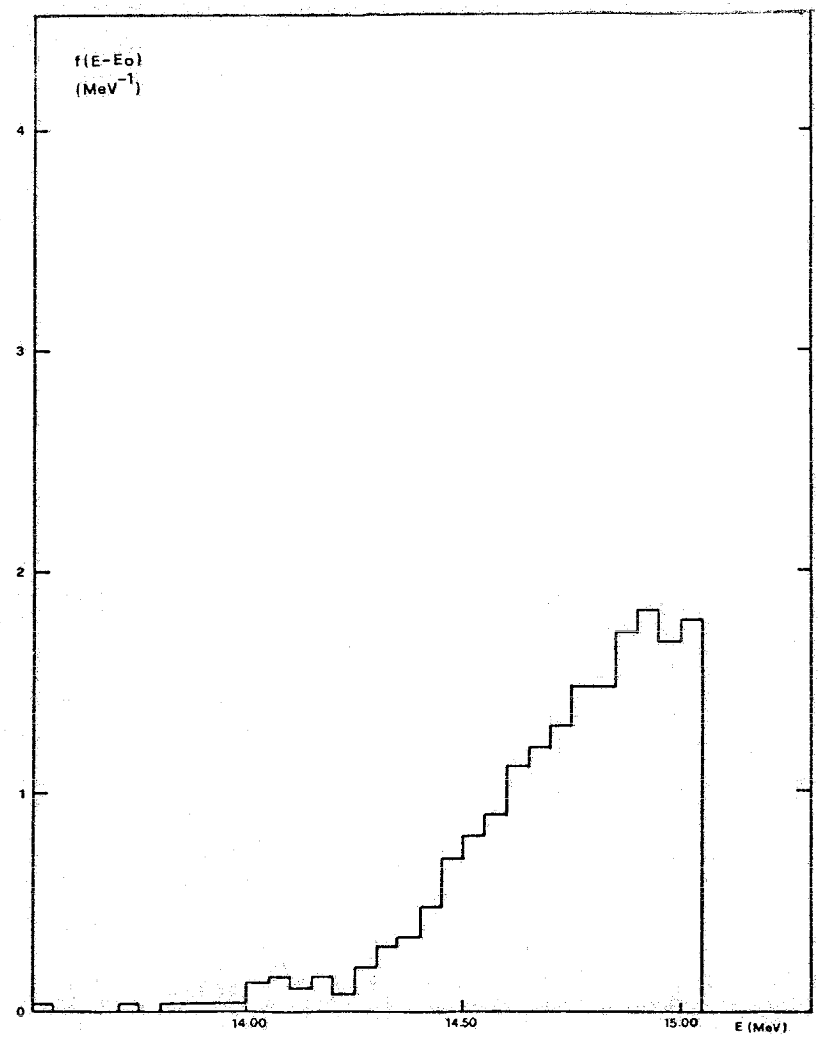


FIG. 2b - Beam energy distribution for $E_o$ = 15.11 MeV. Collimator distance = 50 m; collimator radius = 15 mm; $E_{ADONE}$ = 630 MeV; energy resolution = 2.8 %; photon intensity = 5.3 x $10^6$ $\gamma$/s.

## 4. - DETERMINATION OF THE BEAM POLARIZATION.

Let us indicate by $I''(\theta)$ and $I^{\perp}(\theta)$ the scattered photon intensities for $\varphi = 0$ and $\varphi = \pi/2$ respectively. In the case of fully polarized photons ($P = 1$), they can be put in the form (see eqs. 8, 9):

$$I''(\theta) = K \quad , \qquad I^{\perp}(\theta) = K\cos^2\theta \quad , \tag{11}$$

being

$$K = \varepsilon_\gamma (\frac{\mathcal{A}}{A}\, \varrho\, X\, \phi_\gamma)\, f(E_r - E_o)\, \frac{9\pi}{8} (\frac{\Gamma^2_{\gamma o}}{\Gamma})\, E_r^{-2} \Delta\Omega \quad .$$

Moreover, for partially polarized photons we can write :

$$\begin{aligned} I''(\theta) &= K\left[(1 - P)\cos^2\theta + P\right] , \\ I^{\perp}(\theta) &= K\left[P\cos^2\theta + (1 - P)\right] , \end{aligned} \tag{12}$$

where $P$ is the amplitude of the photon polarization vector in the plane $_{ro}$ (see Fig. 1).

An accurate evaluation of the beam polarization parameter P can be obtained with a good experimental determination of the asymmetry parameter $\mathcal{J}(\theta)$ usually defined as :

$$\mathcal{J}(\theta) = \frac{I'' - I^{\perp}}{I'' + I^{\perp}} = (2P - 1)\, \frac{\mathrm{sen}^2\theta}{1 + \cos^2\theta} \quad . \tag{13}$$

The accuracy level one can reach in such a determination is given by the formula :

$$\frac{\Delta P}{P} = \frac{1}{2} (\frac{N'' N^{\perp}}{N'' + N^{\perp}})^{1/2} \frac{1 + \cos^2\theta}{N'' - N^{\perp}\cos^2\theta} \quad , \tag{14}$$

where $N''(\theta)$ and $N^{\perp}(\theta)$ are the total photon countings in two configuration $\varphi = 0, \pi/2$ .

Expression (14) can be reformulated to give the required running time at fixed $(\Delta P/P)$ :

$$t = (\frac{\Delta P}{P})^{-2} \frac{1}{4} \left[\frac{1 + \cos^2\theta}{I'' - I^{\perp}\cos^2\theta}\right]^2 \frac{I'' I^{\perp}}{I'' + I^{\perp}} \quad . \tag{15}$$

The maximum sensitivity is achieved for $\theta = \pi/2$ where[3] :

$$I^{\perp} = 0.05 \text{ phot./sec} \qquad \text{if } P \simeq 0.98 .$$
$$I^{\parallel} = 2.3 \text{ phot./sec}$$

Consequently from (15) the running time needed to obtain $\frac{\Delta P}{P} = 5 \times 10^{-3}$ is 90".

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APPENDIX A

Let us now examine the corrections due to non resonant scattering processes. The physical non resonant processes, we are interested in, are:

1) Thomson and Rayleigh nuclear scattering;
2) Compton scattering on atomic electrons ;
3) Dellbrück scattering.

Both atomic and Dellbrück scattering can be neglected in the backward hemisphere, so we assume $\theta \geq 90^{o}$. Moreover, at energies of the order of 15 MeV, Rayleigh nuclear scattering cannot be neglected with respect to the Thomson one.

By standard methods we obtain:

$$\frac{d\sigma^{\parallel}}{d\Omega} = \left[P\cos^2\theta + (1-P)\right]\left|A_{E_1}\right|^2 + \left[P + (1-P)\cos^2\theta\right]\left|A_{M_1}\right|^2 + + 2\cos\theta \, \mathrm{Re}(A_{E_1} A_{M_1}) , \qquad (A1)$$

$$\frac{d\sigma^{\perp}}{d\Omega} = \left[P + (1-P)\cos^2\theta\right]\left|A_{E_1}\right|^2 + \left[P\cos^2\theta + (1-P)\right]\left|A_{M_1}\right|^2 + $$

$$+ 2\cos\theta\, \mathrm{Re}(A_{E_1} A_{M_1}) \, , \qquad \text{(A2)}$$

where $A_{E1}$ is the electric dipole scattering amplitude (Thomson + Rayleigh effect), $A_{M1}$ is the magnetic dipole amplitude (nuclear resonant scattering). Moreover, for unpolarized photons we obtain :

$$\left(\frac{d\sigma}{d\Omega}\right)_{unp} = \frac{1}{2}(1+\cos^2\theta)\left[\left|A_{E_1}\right|^2 + \left|A_{M_1}\right|^2\right] + 2\cos\theta\,\mathrm{Re}(A_{E_1} A_{M_1}) \, . \qquad \text{(A 3)}$$

In our example we can put :

$$A_{E_1} = A_{Th} + A_{Ray} = -\frac{(Ze)^2}{M_t} + E^2\bar{\alpha} \, ,$$

$$A_{M_1} \simeq \frac{3}{2}\, \frac{\Gamma_{\gamma o}}{(E_r^2 - E^2) - i\Gamma E} \, , \qquad \text{(A4)}$$

where $\bar{\alpha}$ is the nuclear electric polarizability wich, for light nuclei, is approximatively given by the expression $\bar{\alpha} = 0.0143 \times A^{4/3}\ \mathrm{fm}^3$.

In the thin target approximation the non resonant scattering counting rate for unpolarized photons can be written (see eq. (8)) :

$$I^{nr}(X, \theta, \varphi, \Delta\Omega) \simeq \varepsilon_\gamma (n_r X \phi_\gamma)\frac{1}{2}(1+\cos^2\theta)\left[\frac{(Ze)^2}{M_t} - E_o^2\bar{\alpha}\right]^2 \, , \qquad \text{(A5)}$$

resulting pratically energy-independent. At the maximum overlap condition ($E_o = E_r$) we have $I^{nr}/I^{rs} \simeq 10^{-4}$.

Finally, for the interference term we have :

$$I^{int}(X, \theta, \varphi, \Delta\Omega) \simeq 3\varepsilon_\gamma (n_r X \phi_\gamma)\cos\theta\, \Gamma_{\gamma o}\Delta\Omega \, \cdot$$

$$\cdot \int_0^\infty dE\, f(E - E_o)\left\{-\frac{(ze)^2}{M_t} + E^2\bar{\alpha}\right\}\frac{E_2^2 - E^2}{(E_2^2 - E^2)^2 + \Gamma E^2} \qquad \text{(A 6)}$$

wich vanishes for $\theta = \pi/2$.

APPENDIX B.

Let us consider the integral

$$\mathcal{J} = n_r \int_0^X dx\, e^{-n_r \sigma_{aa}(E_r)x} \int_0^\infty dE \left[ e^{-n_r \sigma_{ra}(E)x} \sigma_{rs}(E) \right], \tag{B1}$$

appearing in eq. (6). By a standard Taylor expansion of the exponentials containing $\sigma_{ra}(E)$, it can be put in the form:

$$\mathcal{J} = n_r \sum_{\nu\, 0}^{\infty} \int_0^X dx\, e^{-n_r \sigma_{aa}(E_r)x} x^\nu \left[ \frac{(-1)^\nu}{\nu!} n_r^\nu \left(\frac{\Gamma}{\Gamma_{\gamma o}}\right)^\nu \right] \cdot \int_0^\infty dE \left[\sigma_{rs}(E)\right]^{\nu+1} \left(\frac{E_r}{E}\right)^{2\nu} . \tag{B2}$$

By using the Breit-Wigner form of $\sigma_{rs}(E)$ :

$$\sigma_{rs}(E) = \frac{3\pi}{2} \left(\frac{\hbar c}{E_r^2}\right)^2 \frac{\Gamma_{\gamma o}^2}{(E - E_r)^2 + \Gamma^2/4} , \tag{B3}$$

valid for $E \sim E_r$, we immediately put eq. (B2) in the form:

$$\mathcal{J} = \sum_{\nu\, 0}^{\infty} A_\nu B_\nu \frac{X^{\nu+1}}{\nu+1} \frac{\Gamma_{\gamma o}}{2} \left[ \frac{(-1)^\nu}{\nu!} (n_r \sigma_o)^{\nu+1} \left(\frac{\Gamma}{\Gamma_{\gamma o}}\right)^{\nu+1} \right] , \tag{B4}$$

where

$$\sigma_o = 6\pi \left(\frac{\hbar c}{E_r}\right)^2 \left(\frac{\Gamma_{\gamma o}}{\Gamma}\right)^2 ,$$

$$A_\nu = \left(\frac{\nu+1}{X^{\nu+1}}\right) \left(\frac{1}{n_r \sigma_{aa}}\right)^{\nu+1} \int_0^Y y^\nu e^{-y} dy \tag{B5}$$

$$B_\nu = \int_{-\infty}^{+\infty} dz \frac{1}{(1+z^2)^{\nu+1}} ,$$

and $y = n_r \sigma_{aa}(E_r)x$ , $Y = n_r \sigma_{aa}(E_r)X$ , $z = 2(E - E_r)/\Gamma$. Let us note that the factors $A_\nu$ determine atomic absorption corrections, while the factors $B\ /B_o$ $(\nu \neq 0)$ give resonant absorption corrections.

By standard methods one obtains :

$$A_\nu = \left(\frac{\nu+1}{X^{\nu+1}}\right)\left(\frac{1}{n_r \sigma_{aa}}\right)^{\nu+1} \left| e^{-y} \sum_{r=0}^{\nu} (-1)^r \frac{\nu!\, y^{\nu-r}}{(\nu-r)!\,(-1)^{r+1}} \right|_0^Y , \qquad \text{(B6)}$$

so that

$$A_o = \frac{1}{Y}\left[1 - e^{-Y}\right] \sim 1 - \frac{1}{2}Y + \frac{1}{6}Y^2 \ldots ,$$

$$A_1 = \frac{2}{2}\left[1 - e^{-Y}(1+Y)\right] \sim 1 - \frac{2}{3}Y + \frac{1}{4}Y^2 \ldots , \qquad \text{(B7)}$$

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We also have :

$$B_\nu = \frac{\Gamma(\frac{1}{2})\,\Gamma(\nu+\frac{1}{2})}{\Gamma(\nu+1)} = \frac{\pi(2\nu-1)!!}{2^\nu \cdot \nu!} \qquad \text{(B8)}$$

or more explicitly :

$$B_o = \pi , \quad B_1 = \pi/2 , \quad B_2 = 3\pi/8 , \ \ldots \qquad \text{(B9)}$$

Finally, when $n_r \sigma_{ra}(E_o)X \ll 1$ one can neglect atomic absorption corrections, so that :

$$\mathcal{J} \simeq \frac{\pi}{2} n_r \sigma_o X\, \Gamma\left[1 - \frac{1}{4}\frac{\Gamma}{\Gamma_{\gamma o}} n_r \sigma_o X + \frac{1}{16}\left(\frac{\Gamma}{\Gamma_{\gamma o}}\right)^2 (n_r \sigma_o X)^2 - \frac{5}{384}\left(\frac{\Gamma}{\Gamma_{\gamma o}}\right)^3 (n_r \sigma_o X)^3 + \ldots\right] . \qquad \text{(B10)}$$

In our case we have $(n_r \sigma_o X)(\Gamma/\Gamma_{\gamma o}) \sim 1.2$ and the total "tickness correction" is a factor 0.77 when X = 1 cm.

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