

## MOLECULAR EFFECTS ON THE CROSS SECTION FOR PAIR PRODUCTION AND THEIR IMPORTANCE IN THE EVALUATION OF THE TOTAL PHOTONUCLEAR CROSS SECTION OF $^{16}\text{O}$ IN THE $\Delta$ -RESONANCE REGION\*

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**Abstract:** The screening correction to the coherent pair-production cross section on the oxygen molecule has been calculated using self-consistent relativistic wave functions for the one-center and two-center Coulomb potentials. It is shown that the modification of the wave function due to molecular binding and the interference between contributions from the two atoms have both sizeable effects on the screening correction. The so-obtained coherent pair-production cross section which makes up the largest part of the total atomic cross section was used to evaluate the total nuclear absorption cross section from photon attenuation measurements on liquid oxygen. The result agrees with cross sections for other nuclei if  $A$ -scaling is assumed. The molecular effect on the pair cross section amounts to 15% of the nuclear cross section in the  $\Delta$ -resonance region.

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NUCLEAR REACTIONS  $^{16}\text{O}(\gamma, X)$ ,  $E = 90\text{--}400$  MeV; measured total absorption  $\sigma$ , calculated pair-production  $\sigma(\text{pp})$  on the oxygen molecule.

### 1. Introduction

An important nuclear physics issue is the question whether the intrinsic properties of free nucleons change in nuclei. One such property is the strong isovector M1 transition connecting the nucleon with the  $\Delta(1232)$ . Valuable tools for studying this transition are provided by the absorption and scattering of real photons. The total photon absorption cross section<sup>1</sup>),  $\sigma_{\gamma T}$ , is determined either (i) by measuring the

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total attenuation cross section,  $\sigma_{\text{tot}}$ , and subtracting the calculated atomic absorption cross section <sup>2,3</sup>),  $\sigma_{\text{a}}$ , or (ii) by measuring nuclear partial cross sections and extrapolating towards the total nuclear absorption cross section <sup>4,5</sup>). Existing data from both methods appear to suggest that in the  $\Delta$ -region the total cross section per nucleon  $\sigma_{\gamma\text{T}}/A$  deviates strongly from the free-proton value but is not significantly dependent on the mass number  $A$  of the nucleus. This observation, if verified in general and with high accuracy, certainly is of fundamental importance for our understanding of the interaction of the  $\Delta$ -resonance with nuclear matter. Therefore, any indication for a deviation from the presumed independence of  $\sigma_{\gamma\text{T}}/A$  of the mass number  $A$  should be carefully investigated.

Total attenuation cross section (method *i*) were measured on water and liquid oxygen. The data were analyzed by subtracting the atomic cross section,  $\sigma_{\text{a}}$ , calculated for free atoms. The so obtained result for  $\sigma_{\gamma\text{T}}$  deviated significantly from the cross section expected from  $A$ -scaling (up to 30% for water, 15% for liquid oxygen).

It was suspected <sup>6</sup>) that this deviation was due to molecular binding effects in the pair-production cross section,  $\sigma_{\text{pp}}$ . In the energy region of the  $\Delta$ -resonance the atomic cross section is dominated by the pair-production cross section. Since the nuclear absorption cross section is small compared with the atomic ( $\sigma_{\gamma\text{T}} < 1\% \sigma_{\text{a}}$ ) small uncertainties in  $\sigma_{\text{pp}}$  have significant influence on the derivation of  $\sigma_{\gamma\text{T}}$ .

In vacuum a photon cannot convert into an electron-positron pair because of energy and momentum conservation. In a Coulomb field of a nucleus, however, the momentum mismatch can be cured by a momentum transfer to the nucleus. The pair-production cross section in the Coulomb field of a bare nucleus tends to infinity for increasing photon energy. In reality the Coulomb field is screened by the atomic electron cloud. This leads to a finite pair-production cross section at infinite photon energies. The higher the photon energy the smaller the momentum mismatch. Therefore, the cross section gets increasingly sensitive to small momentum transfers to the atom. Consequently an increasing part of the atomic volume becomes available for the pair-production process and the outer part of the electron cloud becomes important for the pair-production cross section.

Normally, the pair-production cross section is calculated in Born approximation and under the assumption of a point-like bare nucleus. This cross section is then modified by various corrections: Coulomb correction, radiative correction and screening correction. The latter takes into account the atomic or molecular electron cloud and is most important at high energies.

Although atomic charge distributions can be calculated with high precision small differences between the results from different numerical methods are of significance in the deduction of the nuclear absorption from the total attenuation of photons.

The purpose of this paper is to investigate the influence of molecular binding on the screening correction. This correction is found to be significant. It is of the order of the differences obtained by using atomic form factors from different numerical methods.

## 2. Pair production on the molecule

The potential in which pair-production takes place is made up by a superposition of contributions from  $N$  nuclei with charge numbers  $Z_i$ , located at  $\mathbf{R}_i$  with respect to an arbitrary origin. Then the charge distribution is given by

$$\rho(\mathbf{r}') = \sum_{i=1}^N eZ_i\delta(\mathbf{r}' - \mathbf{R}_i) + \sum_{i=1}^N \rho_i(\mathbf{r}') \quad (1)$$

where the first term on the r.h.s. of eq. (1) corresponds to the atomic nuclei and the second term to the charge distribution of electrons, with  $\rho_i(\mathbf{r}')$  corresponding to the electrons, attributed to the nucleus  $i$ . For outer shells the attribution of electrons to nuclei is arbitrary to some extent. For the following, this arbitrariness is not of importance as long as

$$\rho_{\text{el}}(\mathbf{r}') = \sum_{i=1}^N \rho_i(\mathbf{r}') \quad (2)$$

is the total charge distribution of the

$$Z = \sum_{i=1}^N Z_i \quad (3)$$

electrons.

Using the notation of Jost, Luttinger and Slotnik <sup>7)</sup> (JLS) we write the electrostatic potential in momentum space in the form ( $\hbar = c = 1$ ,  $e^2/4\pi = 1/137.04$ ):

$$A_0(\mathbf{q}) = \frac{1}{(2\pi)^3} \sum_{i=1}^N \int \int d^3\mathbf{r}' d^3\mathbf{r} \frac{eZ_i\delta(\mathbf{r}' - \mathbf{R}_i) + \rho_i(\mathbf{r}')}{4\pi|\mathbf{r} - \mathbf{r}'|} e^{i\mathbf{q}\cdot\mathbf{r}} \quad (4)$$

In (4) we replace  $\rho_i(\mathbf{r}')$  by  $\rho_i(\mathbf{r}' - \mathbf{R}_i)$ . Furthermore, we use the identity

$$\mathbf{r} = (\mathbf{r} - \mathbf{r}') + (\mathbf{r}' - \mathbf{R}_i) + \mathbf{R}_i \quad (5)$$

and arrive at

$$\begin{aligned} A_0(\mathbf{q}) &= \frac{1}{(2\pi)^3} \int d^3(\mathbf{r} - \mathbf{r}') \frac{e^{i\mathbf{q}\cdot(\mathbf{r} - \mathbf{r}')}}{4\pi|\mathbf{r} - \mathbf{r}'|} \\ &\quad \times \sum_{i=1}^N e^{i\mathbf{q}\cdot\mathbf{R}_i} \int d^3(\mathbf{r}' - \mathbf{R}_i) \{eZ_i\delta(\mathbf{r}' - \mathbf{R}_i) + \rho_i(\mathbf{r}' - \mathbf{R}_i)\} e^{i\mathbf{q}\cdot(\mathbf{r}' - \mathbf{R}_i)} \\ &= \frac{1}{(2\pi)^3} \frac{e}{q^2} \sum_{i=1}^N e^{i\mathbf{q}\cdot\mathbf{R}_i} [Z_i - \eta_i F_i(\mathbf{q})] \end{aligned} \quad (6)$$

with  $\eta_i$  representing the number of electrons attributed to the  $i$ th atom. Eq. (6) differs from eq. (34) of ref. <sup>7)</sup> by fact that the charge distributions  $\rho_i$  in eq. (6) are not necessarily spherically symmetric, i.e. the form factors  $F_i(\mathbf{q})$  may depend on the orientation of the molecule with respect to the momentum transfer  $\mathbf{q}$ . In order to avoid this difficulty, we represent the total charge distribution in terms of spherical

charge distributions. Then the quantities  $\mathbf{R}_i$  in eq. (6) denote the centers of these charge distributions, where a nucleus may or may not be located. With this simplification we rewrite eq. (6) in the form

$$A_0(\mathbf{q}) = \frac{1}{(2\pi)^3} \frac{e}{q^2} \sum_{i=1}^N e^{i\mathbf{q}\cdot\mathbf{R}_i} [Z_i - \eta_i F_i(\mathbf{q}^2)] \quad (7)$$

with the form factors not depending on the orientation of the molecule. The quantities  $Z_i$  are equal to charge numbers of nuclei, in case a nucleus is located in the center of the  $i$ th charged sphere, or equal to zero in the other case. The molecules are randomly oriented and the nucleus is initially at rest. Therefore, eq. (2) of ref.<sup>7)</sup> may be rewritten in the form

$$\sigma(k_0) = \int d^3\mathbf{q} T_{00}(\mathbf{q}; k) \int \frac{d\Omega_R}{4\pi} A_0(\mathbf{q}) A_0(-\mathbf{q}), \quad (8)$$

where  $k_0$  is the photon energy,  $\mathbf{q}$  the momentum transferred to the field and  $k$  the energy momentum 4-vector of the photon. The quantity  $T_{00}(\mathbf{q}, k)$  is the distribution of the momentum vectors  $\mathbf{q}$ . The second integral on the r.h.s. denotes an average over all orientations of the molecule with  $\mathbf{q}$  fixed. This integral may be replaced by an integral over all directions of  $\mathbf{q}$  with the orientation of the molecule fixed, i.e.

$$\begin{aligned} \int \frac{d\Omega_q}{4\pi} A_0(\mathbf{q}) A_0(-\mathbf{q}) &= \frac{e^2}{(2\pi)^6} \frac{1}{q^4} \sum_{i=1}^N \sum_{j=1}^N [Z_i - \eta_i F_i(\mathbf{q}^2)] [Z_j - \eta_j F_j(\mathbf{q}^2)] \\ &\quad \times \int \frac{d\Omega_q}{4\pi} e^{i\mathbf{q}\cdot(\mathbf{R}_i - \mathbf{R}_j)} \\ &= \frac{e^2}{(2\pi)^6} \frac{1}{q^4} \sum_{i=1}^N \sum_{j=1}^N \frac{\sin(q|\mathbf{R}_i - \mathbf{R}_j|)}{q|\mathbf{R}_i - \mathbf{R}_j|} \\ &\quad \times [Z_i - \eta_i F_i(\mathbf{q}^2)] [Z_j - \eta_j F_j(\mathbf{q}^2)]. \end{aligned} \quad (9)$$

The expression in eq. (9) only depends on the absolute value of  $\mathbf{q}$  and, therefore, may be treated analogous to eq. (35) of ref.<sup>7)</sup> using formulae given in ref.<sup>8)</sup>. The so obtained result represents a general solution for the pair-production cross section of randomly oriented molecules, provided the electronic charge distribution is given by a superposition of spherically symmetric parts, i.e. not necessarily of spherically symmetric charges of the molecular partners. In case of homonuclear diatomic molecules with spherical charge distributions of the two atoms, eq. (9) reduces to

$$\int \frac{d\Omega_q}{4\pi} A_0(\mathbf{q}) A_0(-\mathbf{q}) = \frac{Z^2 e^2}{(2\pi)^6} \frac{1}{q^4} 2 \left( 1 + \frac{\sin qR_0}{qR_0} \right) [1 - F(q^2)]^2, \quad (10)$$

where  $R_0$  is the internuclear distance and  $F(q^2)$  the atomic form factor. According to eq. (10) molecular effects enter twice: (i) via a modification of the form factor  $F(q^2)$  which has to be calculated from the charge distribution of a bound atom

instead of a free atom, and (ii) via the interference term  $\sin(qR_0)/qR_0$ . The factor of 2 in front of the brackets normalizes the pair-production cross section on two atoms. Looking at eq. (10) the coherent molecular pair-production cross section  $\sigma_{pp}^{\text{molec}}$  may be written in the form

$$\sigma_{pp}^{\text{molec}} = 2(\sigma_{pp}^{\text{bound atom}} + \sigma_{pp}^{\text{int}}), \quad (11)$$

where  $\sigma_{pp}^{\text{bound atom}}$  stands for the coherent pair-production cross section of an atom with the charge density modified due to binding, and  $2\sigma_{pp}^{\text{int}}$  for an interference contribution in the molecular pair-production cross section. Using the procedure outlined above,  $2\sigma_{pp}^{\text{bound atom}}$  and  $2\sigma_{pp}^{\text{int}}$  are obtained by replacing the first bracket in eq. (10) by 1 and  $\sin(qR_0)/qR_0$ , respectively.

### 3. Molecular charge distribution

The charge distribution of the oxygen molecule has been calculated using a relativistic Dirac-Fock-Slater (DFS) computer program for diatomic molecules<sup>9)</sup>. This program uses the local Slater approximation for the exchange term, and therefore, cannot predict the detailed chemical behaviour of molecules in general. On the other hand, this program has the great advantage of taking relativity fully into account. This is very important even for the present small- $Z$  system, because pair-production mainly takes place in inner shells where the relativistic effects are strongest.

One option of the program<sup>9)</sup> is to use the Mullikan population analysis which is an expansion of the total molecular charge distributions centered at the atomic nuclei. With this procedure the final molecular charge distribution can be written as a sum of two modified spherical symmetric oxygen atoms in the distance of their bond length  $R_0$ . This option of the program largely simplifies the calculation of the molecular pair-production cross section, because non-spherical parts of the charge distribution are avoided.

Furthermore, there are good reasons for being convinced that the charge distributions generated by the molecular code or at least differences with respect to the analogous atomic calculation as discussed below are of good accuracy. Numerical atomic DFS wave functions are used as basis functions. These basis functions are much better adapted to the physical problem than any analytical basis set at least in the vicinity of the nuclei which is most important for our problem. For details of the computational procedure and problems like pre-orthogonalization or possible contributions from the negative continuum we refer to ref.<sup>9)</sup>.

### 4. Computational details and results

Three relativistic self-consistent computer programs have been used to calculate atomic or molecular electronic densities: (i) the atomic DFS program of Liberman<sup>10)</sup>, (ii) the atomic DF program of Desclaux<sup>11)</sup> and (iii) the molecular

DFS program<sup>9)</sup> already described in the preceding section. This latter program is used to calculate molecular charge densities. In addition by setting one of the nuclear charges equal to zero, it may also be used to calculate atomic DFS charge distributions in the same molecular symmetry as the molecular calculation itself. Thus it is expected that the difference between the molecular calculation and two such atomic calculations on each atomic site can best describe the molecular part of the charge distributions. On the other hand, one cannot expect that the quality of the molecular program is so good that additional independent atomic calculations are unnecessary. The atomic codes like the ones in refs.<sup>10,11)</sup> are far better from the accuracy point of view because they have to solve only one-dimensional equations whereas the molecular code uses a basis set expansion and has to solve the problem in two dimensions, which leads to a lack of absolute accuracy.

In addition, there are some differences between the atomic codes of Desclaux<sup>11)</sup> and Liberman<sup>10)</sup>. The Desclaux code is a multi-configuration Dirac-Fock code which calculates the exchange part exactly and thus also has no problem with the charge density and the potential at large distances. In addition a coupling to good total angular momentum is achieved via a superposition of several Slater determinants. The Liberman code instead uses Slaters local exchange approximation, the Latter correction at large distances and only one Slater determinant of angular momentum wave functions calculated within a spherical symmetric SCF potential. The same Slater exchange approximation is used in the atomic calculation with the molecular code<sup>9)</sup>, but the symmetry of the problem is different and no Latter correction is introduced because there is no simple recipe how a Latter correction can be introduced in a molecular calculation.

In the first two figures we show the results for the total electron charge density for the different approximations discussed above. The charge densities for oxygen according to the programs of Liberman<sup>10)</sup> and Desclaux<sup>11)</sup> are compared with each other in fig. 1 whereas fig. 2 compares the oxygen atom bound in the molecule using the two-center DFS molecular program<sup>9)</sup> and the analogue atomic calculation using the same program. The differences of the curves (labeled c) can be discussed from a physics point of view. Curve c in fig. 1 is the difference between the two calculations with the atomic codes. Although one should expect that the Desclaux<sup>11)</sup> code should be much better, one has to be aware that still the correlation is missing, which probably is not small. The Liberman code introduces a number of approximations which are discussed above but from experience one knows that the Slater approximation contains some of the correlation, although one does not know explicitly how much. Thus the curve c in fig. 1 indeed gives an estimate of the quality of the atomic charge density. Nevertheless this difference is smaller than the pure "molecular" contribution which is the curve c in fig. 2. How much of the differences comes from a certain approximation or correction is not possible to determine. These effects due to the differences in computer programs for the free atom are rather large, showing that the accuracy of the pair-production cross sections on an absolute scale

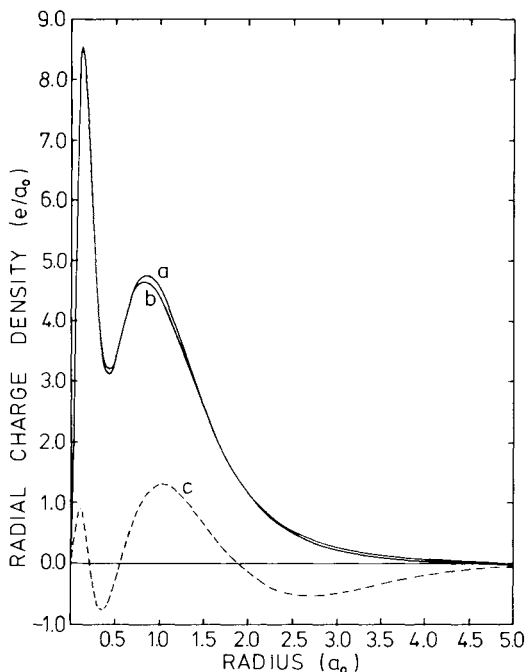


Fig. 1. Radial charge densities in the oxygen atom versus atomic radius ( $a_0=0.529 \text{ \AA}$  Bohr radius). (a) Calculated for the oxygen atom using the computer program of Desclaux <sup>11)</sup>. (b) Calculated for the oxygen atom using the computer program of Liberman <sup>11)</sup>. (c) Ten times the difference between (a) and (b).

is a non-trivial problem. On the other hand, there are good reasons for the assumption that the simplifications contained in the molecular program <sup>9)</sup> enter in the molecular and atomic charge densities in the same way and, therefore, cancel in the difference. Therefore the appropriate way to calculate the pair-production cross section for a molecule, i.e. the quantity  $\sigma_{pp}^{\text{bound atom}}$  in eq. (11), is to use a charge density

$$\rho^{\text{bound atom}} = \rho^{\text{atom}} + \Delta\rho, \tag{12}$$

where  $\rho^{\text{atom}}$  is the free atomic charge density calculated as exactly as possible, and  $\Delta\rho$  the difference in charge densities calculated with the molecular program <sup>9)</sup> with the two atoms located in a distance of the bond length  $R_0$  and located in an infinite distance, respectively. The first part on the r.h.s. of eq. (12),  $\rho^{\text{atom}}$ , is given by curve a or b of fig. 1 and the second part,  $\Delta\rho$ , by curve c of fig. 2.

As outlined in sect. 2 interference has an effect on the molecular pair-production in addition to the modification of the charge density. The interference term  $\sigma_{pp}^{\text{int}}$  defined in eq. (11) is sizeable and depends on the photon energy as well as on the internuclear distance. This is demonstrated by fig. 3 for the oxygen molecule, where at the internuclear distance of  $R_0 = 1.2074 \text{ \AA}$  the interference term is negative above

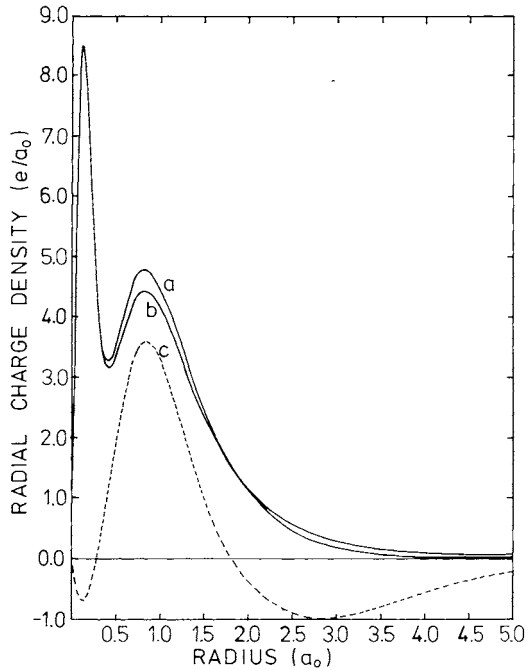


Fig. 2. Radial charge densities in the oxygen atom versus atomic radius ( $a_0 = 0.529 \text{ \AA}$  Bohr radius). (a) Calculated for the oxygen atom bound in the molecule, using the two-center DFS computer program<sup>9)</sup>. (b) Calculated for the free oxygen atom using the same computer program. (c) Ten times the difference between (a) and (b).

140 MeV and increases drastically in magnitude with increasing photon energy. One important conclusion to be drawn from fig. 3 is that for absorbing materials with internuclear distances above  $2 \text{ \AA}$  the interference correction becomes small in the  $\Delta$ -resonance region.

We write the total molecular correction to the pair-production cross section in the form

$$\Delta\sigma_{pp} = \frac{1}{2}\sigma_{pp}^{\text{molec}} - \sigma_{pp}^{\text{atom}}, \quad (13)$$

where  $\sigma_{pp}^{\text{molec}}$  denotes the molecular pair-production cross section defined in eq. (11) and  $\sigma_{pp}^{\text{atom}}$  the pair-production cross section calculated for a free atom. For the numerical evaluation of eq. (13) two alternative procedures may be used, being equivalent except for terms of negligible order. Procedure (i) calculates  $\sigma_{pp}^{\text{molec}}$  using the charge density  $\rho^{\text{bound atom}}$  of eq. (12), and then uses the charge density  $\rho^{\text{atom}}$  entering into eq. (12) for the calculation of  $\sigma_{pp}^{\text{atom}}$ . Procedure (ii) avoids the choice of an "exact" charge density  $\rho^{\text{atom}}$  as required by eq. (12). Instead, both terms,  $\sigma_{pp}^{\text{molec}}$  and  $\sigma_{pp}^{\text{atom}}$ , of eq. (13) are calculated from charge densities as given by the



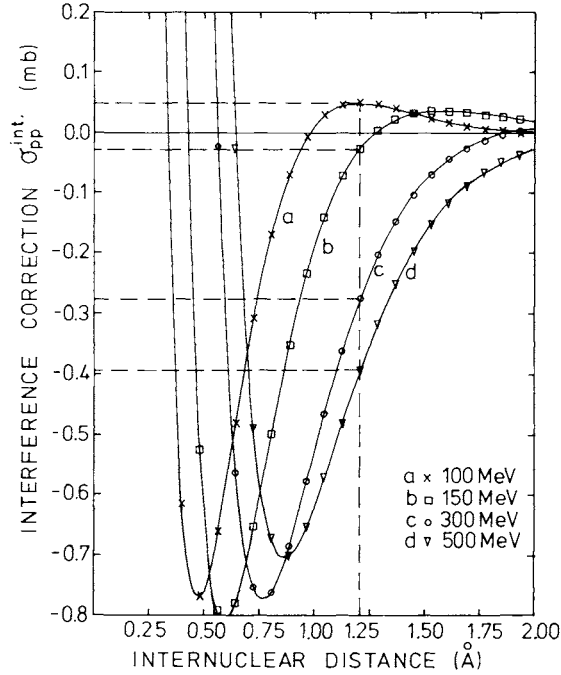


Fig. 3. Interference correction as defined by eqs. (10) and (11) calculated for the oxygen molecule versus internuclear distance. Parameter of the curves is the energy of the photon. The internuclear distance of the oxygen molecule is  $R_0 = 1.2074$  Å (see vertical dashed line).

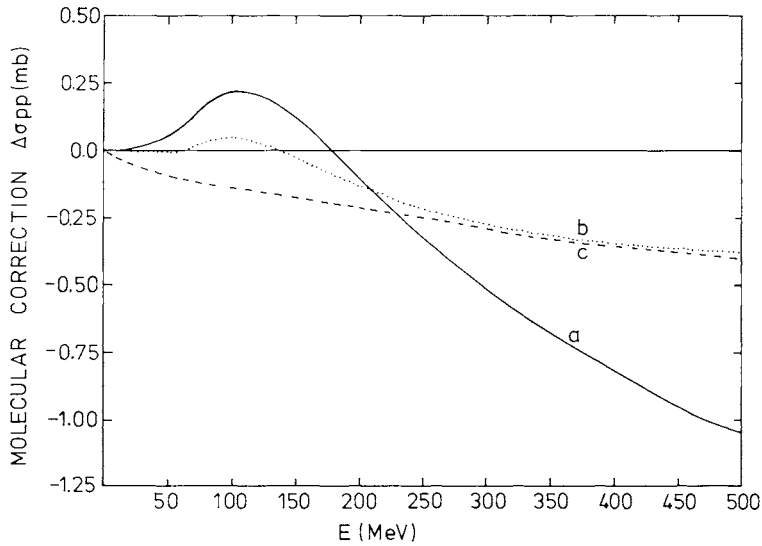


Fig. 4. Curve a: Molecular correction  $\Delta\sigma_{pp} = \frac{1}{2}\sigma_{pp}^{molec} - \sigma_{pp}^{atom}$  of the coherent pair-production cross section. Curve b: Interference term  $\sigma_{pp}^{int}$  entering into  $\Delta\sigma_{pp}$ . Curve c: Difference of atomic pair-production cross section  $\sigma_{pp}^{atom}$  calculated using the Desclaux<sup>11)</sup> and Liberman<sup>10)</sup> codes, respectively.

molecular program<sup>9)</sup> with the atoms at a distance of  $R_0$  and infinity, respectively. For sake of simplicity the latter method has been applied in the present work.

Properties of the molecular correction  $\Delta\sigma_{pp}$  are discussed in fig. 4. Curve a depicts the molecular correction  $\Delta\sigma_{pp} = \frac{1}{2}\sigma_{pp}^{\text{molec}} - \sigma_{pp}^{\text{atom}}$  of the coherent pair-production cross section calculated by the methods described above. Curve b depicts the interference term  $\sigma_{pp}^{\text{int}}$  entering into  $\Delta\sigma_{pp}$ . Curve c shows the difference of atomic pair-production cross sections  $\sigma_{pp}^{\text{atom}}$  calculated using the Desclaux<sup>11)</sup> and Liberman<sup>10)</sup> codes, respectively. It appears to be reasonable to consider the latter difference as a measure for the accuracy of the atomic pair-production cross sections on an absolute scale, except for possible additional inaccuracies due to e.g. the radiative correction. Therefore, we may conclude that for the oxygen molecule, both the absolute accuracy and the interference term amount to about half of the molecular correction, which for liquid oxygen is about 15% in the maximum of the  $\Delta$ -resonance.

## 5. Experiments and results

The measurement of the total photon attenuation by liquid oxygen was performed by the method and with the apparatus published in refs. <sup>2,3)</sup>. By the same method the total absorption cross section in the region of the  $\Delta$ -resonance ( $E_\gamma < 380$  MeV) was measured <sup>2,3)</sup> for <sup>6</sup>Li, <sup>7</sup>Li, Be, and Al.

The target consisted of a 70 cm long stainless steel tube filled with liquid oxygen. The tube was cooled by liquid nitrogen. Because of the smallness of the nuclear absorption compared with the total attenuation of the photon beam the latter quantity has to be determined with high precision ( $< 10^{-4}$ ). The same requirement holds for the determination of the target properties. This could, however, not be achieved for the liquid oxygen target since the amount of thermal contraction of the stainless steel used was not well enough known. The 70 cm long target tube shortens by approximately 4 mm when cooled to liquid nitrogen temperature. Therefore, the data were normalized to the expected value in the quasideuteron region (80–140 MeV). In this region the corrections due to the molecular effects of interest are small.

An extensive work on calculated total atomic cross sections for 1 MeV to 100 GeV photons in elements  $Z = 1$  to 100 has been published by Hubbell, Gimm and Øverbø<sup>12)</sup>. In addition to screening these calculations take into account the Coulomb correction effect and the radiative correction. These tabulations were formerly used to evaluate the nuclear absorption cross sections. In the present work, the so-evaluated photo-absorption cross sections are corrected for molecular effects on the coherent pair-production cross section, using the procedure described in the foregoing sections. We did not attempt to improve on the coherent atomic pair-production cross sections, though improvements on the atomic form factors and on the radiative correction might be advisable. For the case which interests here the coherent pair-production contributes the largest part to the atomic cross section.

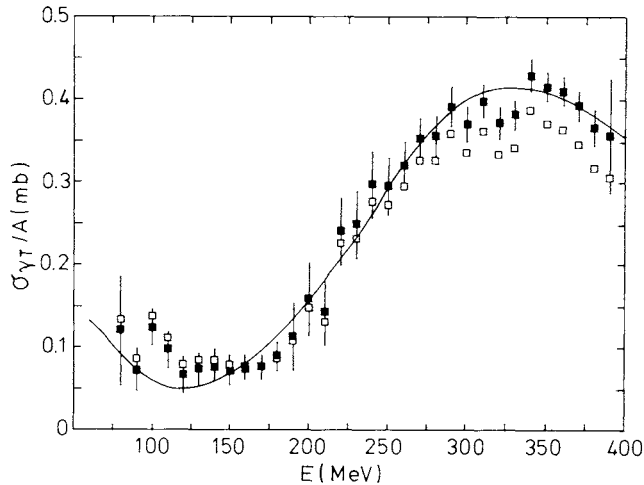


Fig. 5. Total nuclear photo-absorption cross section per nucleon for oxygen. (□) Experimental results evaluated using pair-production cross sections calculated for atomic oxygen<sup>12</sup>. (■) The same data after carrying out the molecular correction as given by curve (a) of fig. 4.

The incoherent scattering contributes another 6% and the triplet pair-production another 13% of the coherent pair-production cross section. Therefore, it is justified to carry out molecular corrections only for the coherent pair-production cross section.

Fig. 5 shows experimental total nuclear photo-absorption cross sections per nucleon for <sup>16</sup>O as measured with the liquid oxygen target, together with the *A*-scaling prediction. This prediction is depicted by the solid line and has been obtained<sup>1)</sup> from experimental data on Li, Be, C, Al, Pb and U. The open squares show the total nuclear absorption cross sections as obtained in the previous data analysis, the closed squares represent the same data after carrying out the molecular correction. The error bars attributed to these data take care of the statistical error only and thus disregard any possible systematic error of the calculated atomic cross sections. Apparently, there is an agreement of the corrected data with the *A*-scaling prediction within the limits given by error bars. In the energy interval between 140 and 400 MeV the reduced  $\chi^2$  is equal to 1.4, whereas without the molecular correction this quantity was as large as 10.9.

## 6. Conclusion

We have shown that for an accurate evaluation of nuclear absorption cross sections,  $\sigma_{\gamma T}$ , from total absorption measurements carried out on oxygen molecules, molecular effects on the coherent pair-production cross section are important. Carrying out the molecular correction, an agreement is obtained with nuclear absorption cross sections,  $\sigma_{\gamma T}$ , of other nuclei, if use is made of the observation, that in the  $\Delta$ -resonance region  $\sigma_{\gamma T}$  is proportional to the mass number *A*.

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