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NUCLEAR PHOTOABSORPTION BY QUASI-DEUTERONS AND AN UPDATED EVALUATION OF LEVINGER'S CONSTANT

by

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Abstract. - Levinger's quasi-deuteron model of nuclear photoabsorption has been used together with modern root-mean-square radius data to obtain Levinger's constant L of nuclei throughout the Periodic Table. It is found that $L = 6.8 - 11.2A^{-2/3} + 5.7A^{-4/3}$, which gives L-values in good agreement with those obtained from measured total nuclear photoabsorption cross sections.

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The present work originated in a study to obtain an estimate of the total nuclear photoabsorption cross section for incident photons of energies between 200 and 1000 MeV. As it is generally accepted, above $\sim$ 150 MeV the interaction of photons with a nucleus of mass number A and atomic number Z has been described by two competing mechanisms, namely the photomesonic (pm) and quasi-deuteron (qd) ones, with the total nuclear photoabsorption cross section given by

$$\sigma^{T}_{\gamma A}(E_\gamma,A) = \sigma^{t}_{pm}(E_\gamma,A) + \sigma^{t}_{qd}(E_\gamma,A) \quad . \qquad (1)$$

In the course of this study we faced the problem of estimating the contribution due to the quasi-deuteron mechanism of interaction to the total cross section as given by (1). The quasi-deuteron model proposed by Levinger [1] represents the total nuclear photoabsorption cross section as

$$\sigma^{t}_{qd}(E_\gamma,A) = L\,\frac{NZ}{A}\,\sigma^{t}_{d}(E_\gamma) \quad , \qquad (2)$$

where $N = A-Z$, σ^{t}_{d} is the total cross section of the deuteron photodisintegration [2], and L is a constant (the so-called Levinger's constant) which can be thought of as a factor which measures the relative probability of two nucleons being near each other in a complex nucleus compared with that in a free deuteron. The aforementioned problem of estimating $\sigma^{T}_{\gamma A}(E_\gamma,A)$ would be thus solved provided that the values assumed by L for different target nuclei throughout the Periodic Table could be evaluated.

In order to evaluate L-values it is believed best to use the original formalism introduced by Levinger [1] in the framework of a model for nuclear photoabsorption via n-p pairs, which is valid for incident photons of energies larger than 150 MeV interacting with nuclear "quasi-deuteron" structures. According to Levinger, the cross section of the quasi-deuteron is that cross section for the deuteron multiplied by the square of the ratio of the wave function of the quasi-deuteron (considered to be in a triplet state) to the wave function of the deuteron ground-state, i.e.,

$$\sigma_{qd}(E_\gamma) = (\psi_k/\psi_d)^2\ \sigma_d^t(E_\gamma) \quad . \tag{3}$$

From the theory of the effective range of nuclear forces [3,4], and taking into account the number of choices for protons (Z) and for neutrons (N), it follows that the total nuclear photoabsorption cross section via n-p pairs is given by

$$\sigma_{qd}^t(E_\gamma,A) = \frac{2\pi}{\alpha^2+k^2}\cdot\frac{1-\alpha r_0}{\alpha}\cdot\frac{A}{v}\cdot\frac{NZ}{A}\,\sigma_d^t(E_\gamma) \quad . \tag{4}$$

Here, v is the nuclear volume, α^{-1} is the scattering length, r_0 is the effective range of the n-p force in the ground state free deuteron, and k is the wave number for the relative motion of proton and neutron. Levinger's constant L is thus identified as

$$L = 2\pi\xi\ \frac{1-\alpha r_0}{\alpha}\ \frac{A}{v} \quad , \tag{5}$$

where ξ is the average value of the quantity $(\alpha^2+k^2)^{-1}$. This last quantity was calculated formerly by Levinger by assuming Fermi distributions up to the same wave number k_m for both protons and neutrons and an isotropic distribution for the angle between $\vec{k}_p$ and $\vec{k}_n$, where $k = (1/2)|\vec{k}_p-\vec{k}_n|$. With these assumptions it was found that

$$\xi = \left(\frac{1}{\alpha^2+k^2}\right)_{av} = \frac{9}{k_m^2} - \frac{24\alpha}{k_m^3}\,\mathrm{arctg}\,\left(\frac{k_m}{\alpha}\right) - \frac{6\alpha^2}{k_m^4} + \left[\frac{18\alpha^2}{k_m^4} + \frac{6\alpha^4}{k_m^6}\right]\ln\left[1 + \left(\frac{k_m}{\alpha}\right)^2\right] . \tag{6}$$

In this way a constant value L = 6.4 was found [1] by taking $\alpha = 0.23\ \mathrm{fm}^{-1}$, $k_m = 1.0\ \mathrm{fm}^{-1}$, and $v=(4/3)\pi A(1.4)^3\ \mathrm{fm}^3$, whereas the value L = 8 was calculated for a nuclear radius parameter of 1.2 fm [5].

Later, Levinger's constant was currently considered as a purely phenomenological parameter, and it was varied by different authors to fit photonuclear data obtained from experiments carried out in a rather wide range of both photon energy and target mass number. In a previous work [6] we noted, however, a dependence of L on nuclear radius parameter, and it was deduced the expression $L = 0.67A^{2.28}/NZ$. Afterwards, this expression was changed into $L = 2.1\ \ln(1.3A)$ to take into account the condition L = 2 for a deuterium target. Also, from an analysis of the total nuclear photoabsorption data taken at $E_\gamma \leq 150$ MeV by the Saclay and Mainz groups [7,8] it was found $L = A^{2.147}/NZ$, to be used in the context of Levinger's modified quasi-deuteron model (see refs. [9,10]).

It seems evident from (5) that the dependence of L on A is eventually connected with the trend of the A/v ratio.

In recent years, new experiments have provided nuclear radius data over an extended range of mass number. It was therefore felt worthwhile to undertake an updated evaluation of Levinger's constant as given by eq. (5) taking advantage, as far as the physical quantities which appear in (5) are concerned, of the new nuclear radius data available.

The analysis has been performed over 63 nuclei lying along the beta-stability valley, from Be up to U. The nuclear volume v was calculated from the "equivalent root-mean-square radius" of the nucleus, Q, which is given by [11]

$$Q = \left(\frac{5}{3}\right)^{1/2} \langle r^2\rangle^{1/2} \quad , \qquad (7)$$

where $\langle r^2\rangle^{1/2}$ is the root-mean-square radius of the nuclear charge distribution, the quantity measured directly by the experiments. To calculate ξ from eq. (6), first we obtained the values of k_m from the corresponding average maximum Fermi momentum p_A^F of the A nucleons, i.e.,

$$k_m = \frac{p_A^F}{\hbar} = \left(\frac{3\pi^2}{2}\right)^{1/3} \left(\frac{A}{v}\right)^{1/3} = \frac{1.18\ A^{1/3}}{\langle r^2\rangle^{1/2}} \quad . \qquad (8)$$

Inspection of eq. (8) shows that if the value of the ratio $A^{1/3}/\langle r^2\rangle^{1/2}$ was constant for all nuclei then one would have constant values for both k_m and ξ, and, therefore, eq. (5) would give a unique value for L whatever the mass number of the target nucleus. The ratio $A^{1/3}/\langle r^2\rangle^{1/2}$ is instead found to increase, even if slightly, throughtout the Periodic Table, e.g., from 0.826 fm^{-1} for ^9Be up to 1.061 fm^{-1} for ^{238}U. As a consequence

L-values are expected to vary with mass number. Values of $\langle r^2\rangle^{1/2}$ used in the present calculation have been taken from the recently published compilations by Brown et al. [12] and Wesolowiski [13] which report available experimental data of $\langle r^2\rangle^{1/2}$ of nuclei ranging between ^4He and ^{238}U. By taking $\alpha = 0.23$ fm^{-1} as reported in [1], and $r_0 = 1.79$ fm as it results from an average of different r_0-values reported in the literature, L-values have been obtained by making use of eq. (5).

Results are reported in fig. 1, where calculated L-values (dots) have been plotted against mass number. A regular trend of L increasing with A is clearly observed (an increase of ∿ 45% from lighter to heavier nuclei). The solid curve is the result of a least-squares treatment of the L-values obtained by the method described above. By imposing the condition L = 2 for A = 2, it has been found that

$$L = 6.8 - 11.2A^{-2/3} + 5.7A^{-4/3} \quad . \qquad (9)$$

The present analysis disregarded only the value of L calculated for ^4He, due to the strong shell effect manifested by such a nucleus.

In order to see for the reliability of the present evaluation of L-values we report in fig. 1 the L data obtained recently by Terranova et al. [14] (points) from a semi-empirical analysis of total nuclear photoabsorption cross section data [7,8,15] as well as data deduced from measurements of a number of effective quasi-deuteron clusters in nuclei [16-18]. Good agreement is indeed found between L-values evaluated in the present work and those obtained from a phenomenological fit [14]. Notice that the present evaluation of Levinger's constant represents, to our knowledge, the first attempt to obtain L-values of nuclei throughout the Periodic Table directly from the formerly proposed model of nuclear photoabsorption by n-p pairs [1], not in a phenomenological way.

FIGURE CAPTION

Fig.1.- Levinger's constant L plotted against mass number A. The dots represent L-values calculated according to Levinger's model as explained in the text. The line is the trend obtained by least-squares fitting of the calculated L-values (eq.(9)). Full circles represent L-values obtained from total nuclear photoabsorption cross section data [14].Open symbols represent L-values deduced from: ○ , data by Stibunov [16]; △, data by Homma et al. [17,18].

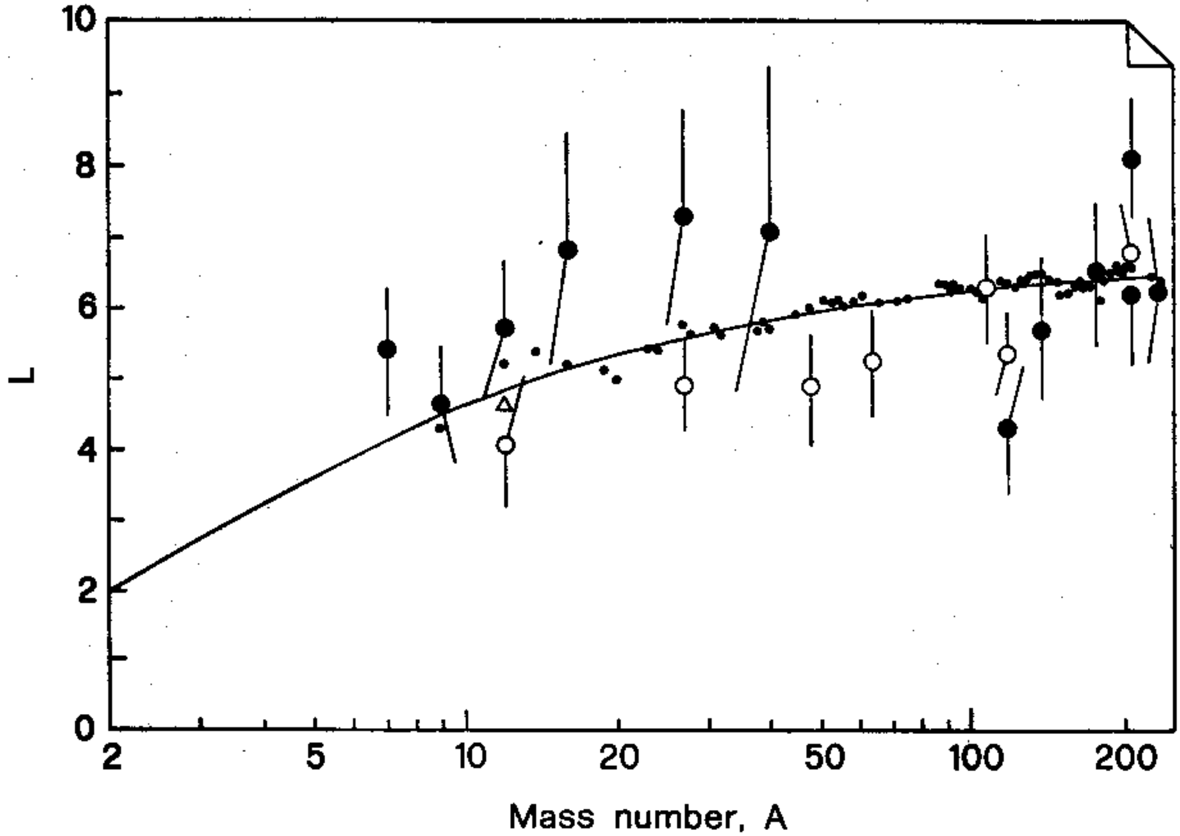

FIG. 1

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