Electromagnetic break-up of nuclei with $A = 3 \div 7$

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This talk contains a short review of some of the progresses made in the last three years in the calculations of electromagnetic cross sections of light nuclei up to $A=7$. Since many of them have been possible thanks to the use of the Lorentz Integral Transform (LIT) method, both for inclusive and exclusive reactions, I will first make a few remarks on the method, stressing its essential points and then show results for different nuclei. One of the interesting outcomes is e.g. the appearing of typical collective motion features from ab initio six-body calculations. When a comparison with available experimental data is attempted, it is rather disappointing to realize that low-energy data are old, incomplete and not accurate enough to disentangle interesting effects, showing the need of a major experimental program in this direction, together with more theoretical efforts to implement modern realistic forces in continuum calculations of $A \geq 4$ systems.

1. General remarks on the LIT for inclusive and exclusive cases

In both inclusive and exclusive electromagnetic reactions one has to deal with the very difficult problem of the continuum wave functions entering the relevant matrix elements. For light systems this is true even at low energies since their discrete spectra are very limited. The essential idea of the LIT method is to calculate integral transforms of these matrix elements (or of proper combinations of them) with Lorentzian kernels and then invert the transforms (see [12]). The reason to take this detour is ”economical”: it turns out that, in order to calculate the Lorentz transforms of these matrix elements, continuum solutions of the Schrödinger equation are not required. Instead one has to find finite norm solutions to Schrödinger-like equations with external sources. This implies that one can use the much simpler bound state methods to solve them.

For the inclusive case one can prove that one only needs to solve

\[
(H - E_0 - \sigma_R + i\sigma_I)\tilde{\psi}_1 = \hat{O}\psi_0,
\]

while for the exclusive case the solution of the following additional equation is required

\[
(H - \sigma_R + i\sigma_I)\tilde{\psi}_2 = \hat{V}\phi.
\]

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In the first equation \(E_0\) and \(|\psi_0\rangle\) denote the nuclear ground state energy and wave function, respectively, \(H\) is the nuclear Hamiltonian, \(\hat{O}\) is the electromagnetic operator and \(\sigma_R\) and \(\sigma_I\) are the Lorentz kernel parameters, i.e. center and width of the Lorentzian, respectively. In the second equation \(\hat{V}\) denotes the potential between particles belonging to different fragments and \(|\phi\rangle\) is the wave function of non interacting fragments.

In the inclusive case the norm of \(|\psi_1\rangle\) is the LIT of the inclusive response function, in the exclusive case the overlap between \(|\psi_1\rangle\) and \(|\psi_2\rangle\) is connected in a simple way to the matrix element of an exclusive reaction. I will not report here the derivation of the LIT method which can be found e.g. in [1,2]. I will only stress that in both cases an essential point is the use of the closure property of the Hamiltonian eigenstates. This means that, in a way, the LIT method is a very powerful extension of sum rule approaches.

Figure 1. Faddeev (dots) and LIT result (upper and lower bounds, full curves) in unretarded E1 approximation and for AV18 potential. From [3].

Figure 2. Total \(^3\)He photoabsorption cross section. LIT results in unretarded E1 approximation with AV18 only (dash-dotted curve) and with AV18+UIX (full curve) compared with two sets of data (see [3]).

It may seem that the difficulties of finding solutions in the continuum are translated into the difficulties of inverting integral transforms. However, it turns out that for the case of a Lorentzian kernel the inversion does not suffer from the uncontrolled instabilities typical of other kernels (like e.g. the Laplace one) and that it is possible to obtain very accurate results. This can be seen comparing LIT results with those obtained using explicit continuum states. The comparison has been possible only for cases where explicit continuum states were available, i.e. the two- and three-body systems (see [1,3]). As an example in Fig. 1 the results obtained in [3] are reported, where the photonuclear cross section of triton has been calculated in unretarded dipole approximation, both by solving the Faddeev equations and by the LIT method. As one can see the agreement is at the
level of few percents. In Fig. 2 the results are compared with available experimental data. It is clear that more accurate experiments are needed if one wants to disentangle the effects of three-body forces.

In the following I will review results obtained in larger systems, where the LIT seems to be at present the only method to calculate electromagnetic cross sections in a large energy range, especially beyond the two-body break-up thresholds.

2. Results for nuclei with $A > 3$

The photonuclear two-body break-up of $^4$He has been calculated (see Fig. 3) applying the exclusive version of the LIT method. This allows to give for the first time a result where the final state interaction is fully taken into account, also beyond the three-body break-up threshold. The potential has been chosen to be simply central (MTI-III, [4]). The experimental situation is very complicated. More comments about the comparison between theory and experiment can be found in the contribution by S. Quaglioni to this conference.

![Figure 3](image_url)

Figure 3. Comparison between the theoretical result for the $^4$He($\gamma,n$)$^3$He photonuclear cross section and data from various experiments (for references see the contribution by S. Quaglioni to this conference)

In Fig. 4 inclusive results on the total dipole photodisintegration cross sections of $^6$He and $^6$Li are presented (see also [5]). A noticeable feature is the appearing of two resonance peaks in the $^6$He case. They may be interpreted as the ”soft dipole mode” due to the collective oscillation of the neutron halo against the alpha core and the classical Gamow-Teller mode of the protons against the neutrons. Of course in the latter case the break-up of the alpha-core is required and therefore this mode appears at higher energy.
It is very interesting to see a collective feature stemming out of a six-body microscopic calculation. This feature seems to persist independently on the potential used. In principle these two modes might exist also in the case of $^6$Li, (in this case the soft mode could be that of the n-p pair against the alpha particle). One possible explanation for the unique peak of $^6$Li could be the existence of an additional dipole mode filling the gap between the soft and the Gamow-Teller mode. This third mode would correspond to a $^3$He-$^3$H oscillation. The corresponding $^3$H-$^3$H channel in $^6$He is absent because it is forbidden in dipole approximation.

In Fig. 5 a comparison with available data is shown. In this case calculations have been performed with the AV4’ potential [7], which includes P-wave interactions. A good agreement with data is obtained for $^6$Li at lower energy. The P-wave potential contribution is crucial for the agreement (compare with Fig. 3 in [3]). Sizeable disagreement is still found for $^6$He and $^6$Li at higher energies. New and more accurate data and calculations with more realistic potentials are needed to draw some conclusions about the role of the different potential terms.
In Figs. 6 and 7 preliminary results of a microscopic seven-body calculation of the total photodisintegration of $^7$Li are presented. Also in this case the theoretical result shows a unique peak at about the same energy as the experimental data. Also the height of the peak is well reproduced. The shoulder below 15 MeV is due to different thresholds for the $T=3/2$ and $T=1/2$ channels, as shown in Fig. 7.

Finally it should be mentioned that Eqs.(1-2) have been solved by correlated hyperspherical harmonics (CHH) expansions for $A=3,4$. For $A=6,7$ the EIH method [9] (using the concept of effective interaction) and a reformulation of the LIT, permitting to take advantage of the Lanczos algorithm [10], have helped the convergence of the results.

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