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## Quasi-free electron scattering on nuclei and atoms<sup>1</sup>

GIOVANNI STEFANI

Dipartimento di Scienze Università Roma Tre, CNR Istituto di Struttura della Materia,  
via della Vasca Navale 84, 00146 Roma - Italy  
E-mail: giofani.ste@gmail.com • ORCID: 0000-0002-2739-2732

**Abstract** – Early in his career, Ugo Amaldi focused on quasi-free scattering experiments to provide experimental evidence for the Shell Model (SM), a pivotal framework in the quantum mechanical description of nuclei, atoms and condensed matter at large. The SM posits that particles bound in a potential well occupy discrete energy levels, characterized by specific binding energies and momentum distributions. During the 1960s, Amaldi's electron-induced quasi-free processes on nuclei ( $e,e'p$ ) allowed for measuring single-particle observables, such as protons binding energy and momentum distribution, thus validating the SM as a cornerstone of nuclear physics. He immediately recognized the general value of the quasi-free scattering as a tool to measure single particle properties of a broader range of quantum systems, including atoms, molecules, and hadrons. An ( $e,e'p$ )-like experiment on an atom, ( $e,2e$ ), had never been conducted, despite few theoretical papers had proposed its feasibility, and in the late 1960s he succeeded in realizing one such ( $e,2e$ ) on a thin carbon film. These breakthroughs marked the birth of momentum spectroscopy that, since then has been adopted, and steadily applied, in a number of laboratories throughout the world to investigate single and many-particle properties of nuclei, atoms, molecules and solids, thus solidifying his visionary legacy

**Keywords:** Nuclear physics, atomic physics, shell model, momentum spectroscopy, quasi-free scattering, impulse approximation, ( $e,e'p$ ), ( $e,2e$ ).

**Riassunto** – All'inizio della sua carriera, Ugo Amaldi si occupò di esperimenti di scattering quasi-libero per fornire prove sperimentali a supporto del Modello a Shell (SM), un modello fondamentale nella descrizione quantomeccanica di nuclei, atomi e materia condensata in generale. Il SM postula che le particelle legate ad una buca di potenziale occupino livelli energetici discreti, caratterizzati da specifiche energie di legame e distribuzioni di momento. Negli anni '60, i processi di scattering quasi-libero indotti da elettroni sui nuclei ( $e,e'p$ ), condotti da Amaldi per la prima volta, permisero di misurare osservabili a particella singola, come l'energia di legame e la distribuzione di momento dei protoni legati nel nucleo, validando così il SM come pilastro della fisica nucleare. Amaldi riconobbe subito il valore generale dello scattering quasi-libero come strumento per misurare le proprietà di particella singola in una più ampia gamma di sistemi quantistici, tra cui atomi, molecole e adroni. Un esperimento simile a ( $e,e'p$ ) sugli

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<sup>1</sup> This peer reviewed article originates from contributions to the "Symposium for Ugo's 90 years" held at CERN (Geneva) on the 4th of April 2025 to celebrate the 90th birthday of Ugo Amaldi, member of the Accademia dei XL since 1992.

atomi, (e,2e), non era mai stato realizzato, nonostante alcuni lavori teorici ne avessero proposto la fattibilità. Alla fine degli anni '60, egli riuscì a realizzare un esperimento (e,2e) su un sottile film di atomi di carbonio. Questi risultati rivoluzionari segnarono l'inizio della spettroscopia del momento, che da allora è stata adottata e applicata in numerosi laboratori in tutto il mondo per indagare le proprietà a particella singola e multipla in nuclei, atomi, molecole e solidi, consolidando il suo straordinario lascito visionario.

**Parole chiave:** Fisica nucleare, fisica atomica, modello a shell, spettroscopia del momento, scattering quasi-libero, approssimazione dell'impulso, (e,e'p), (e,2e).

## Introduction

During the 1950s and 1960s, the Shell Model (SM), a quantum mechanical framework, has proven to be undeniably successful in understanding nuclear and atomic structures. The model represents a significant leap forward in the theoretical description of these many interacting particles systems, providing insights into the arrangement of nucleons within the nucleus and electrons within the atom. The general significance of SM in the quantum mechanical description of matter was cemented by the 1963 Nobel Prize in Physics awarded jointly to the two scientists that firstly proposed it, Maria Goeppert Mayer [1] and Hans Jensen [2]. At the beginning of his career, Ugo Amaldi worked on quasi-free scattering experiments on nuclei and atoms in the pursuit of clear experimental evidence for the validity of the Shell Model (SM), laying experimental foundations that paved the way for advancements in nuclear and atomic physics. This paper will explore and substantiate the latter assertion, reviewing his achievements and their impact on the scientific community's understanding of quantum systems.

According to the Shell Model, in any system made of  $N$  interacting particles bound to a potential well, (be that nucleons in a nucleus or electrons in an atom), in the ground state they occupy the lowest energy eigenstates of the Mean Field Hamiltonian that describes the system. For instance, in  $^{16}\text{O}$  nucleus the first 3 levels are occupied by 8 neutrons and 8 protons. Each level is characterized by a Binding Energy ( $E_n$ , i.e. Spectral Function) and a wavefunction in momentum space whose modulus square ( $|\Psi(q_n)|^2$ ) describes the associate Momentum Distribution probability.

In view of the SM general relevance, in the 1960s, many experimental efforts, and among them quasi-free collisions, were being made to assess its value, in other

words, to understand whether the model is a pure mathematical artifice or whether is a reasonable independent particles approximation of the physical reality of matter. In the second case, it should have been possible to measure the observables associated by the model with the state of a single particle bound within the nucleus or atom, that is the Binding Energy and the associate Momentum Distribution.

Figure 1 illustrates the schematic of a quasi-free collision event: a monochromatic beam of high-energy ( $E_0$ ) structureless particles is directed to collide with an  $N$ -particle target. The resulting break-up process produces a residual  $N-1$  particles target along with scattered and ejected particles (of energy  $E_1$  and  $E_2$ , respectively), between which the energy and momentum of the incoming particle is redistributed in accordance with the conservation laws outlined below:

$$\begin{aligned} E_0 + E_{(N)} &= E_{(N-1)} + E_1 + E_2 \\ \vec{K}_0 &= \vec{q}_R + \vec{K}_1 + \vec{K}_2 \end{aligned}$$

Where  $E_{(N)}$  and  $E_{(N-1)}$  are the target total energy before and after collision, respectively, and  $\vec{q}_R$  is the momentum of the recoiling target assumed at rest in the initial state.

If energy and momentum transferred in the knock-out collision,  $\Delta E = E_0 - E_1$  and  $\Delta \vec{K} = \vec{K}_0 - \vec{K}_1$  respectively, are large enough, the interaction is localized in a radius shorter than the inter-particle distance. Hence, a single particle is ejected leaving the reminder of the nucleus frozen in its previous configuration. Under these conditions, that implies large scattering and ejection angles ( $\vartheta_1$ ,  $\vartheta_2$  respectively), the Impulse Approximation (IA) [3] holds and the quantities:

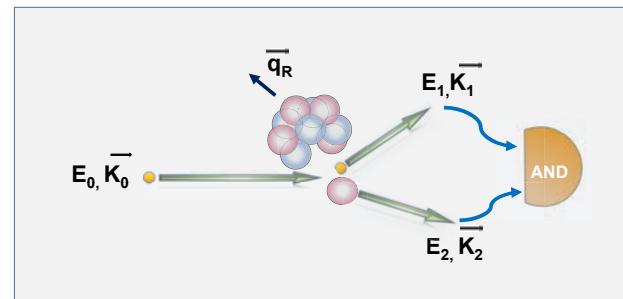


Fig. 1. Diagram of a quasi-free interaction between a projectile  $E_0$  and a target composed of  $N$  interacting particles. After the interaction, the scattered particle  $E_1$  and the particle ejected from the target  $E_2$  are detected. The  $N-1$  particle residual recoils with momentum  $q_R$  and negligible kinetic energy. By measuring the energy and momentum of the two final free particles in coincidence, it becomes possible to measure the spectral function and the momentum distribution of the bound particles in the target.

$$E_n = E_{(N-1)} - E_{(N)} = E_0 - E_1 - E_2$$

$$\vec{q}_n = -\vec{q}_R = \vec{K}_0 - \vec{K}_1 - \vec{K}_2$$

(usually termed Missing Energy and Missing Momentum in nuclear physics) are measured and found to be equivalent to binding energy and linear momentum ( $E_n$  and  $\vec{q}_n$ ) of the individual  $n^{\text{th}}$  particle initially bound in the target.

Obviously, one such experiment requires to detect and measure in time coincidence [4] energy and momentum of the two final free particles. In other words, energy and momentum conservation applied to the collision allow to determine binding energy and Wigner phase-space momentum distribution of the bound particles.

In spite of the intrinsic complexity, the knock-out experiments established the SM as a cornerstone of quantum physics, demonstrating its ability to describe and predict the quantum mechanical behaviour of matter at the atomic and subatomic level.

To this end, knock-out (quasi-free) experiments initiated by proton beams (p,2p) were largely applied [5]. However, the strong proton-nucleon interaction complicated the interpretation of (p,2p) experiments due to distortions from multiple interaction of the two particles involved in the reaction with residual nucleons (N-1 nucleons system), which rapidly worsen with increasing atomic number [6].

Recognizing these challenges, Amaldi foresaw a broader applicability for quasi-free scattering collisions if instead of protons were used electrons (e,e'p), which on the one side offered reduced distortion in nuclear reactions and on the other side made the technique extensible to investigate single particle properties of atoms, molecules and solids. This foresight shaped his research at Istituto Superiore di Sanità (ISS) from 1962 to 1972.

### 1. First (e,e'p) experiment at Frascati: Nuclear spectral function and Momentum distributions

In 1962, while accompanying the Swedish physicist Torleif Erikson, well known theoretical physicist at CERN, to visit the Frascati electrosynchrotron (LNF), Amaldi learned that two Brazilian physicists had proposed to study the quasi-free extraction of protons from nuclei through the reaction (e,e'p) that offered a simpler interpretation as compared to (p,2p) [6]. Due to the weakness of the electromagnetic interaction, distortions are much reduced, and the interaction could be very well described as a single «quasi-free» electron-single proton diffusion in the presence of a “frozen” reminder nucleus,

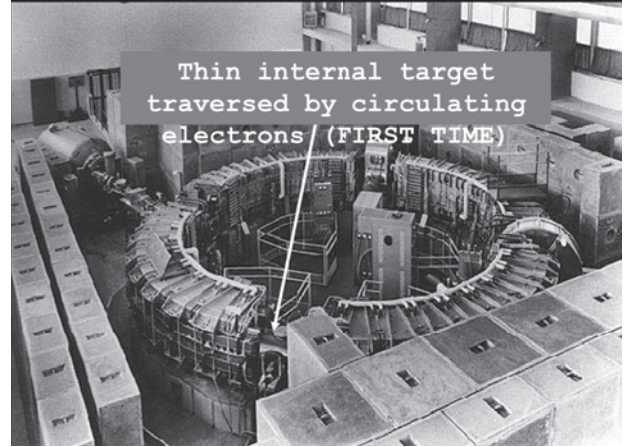


Fig. 2. The Laboratori Nazionali di Frascati electrosynchrotron (LNF) in the early 1960s, site of the first (e,e'p) experiment. Highlighted is the position of the thin target, directly placed in the orbit of the 550 MeV electron beam. See the main text for details (Courtesy of Ugo Amaldi).

as schematically represented in figure 1. All of this amounted to the possibility to measure the momentum distribution associate to a nuclear level of well-defined binding energy prior to the collision with the electron.

Ugo immediately proposed to Mario Ageno, then director of the Laboratorio di Fisica of Istituto Superiore di Sanità (ISS), to develop, in cooperation with LNF, the (e,e'p) spectroscopy as a new experimental activity of the ISS nuclear physics programme. The new activity would fit seamlessly into the long-standing and well-established tradition of the Laboratorio di Fisica in the field of Nuclear Physics. The designed experiment would involve directing the 550 MeV electron beam circulating in the synchrotron ring onto a thin carbon target (see figure 2) and measuring, coincident in time, the energy of the electron scattered and the proton ejected from the nucleus by the collision itself.

Such an experiment had never been conducted before because all previous researchers had used linear accelerators with energies of a few tens or hundreds of MeV, which operate with on-time of only a thousandth of a second, that is, due to the overwhelming number of random coincidences, too short to observe coincidences between the scattered electrons and the ejected protons. On the contrary, a synchrotron has an on-time of about hundred times longer, that makes the rate of random coincidences low enough to make the experiment feasible.

A new research group was soon established with the members of ISS Reparto di Fisica delle Alte Energie led by Giorgio Cortellessa.

Taking advantage of the technical support and of the computing facilities offered by the ISS Laboratorio di Fisica, in 1964 was realized the first (e,e'p) experiment that measured the nuclear spectral function, distribution of binding energies (or missing energy  $E_n = E_0 - E_1 - E_2$ ), of the  $^{12}\text{C}$  and  $^{27}\text{Al}$  nuclei. The experiment, not an easy one, involved detecting protons ejected from the target by high-energy electrons, but challenges arose due to the high electron flux. Assistance from physicist Peter Hillmann, at that time visiting ISS, and the use of scintillation counters bravely placed just 20cm away from the target positioned directly in the internal circulating electron beam of the synchrotron (see figure 2), helped to overcome these difficulties.

The nucleus shell structure was evident and, contrary to (p,2p) experiments, it was possible to investigate the proton binding energies from the outermost 1p to the innermost 1s shell of carbon and from 2s1d to 1s in aluminium [7, 8]. Figure 3, which shows the production rate of electron-proton coincident pairs as a function of the binding energy in the (e,e'p) reaction on  $^{27}\text{Al}$  nucleus (i.e., the proton's binding spectral function), clearly demonstrated that these experiments were capable of measuring the complete energy spectrum of single-particle bound states in the nucleus.

To fully validate the shell model, what was needed was the measurement of the momentum distribution of the nucleon's bound states, particularly the angular correlation measurement of electron-proton pairs generated in a quasi-free (e,e'p) event.

This lack of experimental evidence was filled by the ISS research group led by Ugo who conducted, always

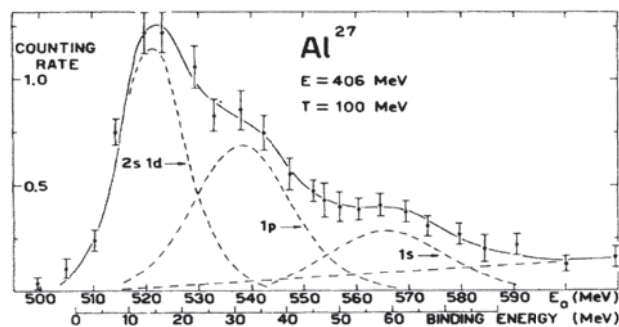


Fig. 3. First (e,e'p) experiment at LNF. Electron-proton coincidence counting rate at 550 MeV, plotted as a function of the incident energy  $E_0$ . The dashed lines represent the contributions from the different nuclear shells and the background. The distribution clearly shows the extraction of protons from the 1s, 1p and 2s 1d shells of the Al nucleus. The scale of the proton Binding Energy in the nucleus is linked to that of the incident electron energy through energy conservation, as detailed in the text [7].

at the LNF electrosynchrotron in Frascati, the first (e,e'p) experiment resolved in energy and angle. The experiment measured the angular distributions of the protons extracted from the  $\text{C}^{12}$  target for two values of the missing energy corresponding to the binding energy of the 1s and 1p shells [9]. The kinematics of the experiment is shown in the inset of the figure 4 left panel. Conservation of linear momentum yield the missing momentum that, upon validity of the impulse approximation, and in absence of Final State interactions with the residual nucleus, i.e. in Plane Wave Impulse Approximation (PWIA), can be interpreted as the linear momentum of the proton bound in the nucleus ( $\vec{q}_n$  in the figure). The measured momentum distribution in 1s (figure 4 left panel) and 1p (figure 4 right panel) orbitals, i.e with momentum distribution maximum and minimum at  $q=0$  respectively, was found to be as expected by the SM for a single particle in a Mean Potential well. Furthermore, the measured momentum probability distribution (experimental points in figure 4) agreed nicely with the ones predicted (continuous lines in figure 4) by an independent particle model wavefunction. A simultaneous theoretical work [10] discussed its capability to discriminate among different models of nucleon wave functions and highlighted the need for a less schematic approach to the theory of quasi-free scattering, especially regarding knock-out from deep shells and from high-momentum components of the single-particle wave function.

Often, breakthrough in physics are facilitated by availability of innovative instrumentation. In this case, it was an original odoscope of scintillators, conceived by Ugo and realized at the ISS Laboratorio di Fisica workshops, to make the experiment feasible. It was this setup of ten concentric ring-shaped scintillation counters, covering a wide solid angle, positioned in front of the large proton telescope that allowed to measure the ejected protons angular distribution.

Following these experiments, the validity of the SM was definitively confirmed as a realistic representation of the nuclear ground state and, more broadly, of quantum aggregates regardless of the nature of particle interactions. Moreover, quasi-free knock-out spectroscopy became a powerful tool for studying the binding energies and momentum distributions of individual particles within any quantum aggregate. It is precisely for these reasons that Denis Haigh Wilkinson valued these results as “the most direct proof of the validity of the nuclear shell model” [11].

By this point, the path was clearly defined, and the ISS research team pursued an extensive series of experi-

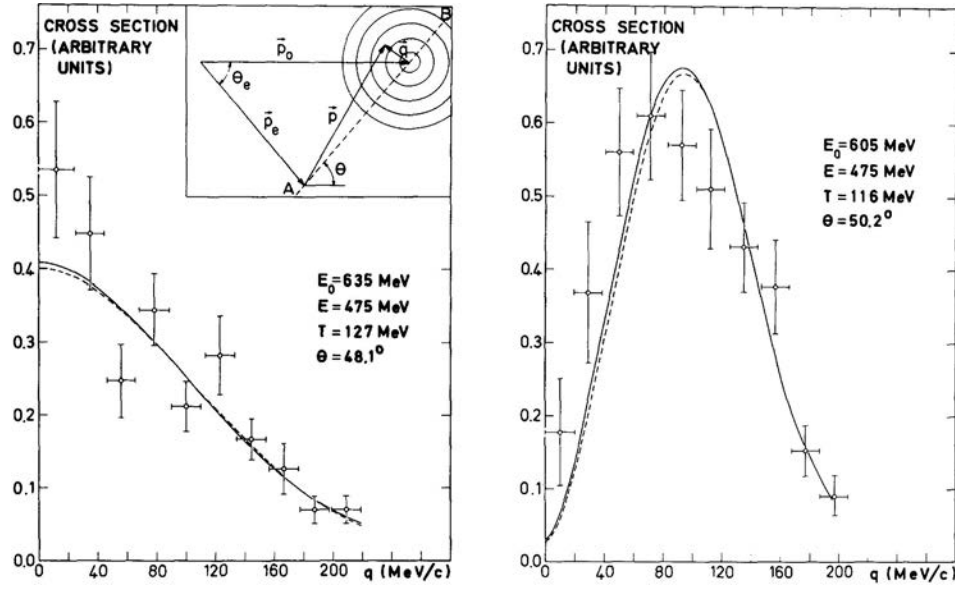


Fig. 4. The first resolved in angle  $(e,e'p)$  experiment on a  $C^{12}$  nucleus. Momentum distributions for 1s (left panel) and 1p (right panel) protons are shown. Dashed and solid lines represent fits with single proton momentum distributions as predicted by harmonic-oscillator and square-well potentials, respectively. The inset in the left panel features a kinematic diagram of the reaction, illustrating how altering the proton ejection angle  $\theta$  correspondingly modifies the individual proton momentum  $\vec{q}_n$  [9].

ments on nuclei ranging from Be to As. These efforts solidified the international standing of the research conducted both at the Frascati electrosynchrotron and through collaborative experiments at the Saclay Linear Accelerator. (ALS). [12]

In the more than fifty years since the publication of the first paper,  $(e,e'p)$  experiments have been carried out at numerous laboratories worldwide, continuously contributing valuable insights into nuclear structure and electromagnetic interactions [13]. Table 1 highlights the key  $(e,e'p)$  experiments conducted at the world's foremost nuclear physics research centers.

Table 1 – Key experimental studies on electron quasi-free scattering from nuclei carried out over the past fifty years at the world's top nuclear physics research facilities.

| Research center        | Starting year | e-beam Energy |
|------------------------|---------------|---------------|
| Frascati I (I)         | 1963          | 500 MeV       |
| Tokyo (JPN)            | 1970          | 750 MeV       |
| Saclay ALS (F)         | 1971          | 500-720 MeV   |
| Frascati II (I)        | 1972          | 700 MeV       |
| Karkov (RU)            | 1972          | 1.2 GeV       |
| Desy (D)               | 1973          | 2.7 GeV       |
| NikHef-K (NL)          | 1984          | 500 MeV       |
| Jefferson Lab I (USA)  | 1989          | 2.2 GeV       |
| Jefferson Lab II (USA) | 1995          | 6.0 GeV       |

The recent advancements at Jefferson Lab's continuous beam accelerator, paired with its two high-resolution spectrometers, have enabled the exploration of previously unreachable regions of missing energy and momentum, far exceeding the typical limits of SM validity. By extending the range of missing energy and momentum examined, the many-body properties of the nucleus can be probed, including meson exchange between interacting nucleons and, more broadly, nucleon-nucleon short-range correlations. In the  $^{16}O$  experiment shown in Figure 5, it becomes clear that as the missing momentum increases, the spectral function at higher missing energies deviates increasingly from the predictions of the SM.

In this experiment, the binding energies and moment distributions of the shell model's nuclear eigenstates have been precisely determined, and besides the effects of nucleon correlations have been uniquely identified. Additionally, valuable insight into the short-range nature of nucleon-nucleon correlations were obtained through  $(e,e'p)$  processes. [14] Figure 5 illustrates, in sequential panels from top to bottom, the cross-section of the  $(e,e'p)$  process plotted against missing energy for progressively higher values of missing momentum  $q_n$  ( $P_{\text{miss}}$  in the figure). The solid line depicts the expected single-particle contribution from the 1s nuclear state, which dominates at low  $q_n$  but becomes largely negligible at higher  $q_n$ , where the quasi-free approximation loses

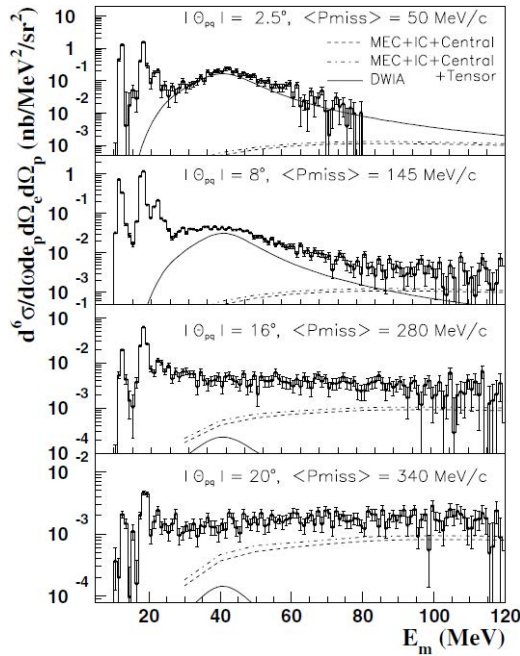


Fig. 5. The evolution of the O missing energy ( $E_m$ ) spectrum in a  $(e,e'p)$  experiment is shown for different proton ejection angles. The data is compared to theoretical single-particle  $s$ -shell models (solid line). As the missing momentum  $\vec{q}_n$  (labelled as  $\langle P_{miss} \rangle$  in the figure) increases, deviations from the SM predictions grow, highlighting the significance of nucleon correlations (dashed lines). Refer to the main text for further details [14].

valid and multi-body effects (represented by the dashed curves) becomes increasingly significant. In other words, as  $q_n$  increases, the reaction transits from a «static» to a «dynamic» regime, shifting the interpretation of missing energy ( $E_m$  in the figure) from the binding energy of a single nucleon to the collective excitation of the nucleus. In later years,  $(e,e'p)$  research has tackled increasingly sophisticated questions in nuclear physics [15].

All of this can be justly regarded as the result of the groundbreaking experiments carried out in Frascati in the late 1960s [13].

## 2. Quasi-free scattering on atoms: First $(e,2e)$ experiments at ISS

In the latter half of the 1960s, Ugo recognized that, despite electron scattering being employed since Thompson's experiment to investigate atomic structure, an experiment analogous to  $(e,e'p)$  had never previously been conducted on atoms. An experiment of this type, designated by the acronym  $(e,2e)$ , involves the simultaneous measurement of the energy  $E_0$  of the electron incident on a target atom, the energies  $E_1$  and  $E_2$  of the two

final electrons resulting from the ionising collision and the probability of their emission into solid angles  $\Omega_1(\theta_1, \phi_1)$  and  $\Omega_2(\theta_2, \phi_2)$ , i.e. the fully differential cross section of an  $(e,2e)$  process.

During that period, two Russian theorists [16] proposed that such an experiment could be conducted on atoms or molecules. They suggested that the factorized cross-section, differential with respect to the ejection angles of the electron pair produced in the collision, would be proportional to the electron momentum distribution (EMD) of the electron ejected from the atom, drawing a direct analogy to the  $(e,e'p)$  process. Around the same time, two American theorists [17] predicted that the frequency of binary collisions would be sufficient to experimentally determine the binding energy and momentum distribution of the initial atomic one-electron orbitals. However, more than these theoretical predictions, it was Ugo's comprehensive understanding of electron-matter interactions that ultimately convinced him to pursue quasi-free scattering experiments on atoms, a process that was, and remains, one of the most challenging phenomena to describe theoretically and to investigate experimentally. His comprehensive perspective is encapsulated in Figure 6, extracted from the ECFA Report authored by a committee he chaired in 1980 [18]. The graphs illustrate an electron energy transfer mechanism that exhibits striking similarities across atoms and nuclei. Specifically, they all feature an energy transfer channel at high energy and momentum transfer, referred to as quasi-free, which serves as the foundation for the quasi-free spectroscopies discussed in this paper. Concurrently with the theoretical predictions, Ugo successfully conducted the first  $(e,2e)$  experiment, leveraging the unique characteristics of a quasi-free collision [19]. The realization of the first  $(e,2e)$  experiment was a genuinely interdisciplinary endeavor. The prototype tabletop spectrometer was constructed at the Istituto di Fisica di La Sapienza. Its development leveraged the expertise in low-energy electron electrostatic analyzers (Guido Pizzella) and fast-timing electron detection techniques (Alberto Egidi and Renzo Marconero) that were, at the time, available within the astrophysics group.

The successful  $(e,2e)$  was performed on a few hundred Å thick Formar film at 14KeV incident electron energy. The method for preparing self-supporting films, adopted from the electron microscopy unit of the ISS Laboratorio di Fisica, played a crucial role in the success of the experiment. As with the  $(e,e'p)$  experiments, collaboration with the ISS computing center was indispensable for designing this experiment. Figure 7 dis-

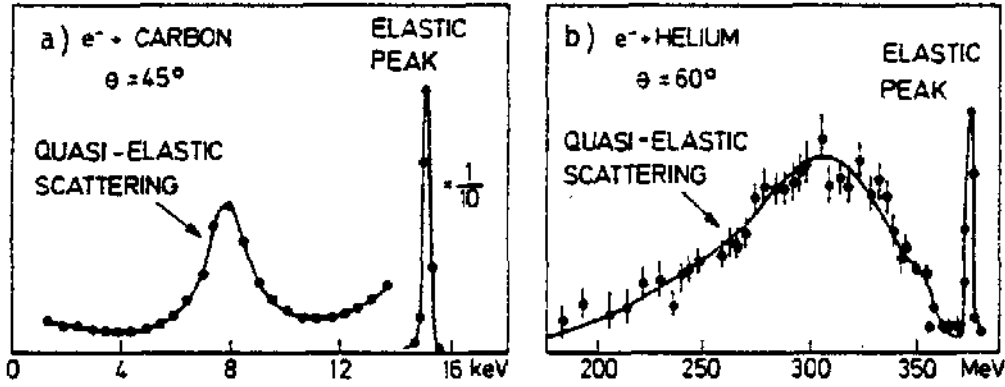


Fig. 6. Examples of the results from experiments in which electrons were scattered from (a) atoms, (b) nuclei. The abscissa is the electron incident energy, that is proportional the energy transferred in the collision if the scattered electron is collected at constant energy. Notice the qualitative similarities between the different spectra. The broad maxima in (b) and (a) correspond to quasi-free scattering event that reveal the constituents of the target nucleus and atom, respectively [18].

plays the electron-electron coincidence rate as a function of binding energy, distinctly revealing separate contributions from the Carbon K and L shells. Furthermore, by varying the relative ejection angles of the final electron pair ( $\Theta_1 = \Theta_2 = 45^\circ$ ;  $41^\circ$  as shown in Figure 7) the dependence of the relative intensities of the K and L orbitals on the missing momentum of the reaction ( $\vec{q}_n = \vec{K}_0 - \vec{K}_1 - \vec{K}_2$ ) is clearly demonstrated. This dependence is predicted within the framework of the Impulse Approximation [5] and, once again, mirrors the (e,e'p) experiment by reflecting the dependence on the single-particle momentum of the electron bound in the  $n^{\text{th}}$

atomic orbital. By precisely measuring the energy and momentum of the two final electrons, an (e,2e) reaction enables the determination of the binding energy and the corresponding three-dimensional momentum distribution of electrons bound in a mean-field eigenstate within atoms, molecules or solids.

This result was immediately met with widespread acclaim and is regarded as one of the pioneering experimental achievements that established a new research direction in atomic physics, now known as Electron Momentum Spectroscopy (EMS).

A theoretical paper by Ugo and Ciofi degli Atti soon

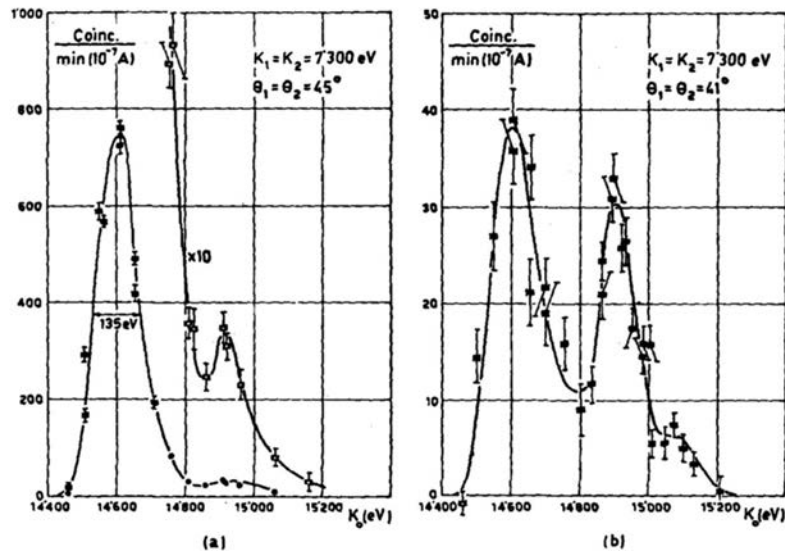


Fig. 7. First (e,2e) experiment conducted on a thin Formvar film. The electron-electron coincidence rate as a function of binding energy reveals distinct contributions from the Carbon K and L shells. The figure shows that varying the ejection angles of the electron pair,  $\Theta_1 = \Theta_2 = 45^\circ$  (panel a) and  $41^\circ$  (panel b), highlights how the K and L orbital intensities depend on the reaction's missing momentum  $\vec{q}_n$ . See the main text for details [19].

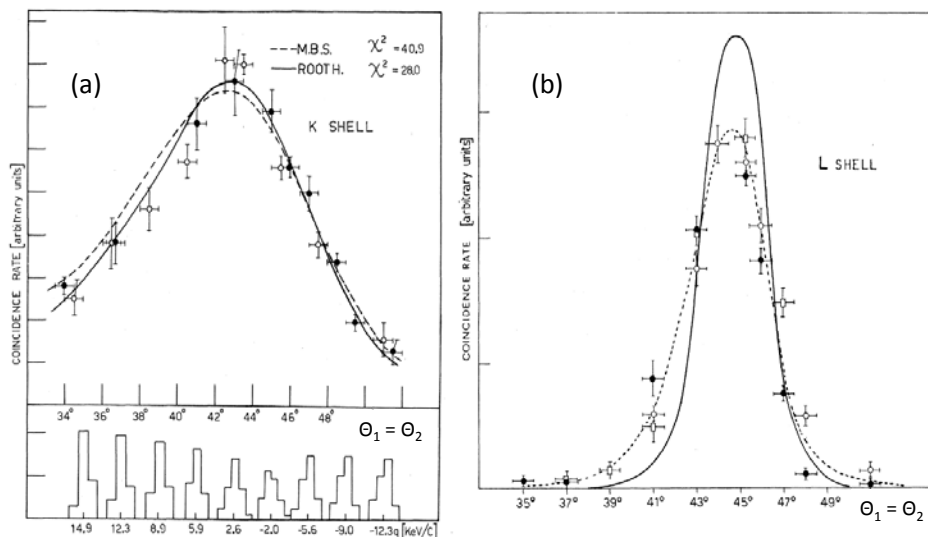


Fig. 8. The angular distribution of the (e,2e) coincidence rate for the K and L shells of carbon (left and right panel respectively) as measured at  $E_0=9.3\text{ keV}$  and  $E_1=E_2=4.5\text{ keV}$  on a  $250\text{ \AA}$ -thick carbon films. The scattering angle was correlated with the initial momentum of the atomic electron  $\vec{q}_n$ . Dashed and solid curves are predictions using MBS and Roothaan wave functions, respectively [21].

followed, in which they clearly outlined the significance and limitations of (e,2e) [20]. The outer shells of light atoms were identified as the optimal EMS domain of application, which are, notably, the most relevant for condensed matter studies.

In 1968, a graduate student at Sapienza (Rossana Camilloni) joined Ugo to assist in modifying and refining the apparatus, which had, in the meantime, been relocated from the Sapienza Istituto di Fisica to the ISS, and a second graduate student (G.S.) followed in 1969. During this period, Ugo was transitioning the focus of his scientific work to CERN and initially had no intention of taking on a second graduate student for the (e,2e) project. However, as Ugo put it, the student's arrival was a sign of Providence, and he was subsequently accepted and involved in the project, tasked with exploring potential applications to crystalline solids. The upgraded (e,2e) spectrometer was employed to conduct the first momentum-density measurement on the individual K and L shells of a carbon self-supported thin foil (100 and  $250\text{ \AA}$ ) [21]. The incident electron beam had an energy of  $9.3\text{ keV}$ , with a modest energy resolution of a few hundred eV, sufficient to clearly distinguish between K and L shell events. The momentum resolution ( $2\text{ KeV/C}$  or  $1\text{ \AA}^{-1}$ ) was more than adequate to measure the complete momentum distribution of the K and L orbitals and to differentiate between two distinct carbon 1s Hartree-Fock wave functions. The results, presented in Figure 8, show the coincidence rate distribution,

which under the validity of the Impulse Approximation is directly proportional to the single-particle momentum distribution, plotted against the ejection angles of the electron pair  $\Theta_1 = \Theta_2$  (with the corresponding individual electron momentum  $q_n$  shown on the lower scale of Fig. 9a). The data is presented for the K shell in Fig. 9a and for the L shell in Fig. 9b. The experimental results close-

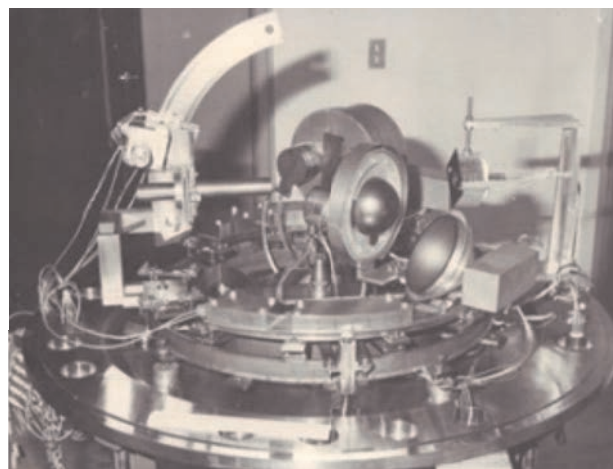


Fig. 9. The (e,2e) spectrometer developed at LNF Frascati in the early 1970s was designed for measurements on gas-phase atoms and molecules. It offered great flexibility in kinematical conditions, ranging from fully symmetric setups ( $E_1=E_2$  and  $\Theta_1 = \Theta_2$ ) within the scattering plane to asymmetric configurations ( $E_1 \neq E_2$  and  $\Theta_1 \neq \Theta_2$ ) (different energies and angles) outside the plane. This allowed for the study of target momentum distributions and for testing the validity of the quasi-free and Impulsive collision approximations.

Table 2 – Concise timeline of some of the activities in Electron Momentum Spectroscopy over the last five decades.

| Starting year | Timeline of the main research activities in Electron Momentum Spectroscopy (EMS) |                                                                             |
|---------------|----------------------------------------------------------------------------------|-----------------------------------------------------------------------------|
| 1967          | ISS & Sapienza (I)                                                               | First (e,2e) experiments on thin film                                       |
| 1972          | LNF Frascati (I)                                                                 | Momentum spectroscopy (EMS) by (e,2e) of atoms and molecules                |
| 1973          | Flinders University (SA)                                                         | EMS of atoms and molecules through binary (e,2e)                            |
| 1978          | University British Columbia Vancouver (CND)                                      | EMS of atoms and molecules through impulsive (e,2e).                        |
| 1978          | Maryland University College Park (USA)                                           | EMS of molecules and atoms through novel multichannel (e,2e) spectrometer.  |
| 1981          | IMAI-CNR Montelibretti (I)                                                       | EMS of atoms, molecules and, from 1984, surfaces                            |
| 1983          | Université Paris Sud. Orsay (F)                                                  | EMS of atoms and molecules by high energy asymmetric (e,2e)                 |
| 1983          | Virginia Polytechnic Institute.(USA)                                             | First EMS of individual valence bands in natural graphite                   |
| 1989          | Tsinghua University Peking (CN)                                                  | EMS of atoms and molecules through high-sensitivity, high-resolution (e,2e) |
| 1996          | Uni Sci & Tech China Hefei (CN)                                                  | EMS of molecules through high sensitivity (e,2e) spectrometers.             |
| 1997          | Tohoku University Sendai (JPN)                                                   | EMS and electron correlation dynamics in atoms and molecules.               |
| 2002          | Tokio University (JPN)                                                           | (e,2e) to study electron correlation and EMS in atoms and molecules         |

ly matched the distribution predicted for clean binary collisions, as described by a Hartree-Fock orbital within a Mean-Field potential.

Atomic physicists and chemists were already captivated by the results of binary nuclear breakup experiments and were energized by the proof that similar quasi-free experiments could be performed on the atomic scale. This led to a dynamic exchange of ideas and visits. At the time, the ISS served as a hub for scientists passionate about atomic physics, and Ugo, as always, was eager to both absorb and share fresh perspectives and ideas. During Ugo Fano's visit, they discussed (e,2e) spectroscopy, which received a lukewarm reaction from Fano. Rather than being discouraged, this only strengthened his resolve to pursue momentum spectroscopy for atoms. His determination was bolstered by the support of Mitio Inokuti, a prominent theorist from the Chicago Fano school, as well as by the growing interest from research groups worldwide, who were beginning to explore and capitalize on the potential of quasi-free (e,2e) processes. In 1969, during his trip to the 6th ICPEAC, Ian McCarthy visited the ISS and discussed the development of (e,2e) spectroscopy at Flinders University, deciding to maintain close contact regarding progress in the field. Soon after, a vibrant theoretical and also experimental (Erik Weigold) EMD research effort began at Flinders, leading to a steady exchange of ideas and visits between the two research groups in the years that followed. Over time, Flinders established itself as a world-class hub for EMD spectroscopy on atoms, molecules, and solids [22, 23].

Ugo was confident that (e,2e) spectroscopy held great potential and did everything in his power (never a small effort) to establish a substantial research group around the experiment. However, two newly minted Laureate fellowship holders did not constitute a solid team. He succeeded in persuading Anna Giardini, a former classmate who was in the process of transferring from CNR to the CNEN Frascati Laboratories (LNF), to take on the responsibility of leading the group.

In 1971, the apparatus was relocated from ISS to Frascati, marking the beginning of the LNF (e,2e) group's activities. Over the following years, the LNF group not only upgraded the prototype (e,2e) spectrometer with a new electron source but also designed and built a second-generation spectrometer (pictured in Figure 9). This new instrument featured advanced electron spectrometers designed to achieve improved energy and angular resolution. The development of the new spectrometer was carried out in collaboration with Guido Missoni at Bari University, where C. E. Kuyat had introduced expertise in electron optics acquired at NBS (now NIST). On this occasion, Ugo's generosity shone through. He was a constant source of inspiration and support for the LNF (e,2e) group, yet he chose not to co-author the papers they published, including the first one [21]. His primary goal was always to see worthwhile projects come to fruition, without concern for his own personal recognition.

The two ground-breaking (e,2e) experiments laid the foundation for a spectroscopy technique that has since been widely applied, and continues to be used, to study

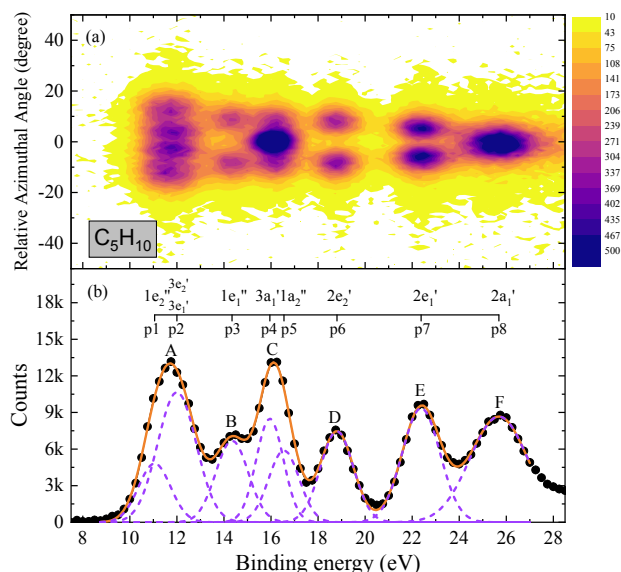


Fig. 10. 2D map of the electron momentum density versus binding energy and azimuthal angle for cyclopentane's valence orbitals (panel a). The binding energy spectrum, integrated over angles, features blue dashed lines for Gaussian peak fits, with their total shown as a red solid line (panel b) [29] (courtesy of Dr. Enliang Wang).

atoms, molecules, and solids in numerous laboratories worldwide for cutting-edge research in chemical physics. Table 2 highlights most of the laboratories that have been active in this field over the past decades. Their contributions are encapsulated in a series of outstanding review papers [24, 25, 26, 27], the most recent of which was written forty years after the initial publications [28], with the latest research papers appearing fifty years later. [29]. With these latter papers, the chemists' dream of visualizing molecular orbitals by (e,2e) spectroscopy is finally realized, after 55 years of uninterrupted evolution. Lately, at Hefei University (China) Liu et al., with a multichannel (in energy and momentum) (e,2e) apparatus, have measured the cyclopentane molecular momentum density that is shown, in scale of false colours, in figure 10a where the azimuthal angles on the y-axis correspond to the bound valence electron momenta  $q_n$ . The correspondent binding energies of the individual molecular valence orbitals  $E_n$  (from the outermost  $1e_1$  to the innermost  $2a_1$ ) are reported on the x-axis.

In panel 10b is the angle integrated (e,2e) cross-section projected onto the binding energy scale, i.e. the spectral function of single particle molecular orbitals.

These results clearly show that (e,2e) has now evolved into an accurate tool to picture, in binding energy vs. momentum space, ( $E_n$ - $q_n$ ) atomic and molecular orbitals.

## Conclusions

The legacy of quasi-free collision experiments is likely to extend far beyond the current era. Future research endeavors will probably leverage these techniques to probe the intricate properties of nuclei, atoms, molecules, and solids, delving into complex phenomena such as nucleon-nucleon and electron-electron correlations that transcend the independent particle model. The pioneering work conducted by Ugo in this field has undoubtedly left an indelible mark, continuing to inspire and motivate new generations of researchers. Throughout his career, Ugo has consistently demonstrated his capacity as a trailblazer, characterized by a clear and unencumbered vision of the scientific trajectory to pursue. His openness to novel ideas and willingness to share insights have been instrumental in shaping the development of various fields, fostering a lasting impact that persists to this day.

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