Microscopic Nuclear Reaction Models: Bridging Microscopic Theory and Nuclear Data. In Memory of Eric Bauge

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Abstract. A major goal in the field of nuclear reaction modeling has been to move from phenomenological models to predictive, microscopic theories—a central focus at CEA/DAM since the mid-1970s. A significant milestone in achieving this objective was reached in the early 1980s with the first applications of the JLM folding model by Lagrange *et al.*, using HF and RPA ground and transition densities, and later deformed HFB densities. From the mid-1990s, E. Bauge advanced these efforts by encouraging and systematically applying them, playing a key role in advancing the field. These developments include detailed methods to describe direct reactions, such as elastic and inelastic scattering, and pre-equilibrium emission. This work has greatly improved our understanding of direct reactions in nuclear structure studies and laid the foundation for practical applications, benefiting users from astrophysical modelers to energy specialists. Building on the foundational work of researchers worldwide, and in particular the contributions of pioneers from CEA/DAM such as D. Gogny, M. Girod, Ch. Lagrange, and J.-P. Delaroche, Eric's vision helped bring long-standing efforts to fruition. Today, his former students and collaborators continue these efforts, integrating results from various nuclear structure approaches into reaction studies, supported by the international partnerships he fostered. This has helped encourage similar advancements in other laboratories and supported a collaborative legacy that continues to drive the field forward.

1 Introduction

Building upon the foundational works of Jeukenne, Lejeune, and Mahaux (JLM) [1] and Ch. Lagrange *et al.* [2], Eric Bauge, in collaboration with J.P. Delaroche and M. Girod, made significant advancements in nuclear reaction modeling during the mid-1990s. They developed a semimicroscopic nucleon-nucleus spherical optical model for nuclei with mass numbers $A > 40$ and energies up to 200 MeV [3]. This groundbreaking work systematically integrated microscopic nuclear structure calculations within optical model potentials (OMPs) over a broad range of nuclei and energies. By extending the JLM nuclear matter approach to higher energies and performing Hartree-Fock-Bogoliubov (HFB) calculations with the Gogny force for consistent radial densities, they demonstrated that the extended JLM model could reliably predict neutron and proton scattering across a wide energy range. Analyzing over 300 datasets—including differential cross-sections, analyzing powers, spin rotation functions, and reaction cross-sections—they showed the effectiveness of optimized Local Density Approximation (LDA) and spin-orbit prescriptions. In 2001, Bauge and collaborators further enhanced this model by introducing a Lane-consistent, semimicroscopic nucleon-nucleus optical model [4], addressing limitations in the isovector components of the JLM OMP and achieving better agreement with experimental data.

Bauge's efforts bridged the gap between nuclear structure and reaction models, shifting from phenomenological to predictive microscopic frameworks. The evolved JLM folding approach accurately describes elastic and inelastic neutron and proton scattering for both spherical and deformed nuclei, supporting DWBA and coupled-channel calculations with rotational couplings. It has also been applied to ^{4}He and ^{12}C scattering using the double-folding method within the "frozen projectile" approximation.

At CEA DAM, advanced nuclear structure methods are being developed across the nuclear chart, including Hartree-Fock(-Bogoliubov) (HF(B)), (Quasiparticle) Random Phase Approximation ((Q)RPA), Multi-Particle Multi-Hole (MPMH), and five-dimensional collective Hamiltonian (5DCH) techniques. Efforts are underway to incorporate new *ab initio* approaches with Projected Generator Coordinate Method (PGCM) [5] and Quasi-particle Finite Amplitude Methode (QFAM) [6] implemented with chiral interactions. The JLM folding model effectively bridges these nuclear structure models and cross-section calculations, enabling broader reaction predictions and testing nuclear structure predictions against observables.

These advancements have significantly contributed to nuclear structure studies, particularly in direct inelastic scattering [7] and pre-equilibrium emission processes. For

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actinides, the models have addressed pseudo-state contributions [8] and accurately predicted high-energy neutron emissions, successfully replicating double-differential (n,xn) measurements. Predicted spin distributions for nuclei with masses from $A = 20$ to 240 have been instrumental in (n,n' γ) studies and as inputs for surrogate reaction methodologies [9], providing crucial data for reactions that are challenging or impossible to perform directly.

From the early 2000s, Eric Bauge promoted efforts to go beyond the JLM approximation by initiating the application of the full g-matrix folding model. He encouraged the consistent use of the Melbourne g-matrix [10] for various applications, from elastic [11] to inelastic scattering, encompassing both discrete excitations [12] and continuum excitations [13, 14]. This initiative led to collaborative work by researchers like S. Karataglidis and colleagues. Eric's support also encouraged work to improve the derivation of the g-matrix from Santiago, in collaboration with H.F. Arellano, to increase its predictive power [15, 16]. Recognizing limitations of the nuclear matter approach below 30–40 MeV per nucleon, he initiated a fruitful collaboration with N. Vinh Mau to derive the optical potential directly within finite nuclei using the Green's function formalism. While others carried out the detailed work, his efforts helped treat nuclear structure and reactions on an equal footing, yielding promising results, particularly for doubly magic nuclei [17, 18].

A long-term collaboration with J. Raynal, the author of the well-known ECIS [19] and DWBA codes [20], later continued by collaborators at CEA, greatly contributed to the development of microscopic reaction calculations.

Providing a comprehensive summary of Eric's contributions and the work he inspired is a significant task. This text offers a broad overview by highlighting key examples that showcase the depth and diversity of his contributions, while acknowledging that many important aspects may extend beyond the scope of this article. Notably, uncertainties and other intricate topics will be covered in dedicated articles honoring his memory.

This paper begins by revisiting Eric's significant contributions to the development and application of the JLM folding model in Sec. 2. Section 3 highlights advancements beyond the JLM approximation, including collaborative efforts on the full g-matrix folding approach. Recent developments and applications of the JLM model in surrogate studies, actinide reactions, nuclear structure investigations, and (n,n' γ) studies are briefly reviewed in Sec. 4. Finally, Sec. 5 explores ongoing projects stemming from Eric's foundational work, such as coupled-channel calculations with non-local potentials for deformed targets and extensions in pre-equilibrium reactions. Eric's pivotal contributions to the P(ND)^2 conferences and the integration of microscopic models into nuclear data will be briefly mentioned in Sec. 5. The paper concludes with final remarks summarizing the key points discussed.

2 Application of semi-microscopic JLM nucleon-nucleus optical model

Eric Bauge's work on the 1998 and 2001 Lane-consistent parameterizations of JLM, now called JLMB for JLM Bruyères, has been successfully applied beyond the scope of elastic and charge-exchange processes to inelastic scattering of discrete excitations in spherical [7, 21] and deformed targets [22, 23]. In the last case, the deformed optical potential is obtained by folding the deformed ground-state HFB densities with the JLMB effective interaction. Projection techniques provide all the necessary diagonal and transition potentials. Applications have utilized results from both the RPA approach with the Gogny force and the five-dimensional collective Hamiltonian (5DCH) method.

Figure 1 shows an example of a comparison between JLM calculations using QRPA and 5DCH nuclear structure input performed by E. Bauge. This was the first application of the newly implemented QRPA method with the Gogny D1S force to reaction studies, conducted in collaboration with S. Péru. The calculations demonstrate that the QRPA approach successfully reproduces the magnitude of the measurements, whereas the 5DCH approach does not. Numerous applications using QRPA to direct and pre-equilibrium reaction modeling followed in the 2010s.

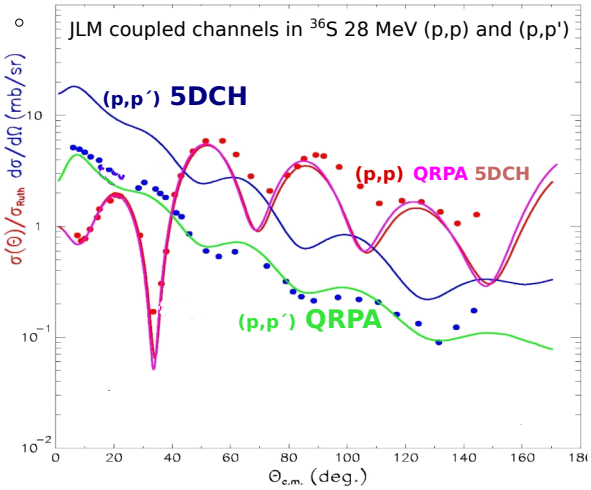

Figure 1. 28 MeV proton elastic and direct inelastic cross section to the first 2^+ level in ^{36}S. Cross section calculated from both 5DCH and QRPA nuclear structure models within the JLM folding model are compared to measurements.

Indeed, microscopic modeling has been essential for interpreting new nuclear data, such as those obtained from the measurements conducted by G. Haouat and colleagues. This foundational work paved the way for further studies involving deformed HFB calculations and coupled channel (CC) analyses within the ground-state band, particularly in the context of neutron elastic and inelastic scattering from Gd isotopes with $A = 155$ to 160 [23, 24]. Haouat's data also extend to ^{206,207,208}Pb and ^{209}Bi. The use of RPA and QRPA transition densities has been crucial for accurately modeling these scattering processes. This approach

not only revisits and refines aspects of reaction modeling, such as rearrangement, but also underscores the challenges of integrating reliable nuclear structure inputs into these models [7].

3 Full folding model

Beyond the JLM folding model lies the full folding model, based on the determination of the Brueckner g-matrix in nuclear matter (NM). The Melbourne [10] version provides a g-matrix in coordinate space that is complex, energy- and density-dependent, with finite-range Yukawa functions, including central, spin-orbit, and tensor components in all relevant S, T channels. This effective two-body interaction was used within the LDA to describe elastic [11] and inelastic scattering to both discrete and continuum levels [12, 14] (the first step of pre-equilibrium), using one-body density matrices calculated from RPA and MPMH [25] approaches implemented with the D1S Gogny force. Figure 2 provides an example of a full folding calculation of inelastic scattering to giant resonances in ^{208}Pb, where RPA density matrices and the Melbourne g-matrix were used to generate both the optical and transition potentials within DWBA.

The nuclear matter approach was further developed in collaboration with the University of Chile in Santiago, led by H. F. Arellano. This work emphasized the explicit separation between medium-free and medium-dependent contributions [15], aiming to move beyond previous approximations in g-matrix calculations. By fully accounting for the Fermi motion of the struck nucleon throughout the nucleus and retaining the genuine off-shell structure of the nucleon-nucleon effective interaction, the collaboration achieved a significant advancement: the development of a 7D-folding integral in a density-dependent microscopic optical model potential for nucleon-nucleus scattering [16].

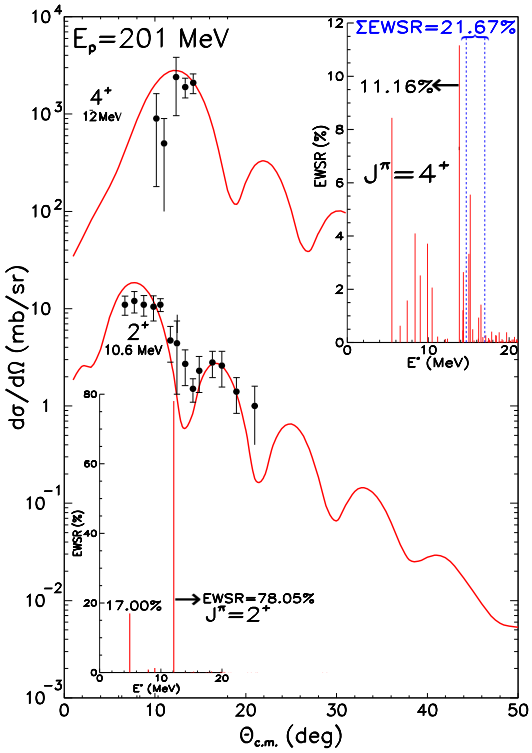

Figure 2. Inelastic scattering of 201 MeV protons to the 2^+ and 4^+ giant resonances in ^{208}Pb. The contribution to the Energy-Weighted Sum Rule (EWSR) for each resonance, considered in the calculations, is shown in the two inserts. The DWBA scattering calculations were performed using the Melbourne g-matrix, and the nuclear structure was modeled with the RPA using the Gogny D1S interaction.

4 JLM folding model for various reaction observables

Applications at lower energies highlighted the challenge of addressing "pseudo states" in actinides, initially studied by T. Kawano in collaboration with E. Bauge. Subsequent studies extended to neutron energies below 30 MeV in actinides, revealing that quasiparticle excitations from HFB alone were insufficient, emphasizing the need for low-energy collective states and deformed QRPA methods.

The first investigation on the spherical nucleus ^{90}Zr [13] explored low-energy collective states and tested various DDM3Y interactions, reproducing doubly differential (n,xn) cross sections below 20 MeV.

In actinides, challenges related to deformation and coupled channels arose. The JLM model was employed for its broad energy coverage and ease of implementation with local potentials, coupled with ECIS for coupled channel calculations between the ground state and excited bands. All QRPA one-phonon excitations were included within the QRPA/D1S framework [26], providing detailed insights into reaction mechanisms at low energies [8]. Figure 3 shows the 9.1 MeV ^{238}U(n, xn) double differential cross section at $\Theta_{cm} = 60°$, highlighting contributions from QRPA one-phonon excitations within the CC formalism and JLM folding model. These predictions capture the measured magnitude of the cross section at high energy, removing the need to resort to ad hoc pseudo-states.

5 Future developpements

The Melbourne or Santiago g-matrices are typically applied for energies above 40 or 30 MeV. In contrast, the JLM folding model covers a broad energy range from 1 keV to 200 MeV, making it particularly suitable for applications at energies below 30 MeV due to its phenomenological basis and certain approximations, such as locality and non-dispersive properties.

The pre-equilibrium model introduces open questions, including the determination of two-step processes and

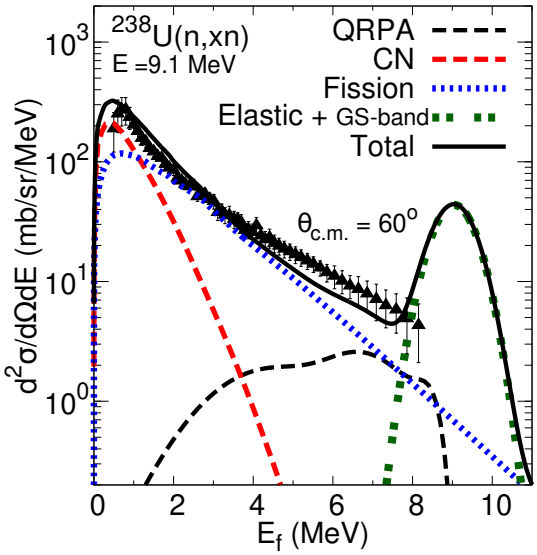

Figure 3. 9.1 MeV ^{238}U(n, xn) double differential cross section at Θ_{cm} = 60°. The inelastic scattering to the continuum contribution from QRPA one-phonon excitations calculated within the CC formalism and JLM folding model is shown as a black dashed line. Other components, including elastic and inelastic scattering to the GS band members (double dashed green line), neutrons evaporated from the compound nucleus before fission (red dashed line), and neutrons evaporated from fission fragments (dotted blue line), are also shown, as well as the sum of all these contributions (solid black line).

other approximations needed for accurate applications. Extending these studies to lower energies and applying them to deformed targets such as actinides remain important objectives for comprehensive reaction analysis the require new developpments.

To enhance the capabilities of nuclear reaction modeling, the integration of features from three well-known codes has been pursued. HYDRA, developed by H. Arellano, is a charge-exchange code that handles two coupled channels with non-local potentials. DWBA98 [20], authored by J. Raynal, performs DWBA calculations using non-local potentials. ECIS [19], also by J. Raynal, is designed for coupled channel calculations with local potentials and allows external inputs. To combine the functionalities of these codes and extend their applications to more complex methods such as second-order Born approximation, coupled channels with non-local potentials, and the inclusion of couplings between excited states, two new codes have been developed [27]. The first, MINILOP, supports both local and non-local potentials, takes input from the G-matrix and nuclear structure data, and incorporates generalized couplings. The second, ECANOL, solves scattering equations for coupled channels with non-local potentials, accepts external inputs, and includes a DWBA option. ECANOL also employs numerical methods derived from both HYDRA and DWBA98.

These advancements pave the way for more comprehensive and accurate nuclear reaction calculations.

6 Nuclear data

Eric played a pivotal role in organizing the first edition of the conference "Perspectives in the Nuclear Data for the Next Decade P(ND)^2" in 2006 and co-organized the second edition in 2015 [28]. These efforts underscored his commitment to advancing reaction models, particularly in the development of microscopic models, and fostering their integration into the nuclear data community. This topic is highlighted in the paper by S. Hilaire *et al.* [29], which Eric co-authored, showcasing the contributions of microscopic approaches to nuclear reactions and data, to which Eric made significant contributions.

The third edition of this conference, P(ND)^2, is anticipated in 2025, underscoring the ongoing legacy of his contributions. His work has been instrumental in bridging the gap between theoretical model development and practical applications in nuclear data.

7 Conclusion

The work initiated and strongly encouraged by Eric laid the groundwork for research efforts that are now being advanced collaboratively with other laboratories, using approaches that share similar underlying principles. His vision extended the pioneering work of former CEA/DAM researchers such as D. Gogny, Ch. Lagrange, J.-P. Delaroche, and others worldwide, building on their foundational contributions. By fostering and nurturing collaborations, Eric ensured that these longstanding efforts have led to significant advancements, promoting mutual enrichment and innovation. His initiatives allowed the groundwork laid by previous generations to evolve and expand, creating a legacy of collaborative progress and practical applications.

The integration of microscopic modeling of nuclear structure and reactions into the nuclear data domain is a transformative step currently being pursued in our laboratory and others [30, 31]. The application of methods such as the JLM folding model is progressing, building on developments that started many years ago and reflect the dedicated efforts of numerous researchers. This ongoing work demonstrates the growth of these models and their potential to bridge the gap between theoretical nuclear structure and practical reaction data, marking an important step forward in the field.

Eric consistently demonstrated encouragement and positivity. His attentive listening, valuable advice, and commitment to staying informed inspired the team. I am grateful for his guidance, which continues to have a lasting impact on our work.

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