Ettore Gadioli's Research in Preequilibrium Reactions and Los Alamos' Interest in This Field

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It is a great honor to be able to speak tonight in celebration of Ettore's research career in preequilibrium reaction physics. This talk provided me with an opportunity to read Ettore's papers, or rather I should say re-read, since I first read those papers more than 20 years ago when first starting out as a PhD student in Oxford. In those days, Ettore used to regularly visit and work with Peter Hodgson, and us graduate students enjoyed our many discussions with Professor Gadioli and valued the insightful suggestions he would make on our research work.

This conference is at least the third Celebration of Ettore's Work. In recent years we have also seen celebrations at the Latin-American Symposium, organized by Laszlo Sajo-Bohus, and the Americium Workshop that we organized in Santa Fe. The americium-241 (n,2n) reaction is important for various applications, and its accurate prediction requires an understanding of preequilibrium reactions as well as fission competition, and it therefore seemed appropriate to use the meeting to honor Gadioli's contributions.

When I think of Ettore's major contributions to physics I think of his work in helping found and develop the exciton model; his pioneering work on nuclear level densities; his interest in extending exciton model concepts to ion reactions using the Boltzmann master equation approach that has dominated his research interests in more recent years with his collaborators at iThemba; and his service to the community in leading the Varenna conference series for thirty years. For preequilibrium reactions, the Varenna conferece series was the place for friendly but passionate preequilibrum arguments. Arguments on the relative merits of various statistical assumptions embodied in the exciton versus the hydrid semiclassical models, and arguments about various quantum formulations such as FKK, NYW, and TUL. Of course the fathers of these various quantum formulations have been regular attendees at Varenna, including Feshbach, Kerman, and Lenske. I personally found the Varenna meetings to be a very exciting place to discuss preequilibrium physics.

I decided to select three early papers that Ettore wrote, to frame my talk, papers that have been cited many hundreds of times by other researchers in the community. Even though these papers were written more than thirty years ago, they laid the foundations of the field and they have stood the test of time. They are still fun to read, and their conclusions and insights are still valid. They are the paper from 1968 with Zetta on nuclear level densities, the 1973 paper with Enrica Gadioli Erba and with Sona on particle-hole decay rates in the exciton model, and the 1977 paper on comprehenive modeling of excitation functions and emission spectra, with Enrica Gadioli Erba and with Hogan.

Some of the themes present in these papers have continued throughout much of Ettore's career. They are the realization that understanding the phase space for various transitions can be a powerful tool for understanding reaction mechanisms; a love of statistical properties of nuclear structure and reactions; the ability to crafts clever experiments & develops models for their interpretation; an emphasis on the importance of models that comprehensively describe all competing reactions; and an interest in applications of nuclear science for areas as diverse as cancer therapy and space radiation protection.

So let me say a few words about the three important papers I just mentioned.

Firstly, we'll discuss Ettore's 1968 paper on nuclear level densities. This paper proposed a functional form for the level density based on the shapes of emission spectra from the compound reactions (n,p), (n,α), from slow-neutron resonances at the binding energy, and from level widths at high excitation energies. Nowadays, other global parameterizations – that also include collective effects and the washing out of shell effects - tend to be implemented in modeling codes, but they all build on Ettore's early insights.

Secondly, we'll look at Ettore's paper from 1973 that laid the foundations for the exciton model. In this work, Ettore was inspired by some other papers that had recently been written. Griffin, from Los Alamos, had written his seminal paper suggesting an exciton model to understand observed reaction data. And Feshbach, Kerman, and Lemmer had written their paper on how the compound nucleus is reached via doorways states. The paper by Harp, Miller, and Berne, was also written, a paper that had a profound influence on Ettore's later work on BME approaches.

This paper presented a number of insights that extended Griffin's early work. He did not make a single-particle equidistant assumption, but instead calculated exciton state densities with square well and harmonic oscillator potentials. He discussed the role of a finite potential well depth in the level density calculations. Nucleon-nucleon collision rates for damping were calculated, and he found that multipliers to this rate were needed to match observed data (later he derived such damping rates from the imaginary part of the optical potential). And very importantly, he established the model's predictive power, comparing model calculations against his own data for *(p,n)* activation reactions up to 50 MeV. Many features in this paper have become standard in the modeling codes used in the community today, for example codes developed by Los Alamos researchers Ed Arthur, Phil Young, Connie Kalbach, & more recently Toshihiko Kawano, Patrick Talou, and myself, not to mention the important codes developed by Herman and by Koning and Hilaire.

Thirdly, I will discuss the paper with Hogan, on a comprehensive modeling of reactions up to 100 MeV, studying both emission spectra of light ejectiles, and excitation functions of (p,xn yz) reactions. Around this time, Marshall Blann had published some of his early papers on the hybrid model, and there is a striking commonality of interests between Ettore and Marshall's interests (and I should say that Marshall gave a moving speech in honor of Ettore's work a our Santa Fe meeting). Also, the quantum paper of Agassi and Weidenmuller had just been written, soon to be followed by the Feshbach-Kerman-Koonin paper, the ideas embodied in FKK having been first presented by Feshbach at Varenna conferences. Gadioli's work was notable for using one set of physics-motivated input parameters to comprehensively model a broad suite of competing reactions. The paper was one of the first, perhaps the first, to compute multiple preequilibrium emission events that become important above about 50 MeV. Models were also presented for interpreting alpha emission, including the role of preformed alphas clusters. This work laid the foundations for later approaches for modeling nuclear cross sections for applications, *e.g.* my own LA150 ENDF cross sections for accelerator-driven nuclear waste transmutation and hadron therapy applications.

It is interesting to note that the generation of scientists who were first excited by the quantum multistep formulations that appeared in the early 1980s, and who worked to implement and extend these formulations, have now also embraced the predictive power embodied in the simpler semiclassical models. Despite all the important advances made on the quantum approaches, their more rigorous theoretical foundation, and their strength in modeling certain phenomena – for example angular distributions, analyzing powers, and spin distributions – the exciton model still has the more impressive global predictive power!

So I would like to end by thanking Ettore for a wonderful set of tools that he invented that allow us to model, and interpet, a broad array of nuclear reactions, and that continue to be essential for advancing our understanding of cross sections, especially for the application of nuclear science to various technology fields.