Specialists' Meeting on the Nucleon-Nucleus Optical Model up to 200 MeV: Conclusions and Recommendations

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If I may be permitted to speak for the participants of this meeting, we owe our very warm thanks and therefore a very strong round of applause to the ORGANIZERS of the meeting: Olivier Bersillon, Jean Paul Delaroche, Arjan J. Koning, and Pierre Nagel, to the HOSTS of the meeting: the *Service de Physique et Techniques Nucléaires, Centre d'études de Bruyères-le-Châtel*, and to our SECRETARY: Nadine Labbal. I believe that seldom, if ever, have we simultaneously experienced such warmth and elegance at a scientific gathering. We thank you and we salute you.

May I also say, for all of us here, that we remember with respect our colleague here at B-III, Dr. Christian Lagrange, who during his life did much to advance our knowledge and understanding of the optical model.

Now what has our meeting been about? Experimentalists and theorists who have been addressing the medium-energy nucleon-nucleus optical model potential have been invited here to discuss their work so that we can assess our present understanding and to determine what next is to be done. All of this is driven by (a) the goals of fundamental physics understanding and complete predictive power for the elastic scattering observables and (b) the crucial importance of the optical model to the nuclear reaction codes that treat simultaneously all competing non-elastic channels. In particular, accurate knowledge of the total scattering flux and its partition into elastic and non-elastic components is provided by a physically correct optical potential. This is the very first step in obtaining a physically realistic evaluation of the complete set of cross sections for all open channels at a given projectile energy. The optical potential is thus a crucial ingredient in such evaluations for the above reason and also because the scattering S matrix that it provides is itself an essential input to an array of nuclear reaction codes that treat specific open channels. Therefore, the generation of accurate medium-energy cross section and spectra libraries for applied purposes depends critically upon the medium-energy nucleon-nucleus optical potential.

So, what have we learned and concluded, and what recommendations should be made? Considering experiment first, there exists a fairly extensive medium-energy proton-nucleus scattering data base consisting of well-measured differential elastic cross sections, asymmetries, and spin rotations. However, there are relatively few proton total reaction cross section measurements at medium energies and many of these have large experimental uncertainties [Lhenry]. Thus, a number of medium-energy proton total reaction cross section measurements are needed at accuracies of (say) better than 5%, because this observable constrains the non-elastic scattering flux predicted by the optical potential and, equally important, it discriminates between two (or perhaps more) otherwise equivalent families of potentials in a Dirac phenomenology approach [Madland]. The choice of targets and bombarding energies should, of course, be based on the voids in the existing experimental data base and/or on complementarity with existing measurements of the same (or similar) neutron elastic scattering observables. Turning to medium-energy neutron-nucleus elastic scattering observables, there exists a quite extensive and well-measured total cross section data base [Finlay *et al.*], but very few differential elastic cross sections and spin observables have been measured. Accordingly, given the great difficulty of these latter measurements, a *few* well-chosen experiments should nevertheless be performed in order to obtain complementarity with existing measurements of the same (or similar) proton elastic scattering observables.

One recommendation, from the point of view of benchmarking existing as well as new medium-energy nucleon-nucleus optical potentials, is to consider two targets and three nucleon bombarding energies: $\{^{40}$Ca, ^{208}Pb; 100, 200, 300 MeV$\}$. The neutron experiments would consist of measurements of six differential elastic cross sections and six asymmetries, and these would have considerable overlap with existing proton measurements of the same observables. The proton experiments would consist of measurements of (a) six total reaction cross sections and these would have unit overlap with existing measurements of the neutron total cross sections (these are the integral observables that can be most accurately measured for the two probes). [Note that the proton total reaction cross section for ^{40}Ca has already been reasonably well measured at 100 MeV], and (b) three (p,n) quasi-elastic scattering cross sections to the isobaric analog of the ^{208}Pb target ground state.[1] The two targets both have sufficient numbers of nucleons to justify the assumption of a smooth absorptive potential to simulate the totality of the non-elastic open channels. In addition, they are both doubly-closed major shell nuclei, which allows unambiguous comparisons of the predictions from Dirac and Schrödinger approaches. Furthermore, ^{40}Ca has $N = Z$ and zero isospin whereas ^{208}Pb has $N > Z$ and non-zero isospin, which allows separate studies/tests with and without isospin dependence, at three different bombarding energies for the two nucleon probes. Finally, the two isotopically enriched targets exist in amounts that are adequate for the suggested neutron experiments. This set of measurements, together with the already completed complementary measurements, would constitute a close approximation to a complete and ideal set of measured scattering observables for optical-model studies/tests of medium-energy nucleon-nucleus elastic scattering as defined for this meeting.

A second recommendation, from the point of view of prioritizing measurements for optical potentials important to medium-energy applications, is to examine the High-Priority Nuclear Data Request List for Intermediate Energies for the items indexed to the optical model. Note that the List is periodically updated. It is located on the web at http://www.nea.fr/html/trw/nucdat/iend/docs/doc.s13.21.html [Koning].

Turning to theory and modeling, a number of shared opinions on these topics surfaced during

[1] Following the meeting two of the invitees who were unable to attend [F. S. Dietrich and J. Rapaport] commented that if the (p,n) cross sections are measured with and without polarized protons, (A_y), much more certain information can be extracted on the real and imaginary parts of the isospin-dependent (isovector) terms of the interaction potential and their energy dependencies.

this meeting. These include the views that (1) for medium-energy work it is time to stop extrapolating the low-energy, widely-used and respected, optical-model potentials to medium energies and to instead view these potentials as low-energy boundaries in the development of new medium-energy potentials, (2) conclusions from important microscopic medium-energy optical-model studies should strongly influence the development of phenomenological medium-energy potentials, and (3) the medium-energy optical-model potential user community is especially attracted to global phenomenological potentials because they are so easily hardwired and used in an optical-model routine. These views share the common denominator that we have not yet achieved the goal of a satisfactory medium-energy optical potential (which is why we are having this meeting in the first place).

Five general approaches to the medium-energy optical potential have been discussed. These are (a) Dirac and relativistic Schrödinger phenomenological potentials [Madland, Ishibashi], (b) dispersive potentials [Romain, Delaroche], (c) semi-microscopic potentials [Bauge], (d) microscopic potentials [Elster, von Geramb], and (e) coupled-channel potentials [Koning, Raynal]. Note that in some cases the medium-energy potential presented was actually determined using two or more of these approaches simultaneously [Bauge, for example]. While it is not the purpose here to summarize the many excellent technical presentations that we have heard, but to instead draw conclusions and construct recommendations from them, it is nevertheless impossible not to make note of a few of the advances. One of these is the extension of the Jeukene-Lejeune-Mahaux (JLM) folding model upwards to 200 MeV [Bauge and Delaroche] by refitting the imaginary part, introducing a phenomenological spin-orbit part, and employing H-F-B densities calculated with the Gogny D1S force. A very careful and systematic study of nucleon scattering by spherical nuclei then led to an energy-dependent set of four potential-depth renormalization factors $\{\lambda_{pot}\}$. This work could be viewed as a first step in achieving a global semi-microscopic medium-energy optical potential. Another advance is the recognition of the discriminatory power of highly accurate experimental neutron total cross sections in the various microscopic approaches to the potential. For example, full-folding calculations using the full Bonn NN t-matrix and Dirac-Hartree densities [Elster] as well as off-shell "$t\rho$" approximation calculations [Picklesimer, Ernst] are favored by the data, but calculations neglecting the coupling of the struck target nucleon to the residual nucleus (a medium effect) as well as those using a local, on-shell "$t\rho$" approximation are rejected by the data. Yet another advance is the extension of the dispersive approach to deformed nuclei [Romain and Delaroche] providing a new way to test and utilize the checks and balances existing between the bound and continuum (scattering) states and observables of a many-body deformed system. Still another is the calculation [von Geramb] showing a strong sensitivity of the $\pi\pi$ s-wave scattering phase shift ($T = 0$) to *small* ~ 2 MeV changes in the pion mass, implying a resonance feature due to an in medium effective pion mass. Since it is believed that correlated two pion exchange is responsible for the attractive medium range NN interaction this result may constitute an important medium effect that should be quantified. Finally, the manifestly interactive spherical optical model program ECISVIEW [Koning] built upon ECIS-95 [Raynal] has the possibility to revolutionize the traditional manner of obtaining a phenomenological potential from experimental data, in both speed and (more importantly) completeness.

Based upon the technical presentations, subsequent discussions, and roundtables at the end, some conclusions and recommendations on theory and modeling follow:

1. On the question of Dirac *vs.* Schrödinger approaches to medium-energy nucleon-nucleus scattering this still appears to be an open question. The Schrödinger proponents point out that they have carried out far more detailed investigations: medium effects, non-local effects, off-shell effects, ..., and therefore should and do have (somewhat) better agreement with experiment. Moreover, the Dirac agreement may therefore be fortuitous because the Dirac community has not performed such detailed investigations of these effects. The Dirac proponents point out that the Dirac equation is the *correct* equation for spin $\frac{1}{2}$ (point) fermions, that it has a *natural* spin-orbit term, and that it has a *natural* Coulomb correction term. Therefore, "just give us time to address the detailed effects." Our recommendation is that both approaches should be vigorously pursued so that this question may be settled. At the present time some Schrödinger-based microscopic approaches utilize nucleon density distributions from Dirac-Hartree approaches which is inconsistent. On the other hand the Dirac proponents should address open-shell target nuclei by some approximation.

2. On the question of the influence of the bound-state problem upon the medium-energy scattering problem this appears to be an only somewhat tapped resource at this time. Examples are the dispersion approaches and microscopic approaches where in the former the single-particle levels are an important constraint and in the latter the neutron and proton density distributions define the folding volume. Given that some of the observables used to select a "correct" bound-state approach are extremely well measured (mass, rms charge radius, s.p. levels) means that the bound-state problem can have tremendous influence on the scattering problem. The converse is to some extent also true. Thus, our recommendation is to vigorously pursue the influence of the bound-state problem upon the medium-energy scattering problem in mutually consistent approaches.

3. Some specific recommendations based primarily on the technical presentations at this meeting are:

   (a) Work on the extension of the JLM folding model to higher energy nucleon-nucleus scattering should certainly be continued.

   (b) The various microscopic approaches should all include more detailed comparisons of the calculated and measured integrated scattering observables, proton total reaction cross sections and neutron total cross sections, as functions of projectile energy and target nucleus, than in the past. It is noted here that an accurate predictive capability for these observables is extremely important for the medium-energy applied programs – such as the accelerator transmutation of radioactive waste.

   (c) Work on the extension of the dispersion approach to deformed nuclei should certainly be continued.

(d) The attractive medium-range NN interaction is still not understood and it needs a dedicated systematic attack. This is a topic that is potentially rich in the physics payoff because it connects the fictitious σ meson, two pion exchange, the Walecka model, QHD-I and QHD-II, chiral symmetry, and QCD.

(e) ECISVIEW should include a search package that provides the running χ^2 in a corner box of the interactive display. [I understand that this has been accomplished just after the meeting.]

(f) A global medium-energy nucleon-nucleus optical potential is, and remains, an important goal in this field.

Although this meeting was advertised as addressing the nucleon-nucleus optical model up to 200 MeV, the presentations and discussions here addressed the model at energies as high as 1 GeV. This is fortunate because some of the medium-energy applied programs will require proton beams up to 2 GeV and, therefore, scattering observables up to 2 GeV will have to be well understood. Thus, we should begin addressing the extensions of experiment as well as theory and modeling to the higher energies as soon as possible. Note that a few GeV is where, at the present time, scattering formalisms based upon partial wave expansions become intractable for medium and large mass nuclei. For these reasons, it probably makes sense for us to get together again to assess where we are (1999 $\pm$ 1?). In conclusion I thank the organizers for the privilege of summarizing this meeting.

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