HEAVY ION RESEARCH WITH CYCLOTRONS

David L. Hendrie

The extent and variety of heavy ion experimental work with cyclotron beams is so large that a short discussion could not do justice to the subject, even if presented as an annotated bibliography. I will therefore choose just one experiment that characterizes many of the present capabilities and future needs of heavy ion research. I now apologize for not mentioning many other experiments and experimenters which could have as well formed the basis of this presentation.

The experiment ties in strongly with traditional light ion nuclear reactions, the single particle transfer reactions on well known, near closed shell nuclei. The reaction is the ^{208}Pb(^{16}O,^{15}N)^{209}Bi single proton transfer reaction, leading to isolated sharp single-particle states in ^{209}Bi. Not only has this reaction been studied with light ion reactions such as (^{3}He,d), but the bound state wave functions have been well characterized by nucleon structure calculations.[1] The innovative feature of this work is the systematic performance over a wide range of incident energies.

Figure 1 shows the spectra in ^{209}Bi obtained at 4 incident energies from 104[3] to 312[4] MeV. The work was done at the Berkeley 88" cyclotron; oxygen ions of 4^+ to 6^+ were accelerated to provide the range of energies. The resolution needed to separate out the residual single particle states (and the redundancy and precision of measurement of other particle parameters needed in order to separate cleanly the ^{15}N particles from the multitude of others from the competing reactions) was provided by use of the Berkeley QSD spectrometer[5] as the particle detector. Angular distributions to all the states were taken at all the energies, and gave rise to characteristic bell shaped curves which varied systematically in position, width, and height as a function of energy.

In order to relate our results to structure theory, we resort to the highly successful DWBA treatment. In order to handle the larger amounts and more complex involvement of angular momentum arising from the use of heavy ion projectiles a new code was developed for the purpose.[6] The theory bases its transition predictions on elastic scattering wave functions, which are obtained from separate elastic scattering experiments. The use of these data at 312 MeV to obtain good elastic scattering fits is shown in fig. 2. The code then calculates the transfer cross sections, using the optical potentials obtained as stated, and the previously calculated nuclear structure factors. That it did an excellent job is shown in fig. 3 for the transition to the ground state. The position and widths of the bell shaped curves are well fit at all energies. Even the strong relative enhancement of the $F_{5/2}$ state compared to the $F_{7/2}$ state as the energy is increased is well predicted, as are the relative strengths to all the low lying states. Almost everything looks fine.

Except for one major flaw. The absolute magnitude of the DWBA predictions deviates strongly from the results in a systematic fashion as a function of incident energy. If we include similar data taken near the Coulomb barrier height energy[7] and use that energy as a calibrator, we see that the DWBA predicts a cross section almost an order of magnitude greater at the highest energy (312 MeV), than is actually measured, uniformly for all the low lying states. No reasonable attempt to tinker with adjustable parameters of the calculation was able to significantly change this startling result, which is summarized for two possible parameter sets in fig. 4.

D. L. Hendrie, University of Maryland, Dept. of Physics & Astronomy, College Park, Maryland 20742

The reason for this discrepancy is still not clear. We have considered such effects as variation of parameters, excess high momentum components in the bound state wave function, coupled channel effects (perhaps to states in ^{15}N), and fundamental defects in the formulation of the DWBA. Our present thinking is focussed on the possibility of strength being diverted from the direct interaction channels into fact breakup processes. That this has some validity is seen in the growing continuum strength at 8-10 MeV excitation, as seen in fig. 1.

Clearly, the performance of experiments such as this require the exercise of the highest technological advances. The cyclotron must produce beams with small enough energy spread, and detectors must be available with sufficient resolving power to separate the close lying states. The intensities must be adequate to allow for such resolutions and still permit the measurement of cross sections of 100μ barn/steradian or less. The beams must be easily variable in energy and projectile type. And above all, the energies must be able to go as high as possible to find and explore trends such as those we saw here to their limit, if any. Since the energy available from existing cyclotrons goes as the square of the ionic charge state, the major area for general advancement is in ion source development. The successful implementation of new source technology, such as the supermafios (as discussed in the conference) would keep present cyclotrons in the forefront of heavy ion research far into the future.

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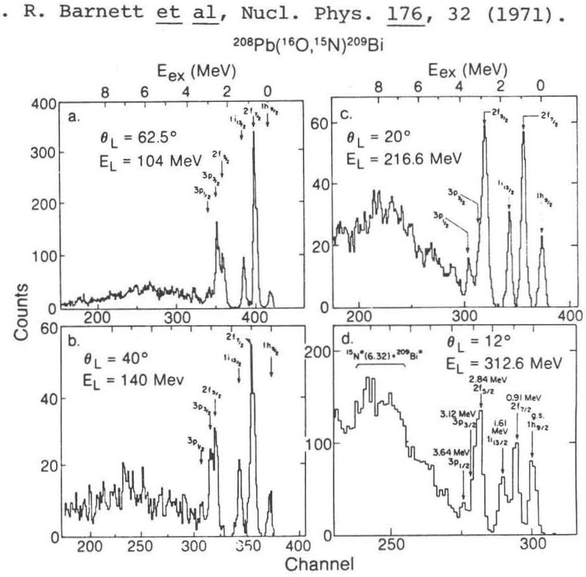

Fig. 1 Energy spectra obtained for the ^{208}Pb(^{16}O,^{15}N)^{209}Bi reaction at incident energies of 104, 138.5, 216.6 and 312.6 MeV. Transitions to known proton single-particle states are labeled according to their shell-model orbitals.

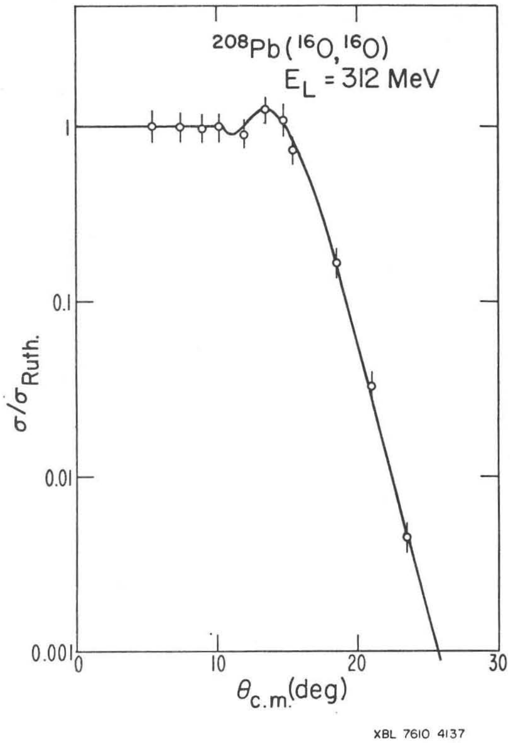

Fig. 2 Elastic scattering angular distributions for 312.6 MeV ^{16}O on ^{208}Pb. The curve is an optical model fit.

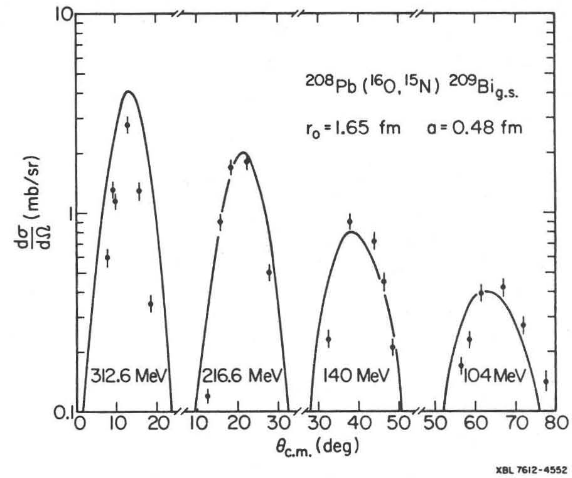

Fig. 3 Differential cross sections for the reaction $^{208}Pb(^{16}O,^{15}N)^{209}Bi$ populating the $h_{9/2}$ ground state at an incident energy of 104, 140, 216.6 and 312.6 MeV, from right to left. The solid lines are DWBA calculations described in the text.

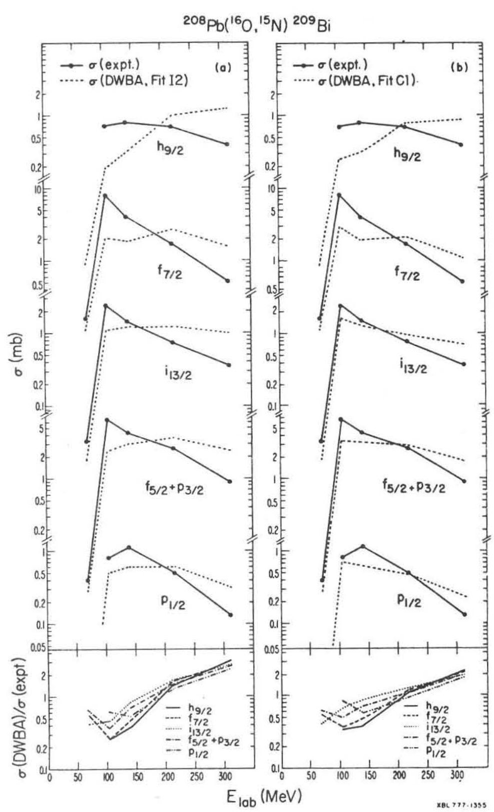

Fig. 4 Experimental and DWBA angle-integrated cross sections for the $^{208}Pb(^{16}O,^{15}N)^{209}Bi$ reaction as a function of incident energy. The curves for two optical potentials, both using spectroscopic factors from structure calculations, are shown.

** DISCUSSION **

F. RESMINI: Would you care to comment, in numbers if possible, on what you mean by sufficient intensity to pursue these lines of research with heavier ions?

D. HENDRIE: A cross-section of one millibarn per steradian with a beam of one particle nA gives about three counts per hour. Now if you're looking at cross-sections that are going to be less than one mb/sr and if you want to be able to do a reasonable experiment with statistics of 5 to 10% in an hour or so, you will need several tens of particle nA at the minimum. So, for an oxygen beam of 6+, that would be at least one hundred and maybe two or three hundred electrical nA. This is after being cleaned up so that you have high resolution.

T. KUO: In reference to the discrepancy in the cross-section ratio of the DWBA to the experiment, is there any other laboratory doing similar experiments and showing a similar discrepancy?

D. HENDRIE: I don't believe that there are any other experiments that show a discrepancy such as this. There was data from some (d,^{3}He) experiments done at Colorado some time ago which gave indications of this, but the discrepancy in that case seemed to be much smaller. As far as I know, no light ion experiments have shown anything like the discrepancy that we see here with heavy ions.