Characterizing Heavy Ion Reactions in the 1980's

Is there Treasure at the end of the Rainbow?
&
What happens and how do different modes compete?

John Schiffer

One of the three research areas for ATLAS, as stated in a 1984 document to Congress:

MACROSCOPIC PHENOMENA: What are the new macroscopic and microscopic phenomena associated with collisions between two nuclei? How and on which time scale is energy absorbed and a new equilibrium established?

ATLAS as well as the present linac represent a powerful facility to study the physics of interaction between colliding nuclei at energies comparable to nuclear binding energies. How do nuclei fuse? What are the systematics for fission? How is mass and energy exchanged by colliding nuclei? These are major areas of study for which the unique energy variability and timing of ATLAS beams make it into a very effective facility. The good energy resolution and easy energy variability also permit exploration of resonance studies -- an important class of physics in this area.

The intellectual push in this area came partly from the tantalizing results of 'molecular resonances', suggesting that possibly there were some new simple symmetries awaiting discovery. *(treasure at the end of the rainbow)*

But it also came from the need to characterize the qualitative phenomenology in terms of the competing processes that take place in the collisions between two complex systems near the Coulomb barrier, collisions that take place on time scales comparable to characteristic nuclear times.

The first path we pursued was the exploration of 'molecular resonances', suggestive bumps seen in systems such as $^{12}C + ^{12}C$, and the like. If one could establish some systematic behavior, perhaps a simple symmetry might emerge.

The most attractive option seemed to be following up on suggestions of resonances in ^{40}Ca, accessible in the $^{16}O + ^{24}Mg \rightarrow ^{12}C + ^{28}Si$ reaction.

This turned out to be a major task – well suited to the s.c. linac system.

Are there some new marvelous symmetries, hidden in resonances in heavier nuclei, beyond $^{12}C+^{12}C$ and its immediate vicinity?

(s.c. linac work, pre-ATLAS)

VOLUME 40, NUMBER 20 PHYSICAL REVIEW LETTERS 15 MAY 1978

Resonant Effects in the Reaction $^{24}Mg(^{16}O,^{12}C)^{28}Si$

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(Received 28 March 1978)

Excitation functions were measured at forward angles for the reaction $^{24}Mg(^{16}O,^{12}C)^{28}Si$ to the ground and first excited states of ^{28}Si. Resonancelike structures were found in both excitation functions with pronounced maxima at center-of-mass energies of ~28, ~31, and ~34 MeV. Angular distributions obtained at these three energies are fitted rather well with $P_L^2(\cos\theta)$ with L = 21, 23, and 25, respectively.

PHYSICAL REVIEW C VOLUME 31, NUMBER 5 M

Energy dependence of the cross sections for the $^{24}Mg(^{16}O,^{12}C)^{28}Si$(g.s.) reaction

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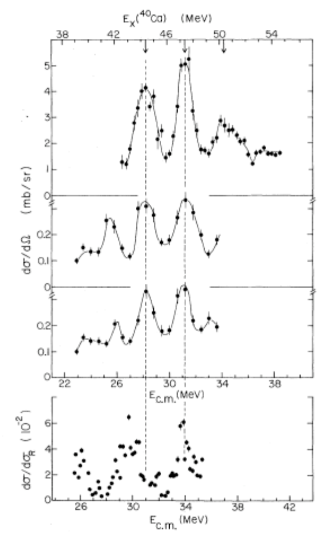

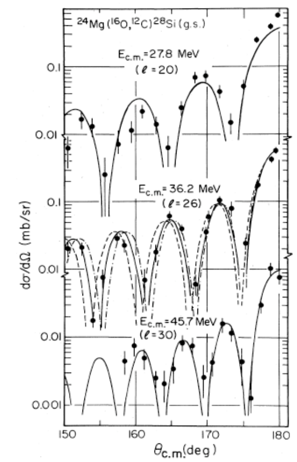

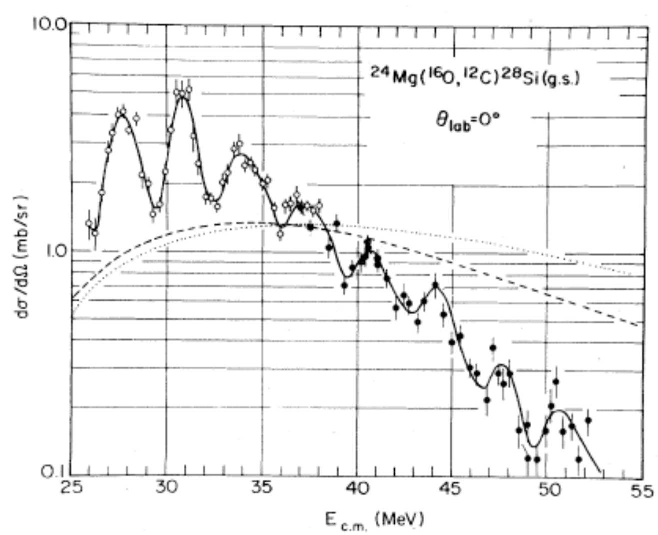

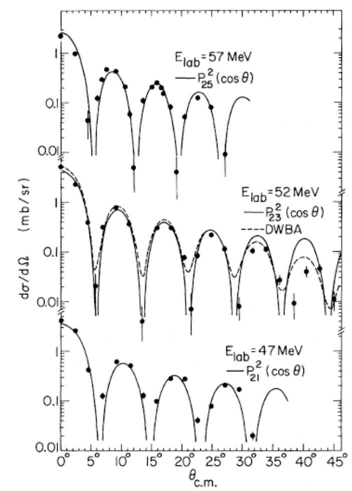

This was a Herculean effort – and in the end inconclusive.

The bumps did seem to correspond to resonances, and their angular momenta were close to the maximum corresponding to the trajectories.

But the pattern of spins was not simple.

Other attempts to chase the rainbow

180º elastic scattering of ^{12}C on ^{40}Ca shows structure

Fusion of ^{16}O on ^{40}Ca does not.

Elastic excitation function of ^{12}C on ^{40}Ca at 180°

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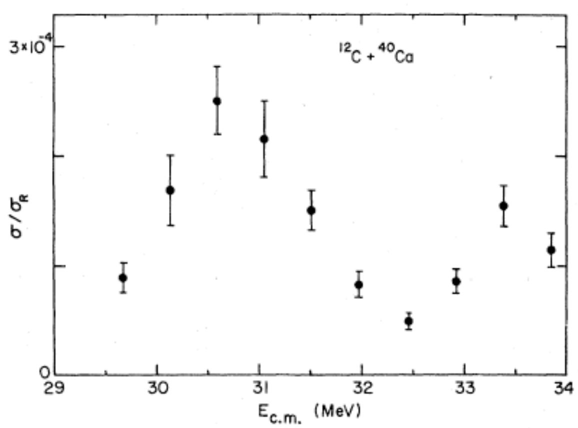
(Received 17 April 1978)

An excitation function of elastically scattered ^{12}C from ^{40}Ca at $\theta_{c.m.} = 180°$ was measured at 10 center-of-mass energies between 30.0 and 34.2 MeV to observe whether the anomalous structure that was seen in the back-angle excitation function of ^{12}C and ^{16}O on ^{28}Si also existed in this system. The cross section is $\sim 10^{-4}$ times that for Rutherford scattering, which is about two orders of magnitude lower than was seen with ^{28}Si. A resonance-like energy dependence was observed.



PHYSICAL REVIEW C VOLUME 18, NUMBER 1 JULY 1978

Search for structure in the fusion of $^{16}O + {}^{40}Ca$

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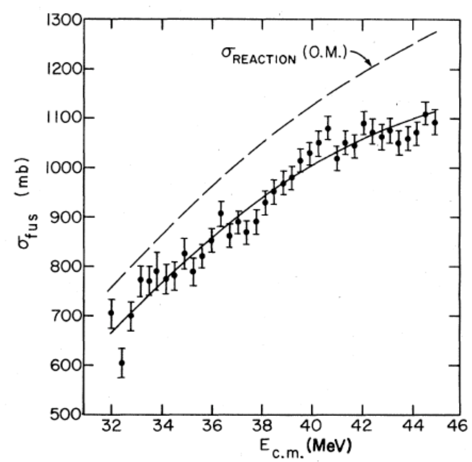
(Received 16 February 1978)

The fusion of $^{16}O + {}^{40}Ca$ has been studied in small energy steps in the energy range $45 \leq E_{lab} \leq 63$ MeV. Fusion cross sections were measured by the detection of evaporation residues in a ΔE-E particle telescope and by measurement of prompt γ-ray activity. The fusion excitation functions show relatively smooth behavior with no evidence for oscillatory structure of the magnitude observed in the fusion of $^{16}O + {}^{12}C$.



In the end, it seemed that these structures were sometimes present in alpha-particle nuclei, but almost never in others. Some optimists, continued the pursuit.

We also looked at the total ***fusion*** cross section in systems that showed resonances in scattering.

Using an ingenious device developed by W.H. we saw resonances in α-particle nuclei, but not in others.

Found a discontinuous increase in the ***maximum*** cross section when a major oscillator shell opens.

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Fusion Cross Sections of Light Heavy-Ion Systems: Resonances and Shell Effects*

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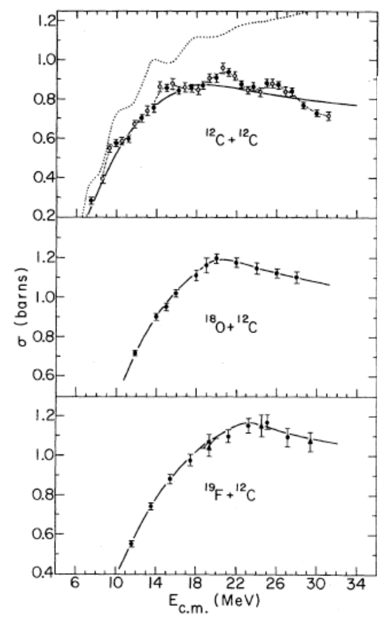
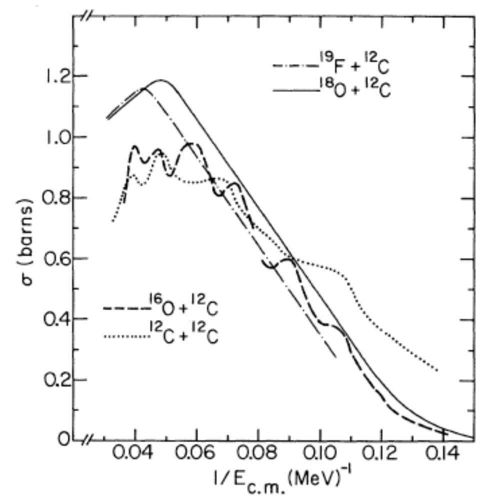
(Received 17 May 1976)

The total fusion cross sections for the systems $^{12}C+^{12}C$, $^{18}O+^{12}C$, and $^{19}F+^{12}C$ have been measured as a function of bombarding energy and compared with results for other light heavy-ion systems. The presence or absence of oscillations in the fusion excitation function and the overall magnitude of the cross section at high energies appear to depend on the structure of the colliding nuclei.





Next we investigated the competing macroscopic reaction modes as a function of energy and of neutron excess, in a region of nuclei where there was no question of resonances.

Sn has seven even isotopes that are stable, and Ni has four, offering a wide range of neutron excess. With the linac we had a range of energies available.

We set out to measure the distribution of cross sections among the competing modes.

When the two nuclei collide with a large impact parameter their interaction is ***quasi-elastic***, where the trajectory remains the same, though a few nucleons may be exchanged.

We explored how such processes depend on neutron number, from ^{112}Sn to ^{124}Sn, and for ^{58}Ni and ^{64}Ni.

PHYSICAL REVIEW C VOLUME 37, NUMBER 1 JANUARY 1988

Quasi-elastic processes in ^{58}Ni- and ^{64}Ni-induced reactions on Sn isotopes

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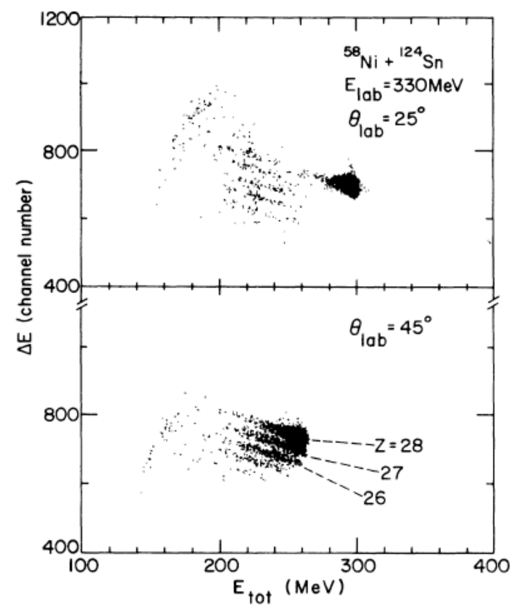
(Received 22 June 1987)

Quasi-elastic reactions were studied for ^{58}Ni beams at 330 MeV and ^{64}Ni beams at 341 and 380 MeV incident energy, respectively, on even-A Sn isotopes. Angular distributions were measured in the range $20° \leq \theta_{lab} \leq 55°$ using a magnetic spectrograph with a gas-filled focal-plane detector yielding single mass and charge resolution; generally individual states were not resolved. Cross sections for quasi-elastic one-neutron pickup and stripping reactions vary smoothly with the ground-state Q value. Total quasi-elastic transfer cross sections range from 340 to 640 mb, corresponding to 20–40 % of the total reaction cross section determined from the elastic scattering angular distributions. The distribution of the total cross section into the various reaction channels is discussed.



Then we measured the competing modes of *fusion* between the same systems over the same energies, First those where the fragments stick together.

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Neutron-Excess Dependence of Fusion—Ni + Sn

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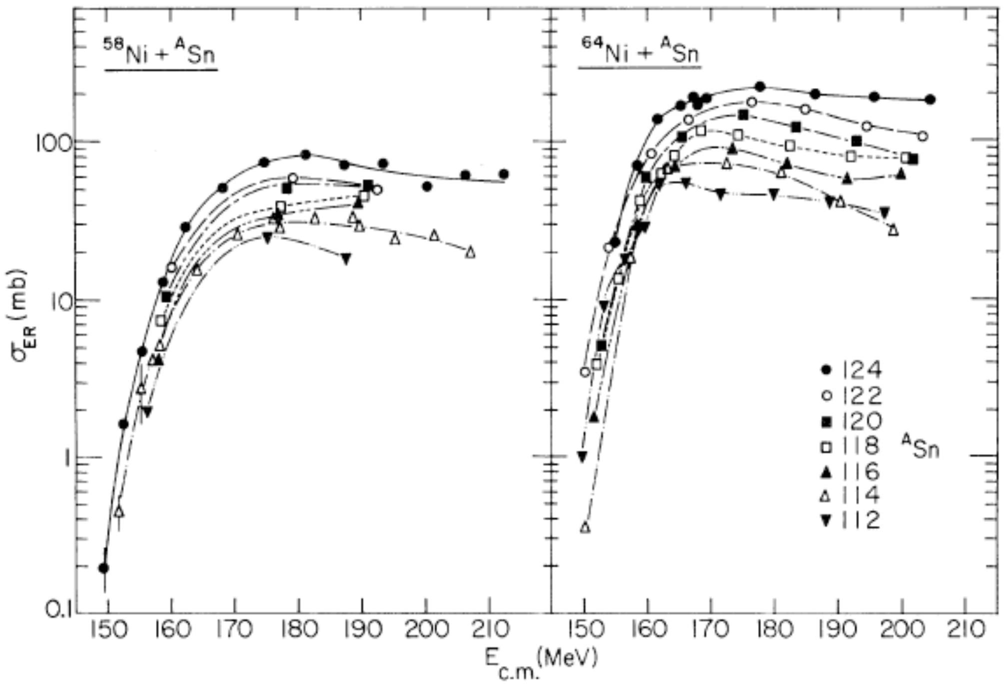
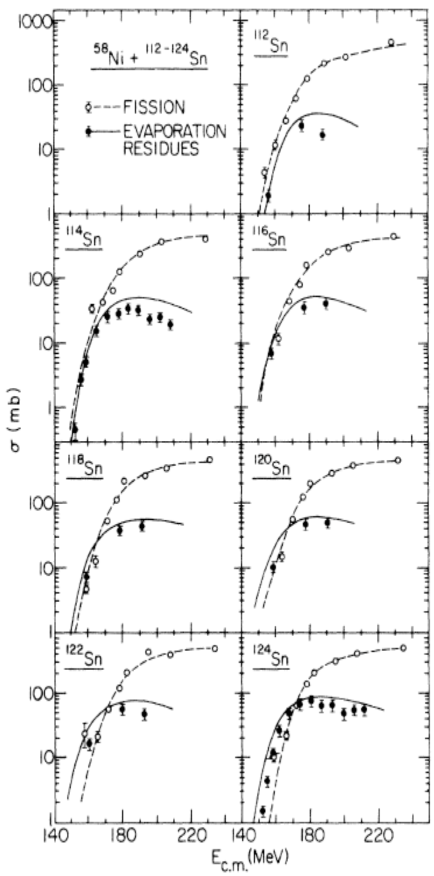
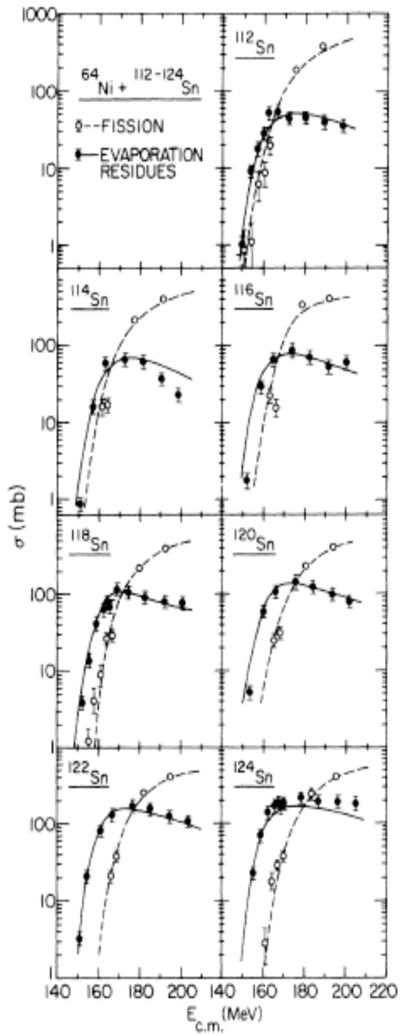
(Received 21 March 1983)

Excitation functions (E_{lab} = 235–320 MeV) for producing nuclei close to the compound system (evaporation residues) were measured for ^{58,64}Ni + $^{112-124}$Sn, corresponding to a 20% variation in the compound-nucleus neutron number. A dramatic, order-of-magnitude increase was observed in the maximum cross section as a function of the compound-nucleus neutron excess. The subbarrier energy dependence of the cross sections is well



Then, those where they fuse and then *fission*.





PHYSICAL REVIEW C VOLUME 34, NUMBER 6 DECEMBER 1986

Fission following fusion of Ni + Sn

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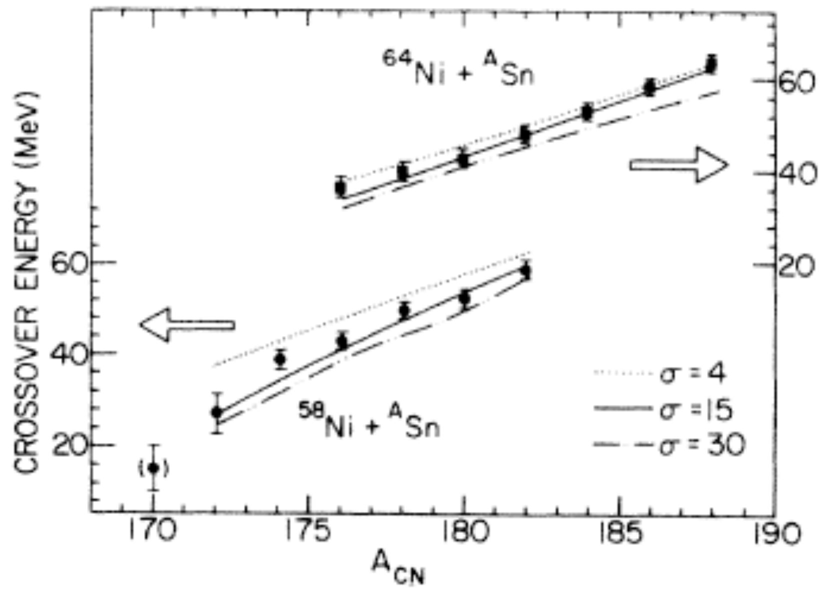
(Received 12 May 1986)

Excitation functions for fission were measured for ^{58,64}Ni beams incident on the even $^{112-124}$Sn targets at energies extending from well below to about 1.5 times the Coulomb barrier. Fission was identified by kinematic coincidence between fission fragments. Angle integrated fission cross sections were obtained from angular distributions taken at several energies for all systems. From these and the previously measured cross sections for evaporation residues, we obtain the total fusion cross sections and fission probabilities over the energy range $150 \lesssim E_{c.m.} \lesssim 240$ MeV. The competition between particle evaporation and fission in the compound nuclei is compared to statistical model calculations. A good description of the data for all 14 systems is achieved with the use of a single set of parameters. The model includes fission barriers with finite range and nuclear diffuseness effects.



Then we explored the interdependence of fusion the quasi-elastic interactions.

VOLUME 58, NUMBER 4 PHYSICAL REVIEW LETTERS 26 JANUARY 1987

Subbarrier Nucleon Transfer: Doorway to Heavy-Ion Fusion

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(Received 20 October 1986)

Nucleon-transfer cross sections have been measured at subbarrier energies in collisions between Sn target nuclei and light ($^{16,18}O$) and heavy (^{58}Ni) projectile nuclei. Large differences in cross sections correlate directly with the subbarrier fusion enhancement, suggesting nucleon transfer as an important doorway to fusion with a direct dependence on the overall transfer strengths. Simple two-level mixing considerations support this picture.

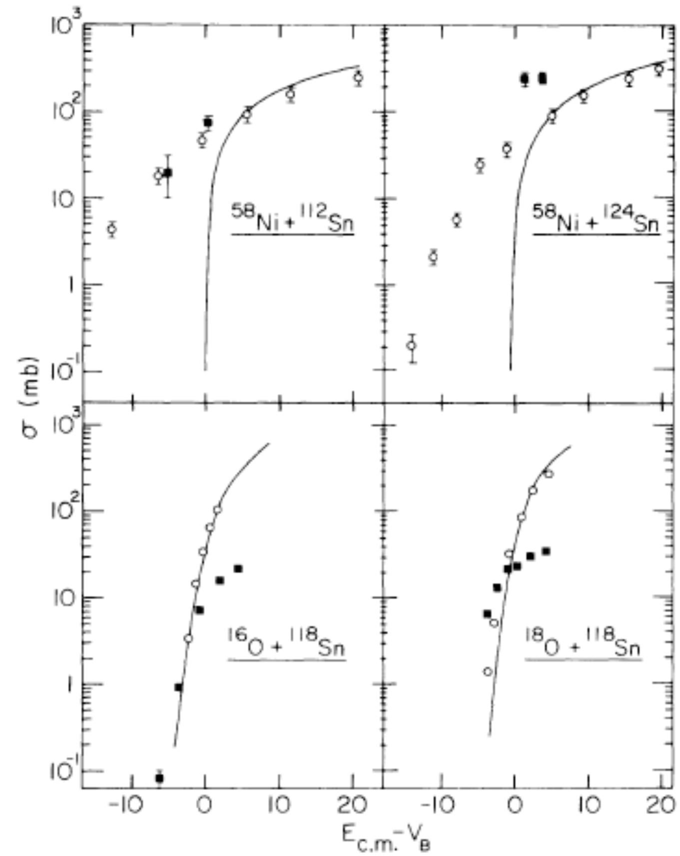
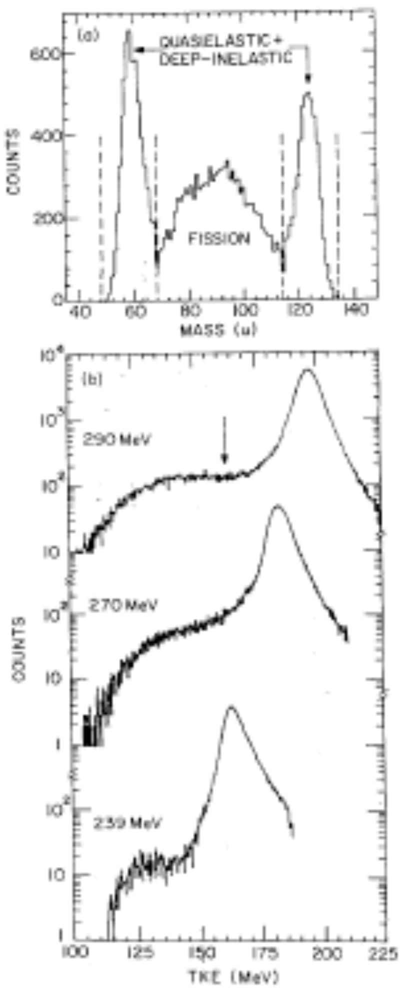


FIG. 1. Total quasielastic transfer cross sections (squares) and total fusion cross sections (circles) as functions of center-of-mass energy for the systems $^{16,18}O + ^{118}Sn$ and ^{58}Ni

We also found that a process that was thought to happen only at higher energies *(**deep-inelastic scattering**)* in fact, extends to incident energies well below the barrier.

In this process, the two fragments loose ***all*** their kinetic energy. and even emerge with less energy than expected for the Coulomb repulsion of two touching spheres, indicating large deformations. Yet their retain their approximate identify and are different from fission.



STRENGTH OF DEEP-INELASTIC SCATTERING FOR ^{58}Ni+^{124}Sn AT SUB-BARRIER ENERGIES

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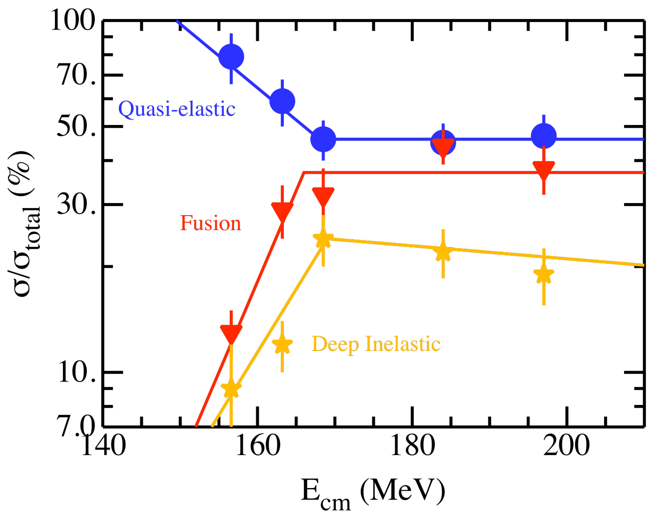
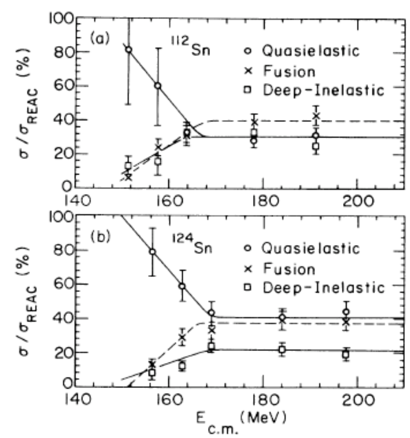
Received 7 July 1987





CONCLUSION

These studies were pretty well finished in the '80-s.

Unfortunately there was no treasure at the end of the rainbow – we had looked pretty hard (especially Steve Sanders). Or perhaps we were not smart enough to recognize it.

The measurements characterizing reaction modes (Ni+Sn) also was a huge effort, the major focus of several postdocs and students (Bill Freeman, Ad van den Berg, Kevin Lesko, Frank Wolfs, etc.). It remains the most comprehensive set of data of its kind (as far as I am aware), and continues to provide a testing ground for any comprehensive theory of heavy ion reactions at 'nuclear' energies.

New, precise studies of sub-barrier fusion at ATLAS by C.L. Jiang et al. are surprising us now, 20 years later.