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RESONANCES IN HEAVY SYSTEMS

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The experimental situation for the study of resonances in heavy-ion collisions is reviewed, with emphasis on the heaviest systems. New data are presented which show some of the systematics of this phenomenon. The narrow resonance structures are established as a feature of the nuclear structure of the composite system rather than a purely entrance channel effect.

1. INTRODUCTION

The advent of a new generation of precision heavy-ion accelerators such as the large tandems and superconducting linac boosters opens up many new possibilities for the detailed study of heavy ion interactions. One area of research which is greatly extended by the characteristics of these new machines is that of resonances in heavy ion reactions, the study of which requires a wide variety of beam species with both excellent energy resolution and easy energy variability.

For many years now, resonances of width 100-200 keV have been known to exist in elastic scattering and reaction cross-sections for systems such as $^{12}C + ^{12}C$,

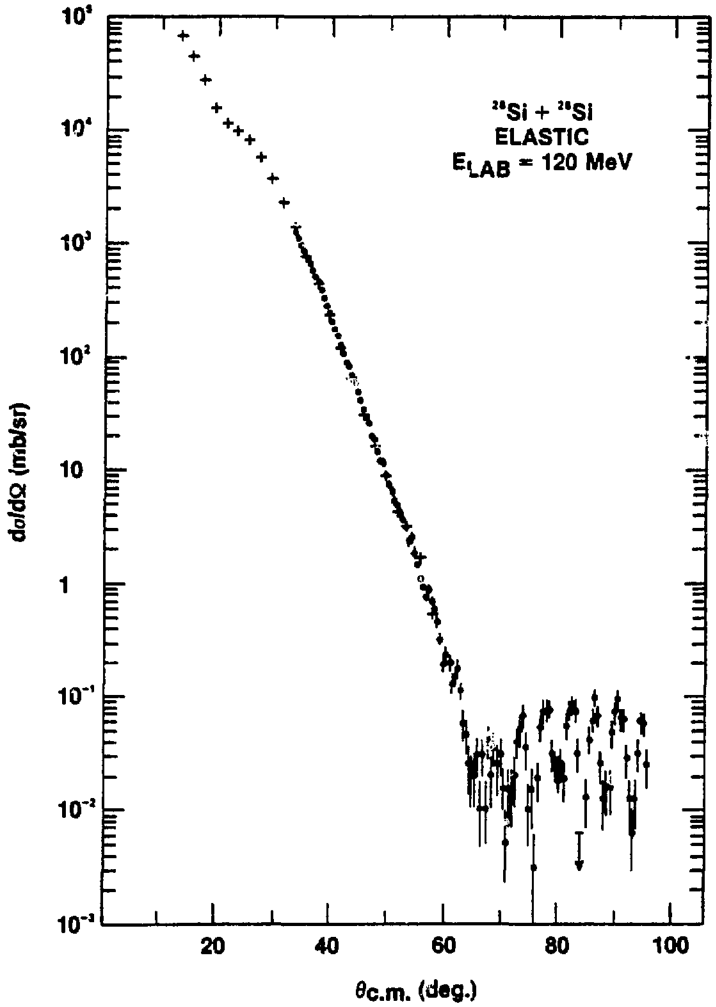
^{12}C + ^{16}O etc., but only very recently have apparently similar structures been observed in much heavier systems such as ^{24}Mg + ^{24}Mg and ^{28}Si + ^{28}Si.[1] The observation of such narrow states at high excitation energies in the compound nucleus points to these resonances possessing some special structure or quantum numbers which inhibits their mixing with the many times more numerous compound nuclear states. In addition, the resonances observed in the heavier nuclear systems appear to have extremely high angular momenta and are among the highest spin states directly observed in any nucleus. The further study and characterization of this phenomenon is therefore of great current interest and it is likely that its understanding will have impact, not only on our views of heavy ion reaction mechanisms, but also on nuclear structure at high spin and large deformations.

2. EXPERIMENTAL SIGNATURES OF RESONANCES

2.1. General Features of Angular Distributions

The early studies of heavy ion elastic scattering at energies not too far above the Coulomb barrier indicated the dominance of the effects of barrier penetration and strong absorption, leading to angular distributions which are well accounted for by simple optical model parametrizations. More detailed studies have shown, however, that at large angles there are dramatic departures from this simple picture. An elastic scattering angular distribution[2] for ^{28}Si + ^{28}Si at a bombarding energy of 120 MeV (twice the Coulomb barrier) is shown in Fig. 1. These data show a smooth fall off in angle beyond the grazing bump, interrupted at $\Theta_{cm} \approx 60°$ by a transition to an oscillatory behavior. The period of the angular oscillations is close to that of $P_L^2(\cos\Theta)$ with L equal to the grazing angular momentum at this energy (40 $\hbar$). The cross sections observed in this angular region are from one to several orders of magnitude larger than those obtained from optical model calculations using a strongly absorbing potential[3] (V=37.5 MeV, r_0 = 1.172 fm, a = 0.624 fm, W = 24.1 MeV, r_0' = 1.090 fm, a' = 0.659 fm) which gives a good account of the data forward of 60°. The magnitude of the predicted large angle cross-section can be brought into agreement with the data by reducing the value of the imaginary diffuseness. This procedure, however, produces angular oscillations forward of 60° which are manifestly not present in the data.

Similar behavior is observed in data[2] for inelastic transitions as shown in Fig. 2. The fall off beyond the grazing angle is again replaced by an almost isotropic or oscillatory behavior. At large angles the cross-sections for inelastic scattering are dominated by transitions at quite negative Q-values as shown in the spectrum displayed in Fig. 3. The average Q-value of -10 MeV corresponds roughly to that given by sticking models of deep inelastic scattering which, together with the angular behavior of these cross-sections, may suggest their explanation in terms of some long-lived orbiting phenomenon.



^{28}Si + ^{28}Si
ELASTIC
E_{LAB} = 120 MeV
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
$d\sigma/d\Omega$ (mb/sr)
20
40
60
80
100
θc.m. (deg.)

Figure 1.

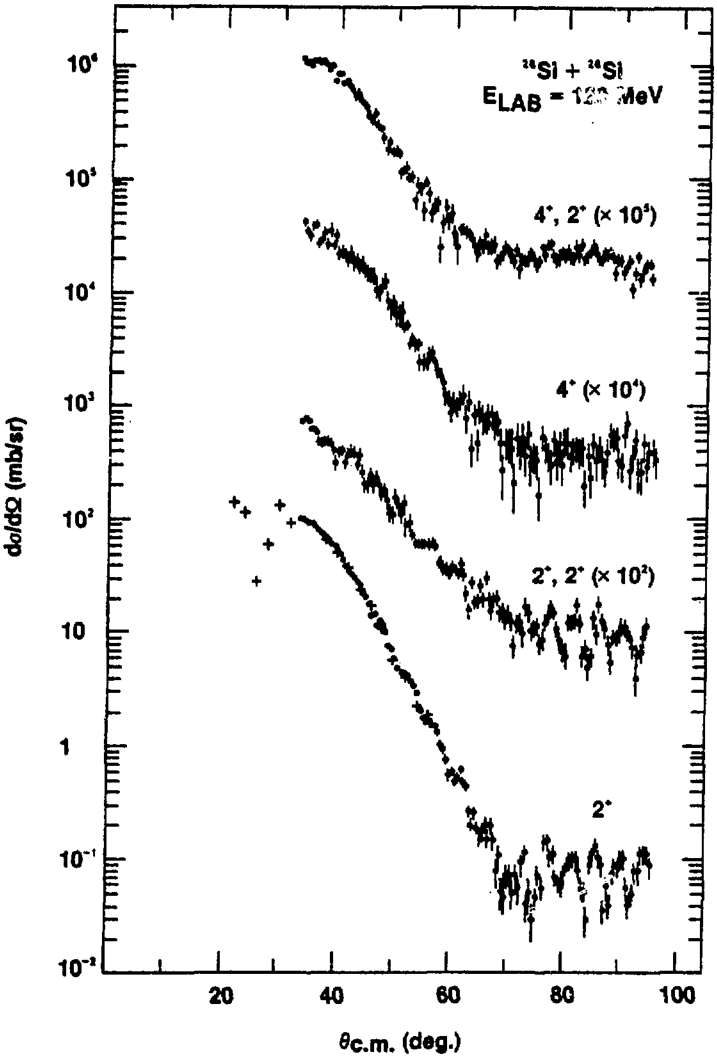

^{28}Si + ^{28}Si
E_{LAB} = 12[illegible] MeV
4$^+$, 2$^+$ (× 10^5)
4$^+$ (× 10^4)
2$^+$, 2$^+$ (× 10^2)
2$^+$
$d\sigma/d\Omega$ (mb/sr)
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
20
40
60
80
100
θc.m. (deg.)

Figure 2.

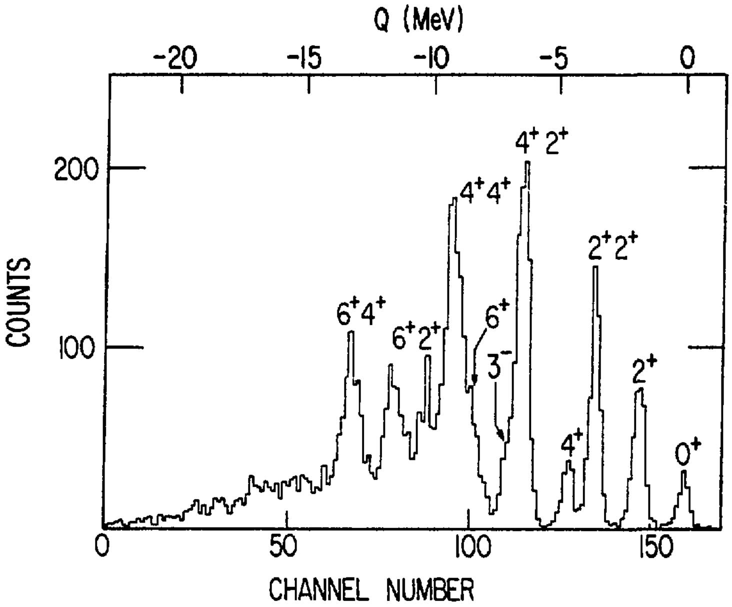


Figure 3.

2.2. Excitation Functions

A further indication of the origin of these anomalous cross-sections comes from excitation function measurements. Figure 4 shows the elastic scattering cross-section[4] integrated over the angular range $\Theta_{cm} \approx 60°-90°$ plotted as a function of bombarding energy. The target thickness corresponded to an energy loss to the beam of 500 keV. We observe a number of broad structures each of width ΔE_{cm} = 1-1.5 MeV. For the broad bump near E_{LAB} = 118 MeV there is some indication of a much narrower structure which is more fully revealed in the data[5] shown in Fig. 5 which were measured in 100 keV steps using a target

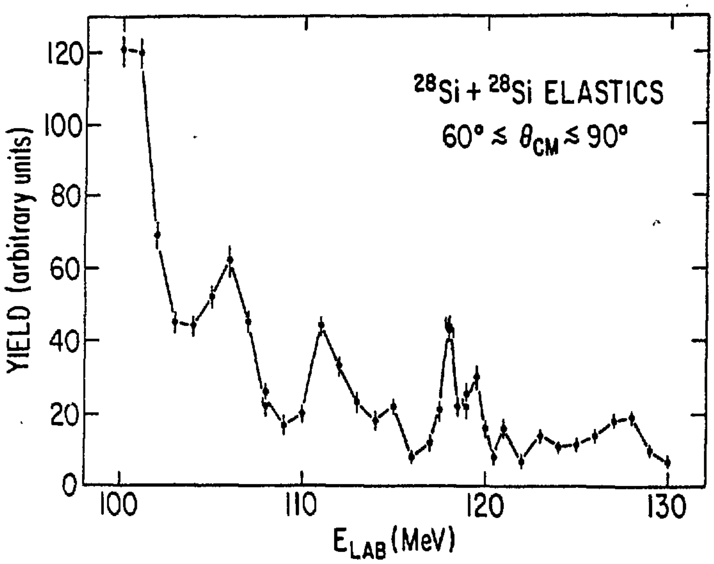


Figure 4.

only 70 keV thick to the beam. These data show that each of the broad structures in the elastic scattering yields is indeed fragmented into a number of much narrower peaks with widths of 100-200 keV. These same narrow peaks appear in virtually all the resolved inelastic channels as well as in the sum of the resolved transitions together with the many unresolved states at higher energy in the spectrum (Fig. 3). Analysis of the correlations between the narrow peaks rules out an interpretation in terms of statistical fluctuations and we therefore conclude that we are indeed observing more or less isolated resonances of the system.

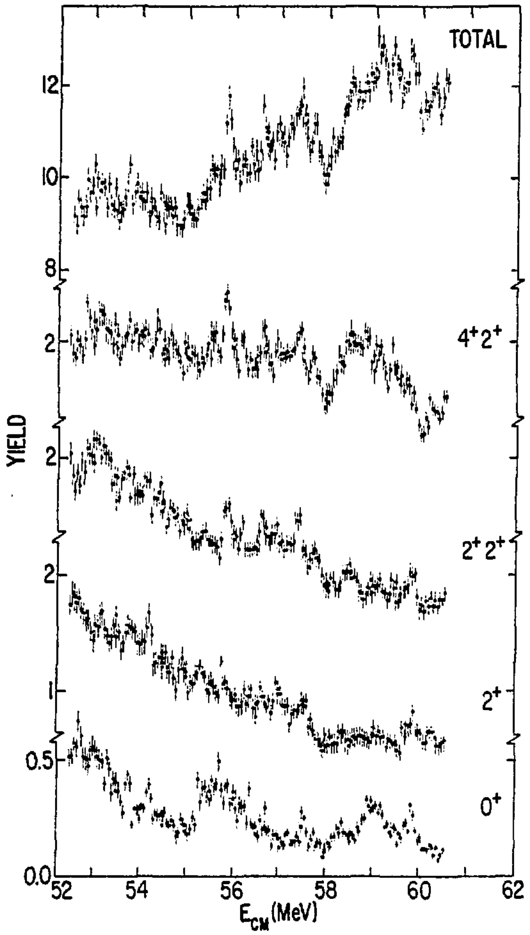


Figure 5.

2.3. Resonance Spins

Although at the present time there are no firm spin assignments for the resonances observed in the $^{28}Si + ^{28}Si$ system, there are strong grounds for believing that they have extremely high spin. Elastic scattering angular

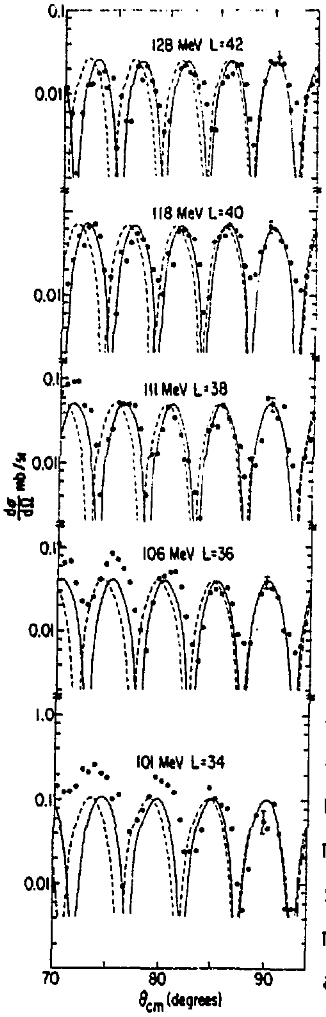


Figure 6.

distributions[4] over the angular range $\Theta_{cm} \approx 70^\circ$-$90^\circ$ have been measured in 1 MeV steps from E_{LAB} = 100 to 130 MeV - corresponding to the data points shown in Fig. 4. Some of these angular distributions are shown in Fig. 6; the energies correspond to peaks in the angle integrated yield. As can be seen, particularly at the higher energies, the data are well described by pure $P_L^2(\cos\Theta)$ shapes (solid lines), as would be expected for the angular distributions of isolated resonances. The experimental angular distributions do not change appreciably within the confines of each broad structure, and only in the minima between broad bumps do we find more complex angular distribution shapes. The sequence of angular momenta obtained from the experimental angular distributions agrees quite closely with that for the grazing partial wave, suggesting a strong connection between the observed broad resonances and a series of potential scattering resonances.

Preliminary calculations in which resonance amplitudes are added to an S-matrix obtained from a strongly absorbing potential indicate that it is possible to obtain extremely good agreement over the whole angular range with the elastic scattering data shown in Fig. 1. Were data of such quality available over a range of energies in fine energy steps it is likely that a parametrized phase-shift analysis would lead to some more definite spin assignments as have been made in lighter systems.

In any case, based on the present data, it is clear that the resonances observed in ^{28}Si + ^{28}Si have spins which range up to as high as 42 $\hbar$ and are therefore among the highest spin excitations directly observed in any nuclear system.

2.4. Systematics as a Function of N and Z

In an attempt to establish the systematics of occurrence of these high spin resonances we have measured excitation functions in 100 keV steps for a number of systems neighboring ^{28}Si + ^{28}Si namely, ^{28}Si + ^{30}Si, ^{30}Si + ^{30}Si and ^{24}Mg + ^{24}Mg.

The results for the Si isotopes are summarized in Fig. 7 where the angle-integrated summed elastic, inelastic and transfer cross-sections[6] for ^{28}Si + ^{28}Si, ^{28}Si + ^{30}Si and ^{30}Si + ^{30}Si are shown plotted as a function of compound nucleus excitation energy. These data show a complete disappearance of the narrow structure, so prominent in the ^{28}Si + ^{28}Si data, leaving only a hint of broad oscillations for ^{28}Si + ^{30}Si. The disappearance of the narrow structure is also accompanied by a decrease in the cross-section by a factor of ~2 between each of the systems.

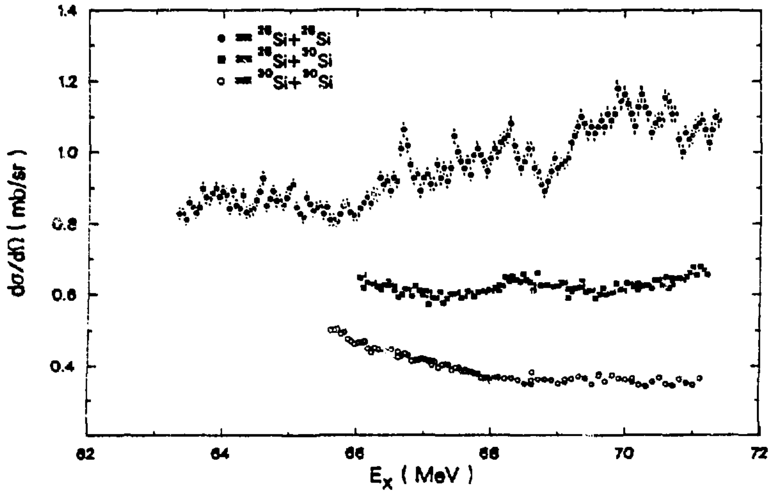


Figure 7.

In contrast, the data[7] for ^{24}Mg + ^{24}Mg is even more striking than for ^{28}Si + ^{28}Si. These data, shown in Fig. 8, show several clearly isolated narrow structures which are very strongly correlated in essentially all the measured channels. Angular distribution data for the narrow structures near E_{cm} = 46 MeV favor spins of J = 34 or 36 ℏ for all three which, surprisingly, is 2-4 ℏ larger than the grazing angular momentum at this energy.

A picture therefore emerges of resonances only appearing in α-particle systems - consistent with the observations for much lighter systems. In the present cases it is unlikely that this disappearance of resonances in non α-particle systems has anything to do with the compound nuclear level densities, which are quite similar for all the systems investigated here. The influence of transfer channels, the effective number of which increases with the addition of neutrons, remains to be investigated.

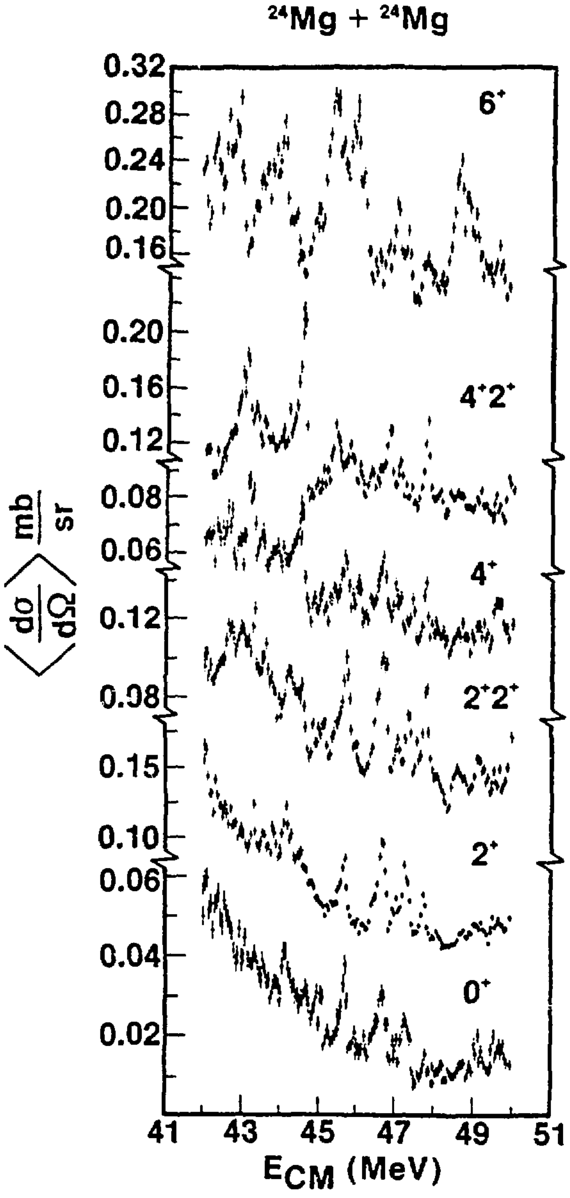

^{24}Mg + ^{24}Mg
$\left\langle \frac{d\sigma}{d\Omega} \right\rangle \frac{mb}{sr}$
0.32
0.28
0.24
0.20
0.16
0.20
0.16
0.12
0.08
0.06
0.12
0.08
0.15
0.10
0.06
0.04
0.02
6$^+$
4$^+$2$^+$
4$^+$
2$^+$2$^+$
2$^+$
0$^+$
41
43
45
47
49
51
E$_{CM}$ (MeV)

Figure 8.

3. COMPOUND STATES OR ENTRANCE CHANNEL PHENOMENON?

Models used to describe the narrow resonances observed in heavy ion reactions fall into two basic categories. Those which attempt to describe the data in terms of coupled entrance channel elastic and inelastic potential resonances and those in which they are described as due to some specific feature of the nuclear structure of the compound nucleus, such as fissioning shape isomers. In an attempt to make a distinction between these two ideas we have studied[8] the $^{16}O + {}^{40}Ca \rightarrow {}^{28}Si + {}^{28}Si$ reaction over the compound nucleus excitation energy range in which the narrow resonances were observed via the $^{28}Si + {}^{28}Si$ entrance channel. The fragments produced in this reaction were identified using a kinematic coincidence technique and Fig. 9 shows a scatter plot of the masses observed in each detector. The mass 28-28 events are clearly visible and are well separated from other masses. The yield of mass 28-28 events is shown in Fig. 10, plotted as a function of compound nucleus excitation energy together with the $^{28}Si + {}^{28}Si$ angle-integrated yields shown previously. The $^{16}O + {}^{40}Ca \rightarrow {}^{28}Si + {}^{28}Si$ data show several peaks of width 100-200 keV which are extremely well correlated with the peaks in the $^{28}Si + {}^{28}Si$ entrance channel data. A preliminary analysis of both these sets of data in terms of single isolated resonances leads to the result that the reduced width for decay into the ^{28}Si elastic channel is approximately a factor of 10 larger than that for decay into the $^{16}O + {}^{40}Ca$ elastic channel. The values of these reduced widths are, however, both considerably larger than estimates of the width for

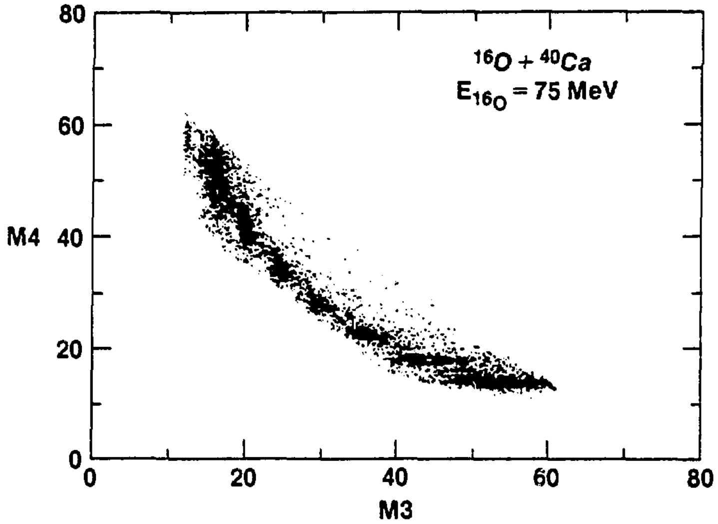


Figure 9.

statistical decay into these channels. This result would seem to be very difficult to explain in any of the current entrance channel models which, as formulated, exclude the coupling of the resonances to channels in which large amounts of mass are transferred. We therefore conclude that the narrow resonances originate from a real nuclear structure effect in the compound nucleus such as, for example, fissioning shape isomers. In addition, for the first time, we see some indication of the spectroscopy of these resonances, the overlap with two ^{28}Si nuclei being apparently much larger than with $^{16}O + ^{40}Ca$.

4. THEORETICAL SPECULATIONS

The idea the the narrow resonances observed in heavy ion reactions may reflect the existence of extremely deformed shape isomeric states in the compound nucleus was first proposed by Leander and collaborators[9] who calculated

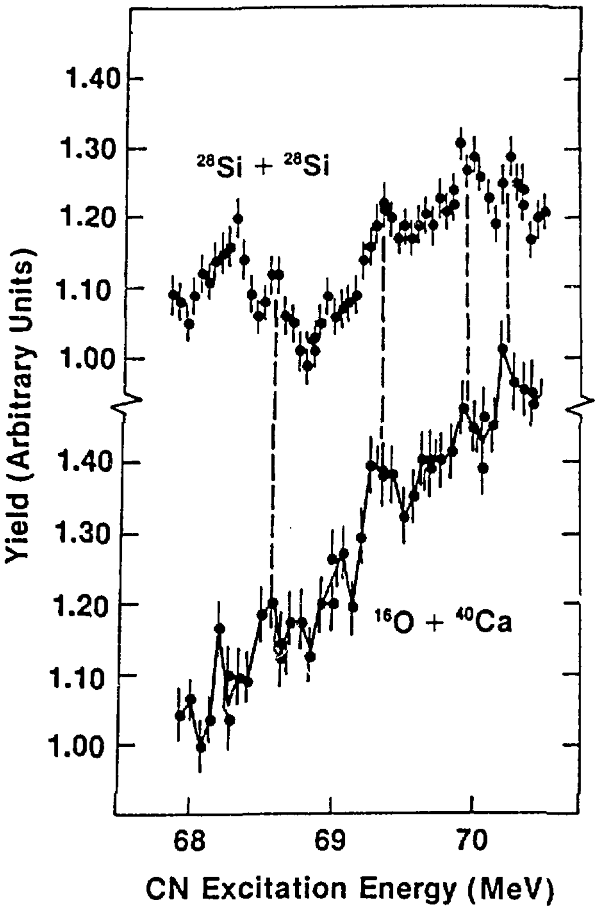


Figure 10.

potential energy surfaces for a number of light nuclei. Since that time these calculations have been extended to heavier nuclei[10] and, due to the interest in the behavior of nuclei at high spin, the effects of rotation of the system have been included.[11,12] The results of these calculations indicate that large shell gaps occur fairly frequently at large deformations and at high spin. The results of some of these calculations[11] are shown in Fig.

11 for ^{56}Ni (I=40), ^{58}Ni (I=40), ^{60}Ni (I=40) and ^{48}Cr (I=36). The figures show potential energy contours as a function of β the deformation and M_r the mass-asymmetry parameters. The shaded regions indicate the locations of the "superdeformed" minima which occur for shapes with an axis ratio of approximately 2:1. Well defined minima are predicted to occur for ^{56}Ni and ^{48}Cr which are predicted to weaken and disappear as neutrons are added to ^{56}Ni going to ^{58}Ni and ^{60}Ni. These features of the calculation are in qualitative agreement with the data. To date however, there is no unambiguous way of associating the observed narrow resonances with states in such "superdeformed" minima. In addition, the calculations as presently performed do not include any residual interactions which might, through α-clustering effects for example, strongly affect the nature of such superdeformed states. It nevertheless appears that these ideas might prove a fruitful avenue for further investigations.

5. HEAVIER SYSTEMS

To date the mass 56 system is the heaviest for which resonance behavior has been observed. There is, however, no reason to believe that even heavier systems might not show resonances. Studies of systems such as Ca + Ca and Ni + Ni are just beginning and although the experimental problems are somewhat greater it should be possible to obtain data of sufficient precision. Data for the elastic scattering[13] of ^{40}Ca + ^{40}Ca are shown in Fig. 12 measured in 10 MeV steps up to an energy of over twice the Coulomb

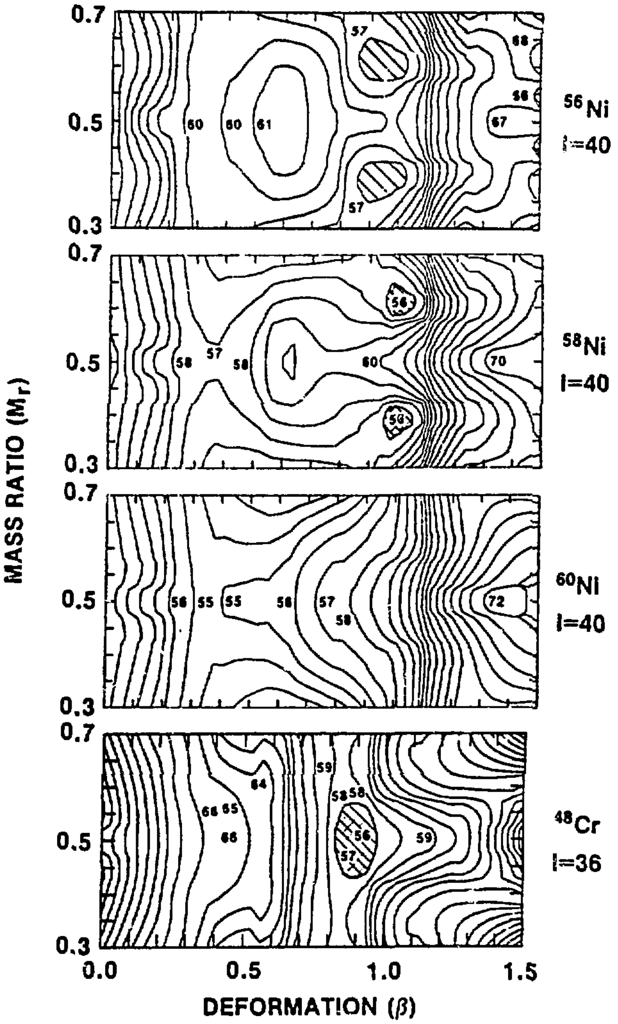


Figure 11.

barrier. These data are completely consistent with the *predictions of a strongly absorbing potential and we* therefore conclude that it is unlikely that resonances will be observed in the elastic scattering channel in this system. A clue as to the reason why this might be so

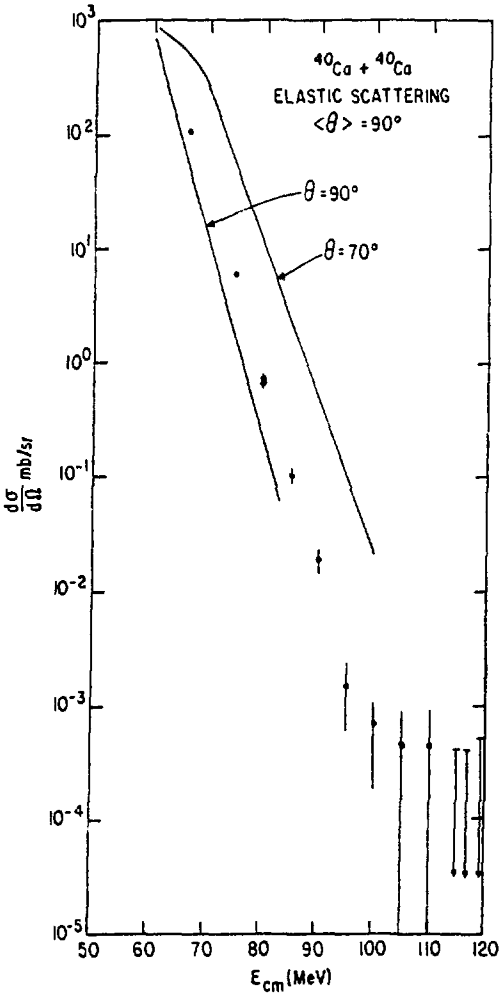


Figure 12.

comes from an examination of the inelastic scattering and transfer reaction spectra[14] shown in Fig. 13. The inelastic scattering spectrum shows an almost complete absence of the mutual excitations which dominate the Si + Si and Mg + Mg spectra and instead we see extremely strong

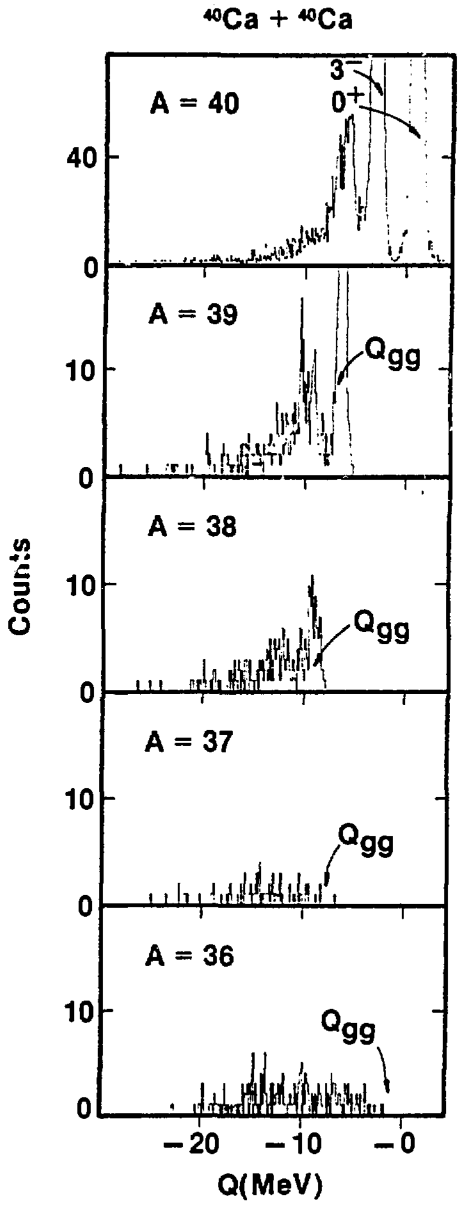


Figure 13.

one and two particle transfer channels. This difference probably arises from the different nuclear structure of

^{40}Ca as compared to ^{28}Si or ^{24}Mg. ^{40}Ca does not possess a band of collective states built on the ground state but rather has a number of rather simple particle-hole states which are more closely related to the transfer degrees of freedom than to other excited states of ^{40}Ca. We believe that the further study of data like this will shed light not only on the mechanism of resonance formation but perhaps also on some of the more macroscopic features of heavy ion reactions such as the energy damping process and orbiting.

6. SUMMARY

The detailed study of excitation functions and angular distributions for heavy ion reactions between s-d shell nuclei has uncovered the existence of extremely narrow high spin resonances in the composite systems. These states apparently represent a new class of nuclear excitation and although the underlying nuclear structure is not understood at the present time, some systematic features of the data are beginning to emerge. The extension of these studies to even heavier systems is an experimental challenge as is the understanding of this phenomenon a theoretical one.

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REFERENCES

1. For a recent review see Resonances in Heavy Ion Reactions ed. K. A. Eberhard (Springer Verlag, Berlin, 1982).
2. R. R. Betts, S. Saini, I. Ahmad and B. D. Wilkins (to be published).
3. O. Hansen, F. Videbaek and P. R. Christensen (to be published).
4. R. R. Betts, S. B. DiCenzo and J. F. Petersen, Phys. Lett. 100B, 117 (1981).
5. R. R. Betts, B. B. Back and B. G. Glagola, Phys. Rev. Lett. 47, 23 (1981).
6. S. J. Sanders, R. R. Betts, B. Dichter, O. Hansen, P. Kutt, S. Saini and R. W. Zurmühle (to be published).
7. P. Kutt, R. W. Zurmühle, R. R. Betts, S. Saini, F. Haas and O. Hansen (to be published).
8. R. R. Betts, S. Saini, S. J. Sanders, B. Dichter, O. Hansen, and R. W. Zurmühle (to be published).
9. G. Leander and S. E. Larsson, Nucl. Phys. A239, 93 (1975).
10. S. E. Larsson, G. Leander, I. Ragnarsson and N. G. Alenius, Nucl. Phys. A261, 77 (1976).
11. M. Ploszajczak and M. Faber (private communication).
12. I. Ragnarsson and S. Åberg (private communication).
13. R. R. Betts, I. Ahmad, B. B. Back, B. G. Glagola, W. Henning, S. Saini and J. L. Yntema (to be published).
14. R. Ledoux, H. Al-Juwair, C. Ordonez, M. Beckerman, E. Cosman, R. R. Betts and S. Saini (to be published).