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HIGH-SPIN RESONANCES IN HEAVY-ION COLLISIONS*

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ABSTRACT

Excitation functions for elastic scattering and reactions of $^{28}Si + {}^{28}Si$ show evidence for the existence of narrow (Γ = 100-200 keV) high-spin ($J \simeq 40\ \hbar$) resonances. The interpretation of these resonances as high-spin fissioning shape isomers is discussed with reference to data for the $^{28}Si + {}^{30}Si$ and $^{30}Si + {}^{30}Si$ systems.

It was initially supposed that the energy dependence of heavy-ion interactions would be dominated by the effects of barrier penetration and absorption and thus contain only information on the gross properties of the colliding nuclei and the composite system. Contrary to this expectation, the earliest detailed measurements [1,2] of the energy dependence of $^{12}C + ^{12}C$ elastic scattering and reactions revealed a number of narrow resonances. These are illustrated in Fig. 1 where the total fusion cross-section for $^{12}C + ^{12}C$, obtained from measurements of γ-rays from the residual nuclei [3,4], divided by a smoothly varying penetrability factor is shown plotted versus bombarding energy. Spin assignments are indicated for a number of resonances. The level density in the compound nucleus ^{24}Mg at excitation energies corresponding to this bombarding energy range (17-24 MeV) is much larger than the observed number of resonances. This, together with the large partial widths of the resonances for decay into two ^{12}C nuclei, has suggested an interpretation in terms of a number of highly deformed states of ^{24}Mg, perhaps akin to fissioning shape isomers or nuclear molecular states.

For many years it was assumed that the $^{12}C + ^{12}C$ system was unique in exhibiting resonant behavior but subsequent investigations have revealed a much wider occurence of this phenomenon than was previously thought likely, although in many cases the evidence that the structures observed in excitation functions are isolated resonances is rather weak. In this contribution we present the results of a detailed study of the $^{28}Si + ^{28}Si$ system and demonstrate the existence of a number of narrow very high spin resonances which are to a certain extent qualitatively similar to those observed at low spin in much lighter systems. The hypothesis that these narrow resonances correspond to high spin fissioning shape isomers in ^{56}Ni is discussed with reference to preliminary results for the $^{28}Si + ^{30}Si$ and $^{30}Si + ^{30}Si$ systems.

Excitation functions at $\theta_{cm} = 90°$ for elastic and inelastic scattering [5] of $^{28}Si + ^{28}Si$ are shown in Fig. 2. The data points are spaced by 1 MeV and the target thickness corresponded to an energy loss of $\sim$0.5 MeV. Instead of the smoothly falling cross-sections expected for the elastic and inelastic scattering of strongly absorbing heavy ions we observe dramatic fluctuations in all channels. There seem to be both structures of width several MeV and also much narrower structure although the spacing of the data points and the energy averaging in the target make this last observation rather uncertain. The structures observed in the single angle excitation functions persist when the elastic and inelastic yields are integrated over a relatively large angular range as shown in Fig. 3 and a qualitative picture of a series of broad structures perhaps fragmented into a much narrower structure emerges.

To further investigate the narrow structure these measurements were repeated using a much thinner target and bombarding energy steps of 100 keV. The angle-integrated yields resulting from these measurements [6] are shown in Fig. 4. The narrow structure suggested in the earlier data is now clearly visible and appears not only in the excitation functions of individual channels but also in the summed yield of elastic and inelastic scattering. An analysis of the correlations between the narrow peaks in the various channels leads to the conclusion that the structure of width 100-200 keV does not arise from statistical Ericson fluctuations and must therefore correspond to relatively long lived states of the composite system at very high excitation energies ($\sim$70 MeV).

In order to try and determine the angular momenta associated with these resonances, measurements of the elastic scattering angular distributions were made. At very forward angles, the behavior of the elastic scattering is dominated by Coulomb repulsion and strong absorption. At large angles, where the cross-sections show resonant behavior, we might expect to observe angular distributions characteristic of the resonant spin. These measurements were made [7] using a novel technique which allowed the determination of the angular distribution over a 30° angular range in a single measurement. The result of one of these measurements is shown in Fig. 5. The energy of 118 MeV corresponds to one of the peaks in the elastic scattering excitation function. The three curves show the behavior of $P^2_{38}(\cos\theta)$, $P^2_{40}(\cos\theta)$ and $P^2_{42}(\cos\theta)$ respectively - the data clearly favoring an angular momentum of 40 $\hbar$ for this resonance. Within each broad structure the shape of the elastic scattering angular distribution is characterized by the same angular momentum. Each of the broad structures is, however, characterized by a different angular momentum - the sequence of which varies with energy as the grazing angular momentum. This result is then consistent with the view of the broad structures arising from a series of elastic scattering potential resonances each of which is fragmented by mixing with more complex excitations.

The question of the nuclear structure underlying these narrow high-spin states which have a large overlap with the symmetric entrance channel is clearly a very interesting one. Various interpretations of the low energy $^{12}C + {}^{12}C$ resonances have been put forward which may be relevant to the present results. A number of these interpretations share the common feature that the narrow excitations are described in a basis of states formed by coupling the rotations of a di-nuclear molecule to the vibrational excitations of the constituent nuclei. The coupling of the elastic scattering potential resonance to these "molecular" states then gives rise to the observed fragmented gross structure [8]. In the present case it remains to be seen whether calculations of this type can reproduce the experimental observations - particularly the extremely small widths of the resonances.

An alternative picture which may prove useful in the $^{28}Si + ^{28}Si$ case is provided by the results of calculations [9] of shell effects in nuclei at large deformations and high angular momenta. Calculations of single particle orbits at angular momenta of approximately 40 $\hbar$ show a large shell gap at N and Z=27 for deformations of the order β_2=0.9. When these single particle levels are used to calculate shell corrections to the liquid drop potential energy surface for ^{56}Ni the result is a significant second minimum just inside the fission barrier, as shown in Fig. 6. We may then hypothesize that the narrow resonances observed in $^{28}Si + ^{28}Si$ reactions correspond to states in this second minimum and may therefore be qualitatively described as high-spin fissioning shape isomers.

Given this qualitative description of the narrow resonances there are then several consequences, independent of the details of any specific calculation, which can then be tested experimentally. One of these is the expected behavior of the second minimum which should become much shallower as particles are added to the system. This should lead to a disappearance of the narrow structure. To test this idea we have measured [10] excitation functions for $^{28}Si + ^{30}Si$ and $^{30}Si + ^{30}Si$ reactions. The grazing angular momenta and excitation energies in the compound nucleus for these two systems are quite similar to those of the $^{28}Si + ^{28}Si$ system. The summed angle-integrated elastic and inelastic scattering cross-sections for the three systems are shown in Fig. 7. The narrow structure, so prominent in the $^{28}Si + ^{28}Si$ data has completely disappeared in the $^{28}Si + ^{30}Si$ and $^{30}Si + ^{30}Si$ data leaving only the hint of broad oscillations for $^{28}Si + ^{30}Si$. The disappearance of the narrow structure is also accompanied by a decrease in cross-section of a factor of ~ 2 between each of the three systems. This result is consistent with the fission isomer hypothesis but does not necessarily exclude other interpretations. Further experiments which may confirm or deny the fission isomer hypothesis such as an attempt to observe the ^{56}Ni resonances via the $^{16}O + ^{40}Ca$ entrance channel, are under way. It is clear, nevertheless, that the final understanding of the mechanism responsible for the existence of such narrow states in the continuum will contribute in a significant way to our understanding of nuclear behavior.

The work presented here has been performed in collaboration with: S. B. DiCenzo, J. F. Petersen, B. B. Back, B. G. Glagola, R. W. Zurmühle, P. W. Kutt, S. J. Sanders, B. Dichter, and O. Hansen.

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FIGURE CAPTIONS

1. Total fusion cross-section for $^{12}C + ^{12}C$ obtained by measurements of γ-rays from residual nuclei. The data have been divided by a smoothly varying penetrability factor and are presented as a relative nuclear structure factor. Spin assignments are indicated for a number of the resonances.

2. Excitation functions for elastic and inelastic scattering of $^{28}Si + ^{28}Si$ measured at $\theta_{cm} = 90°$. The data points are spaced by 1 MeV and the target was approximately 500 keV thick to the beam.

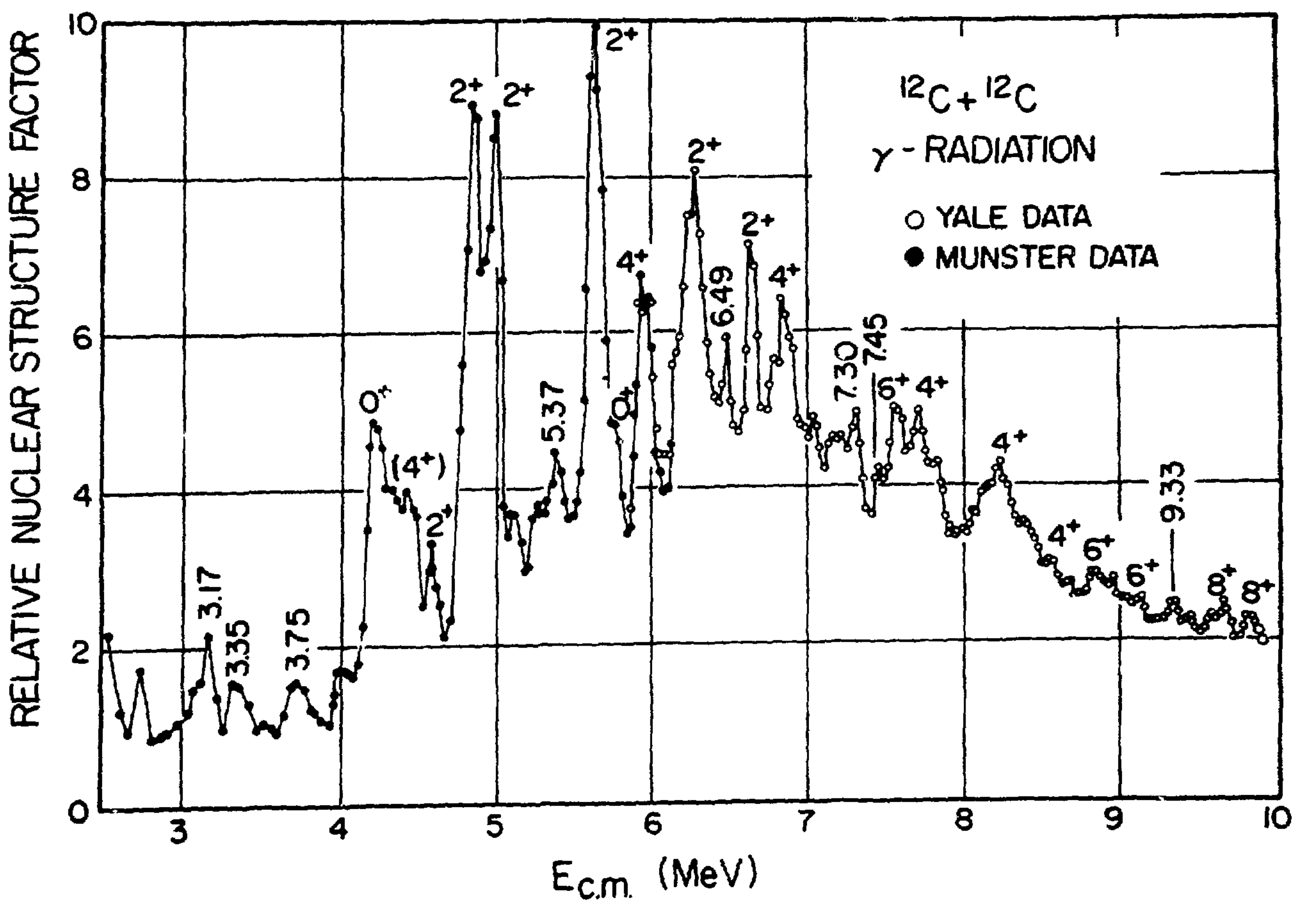
3. Angle-integrated cross-sections for $^{28}Si + ^{28}Si$ elastic and inelastic scattering plotted as a function of bombarding energy. The data were integrated over an angular range from $\theta_{cm} \approx 60°$ to 90°.

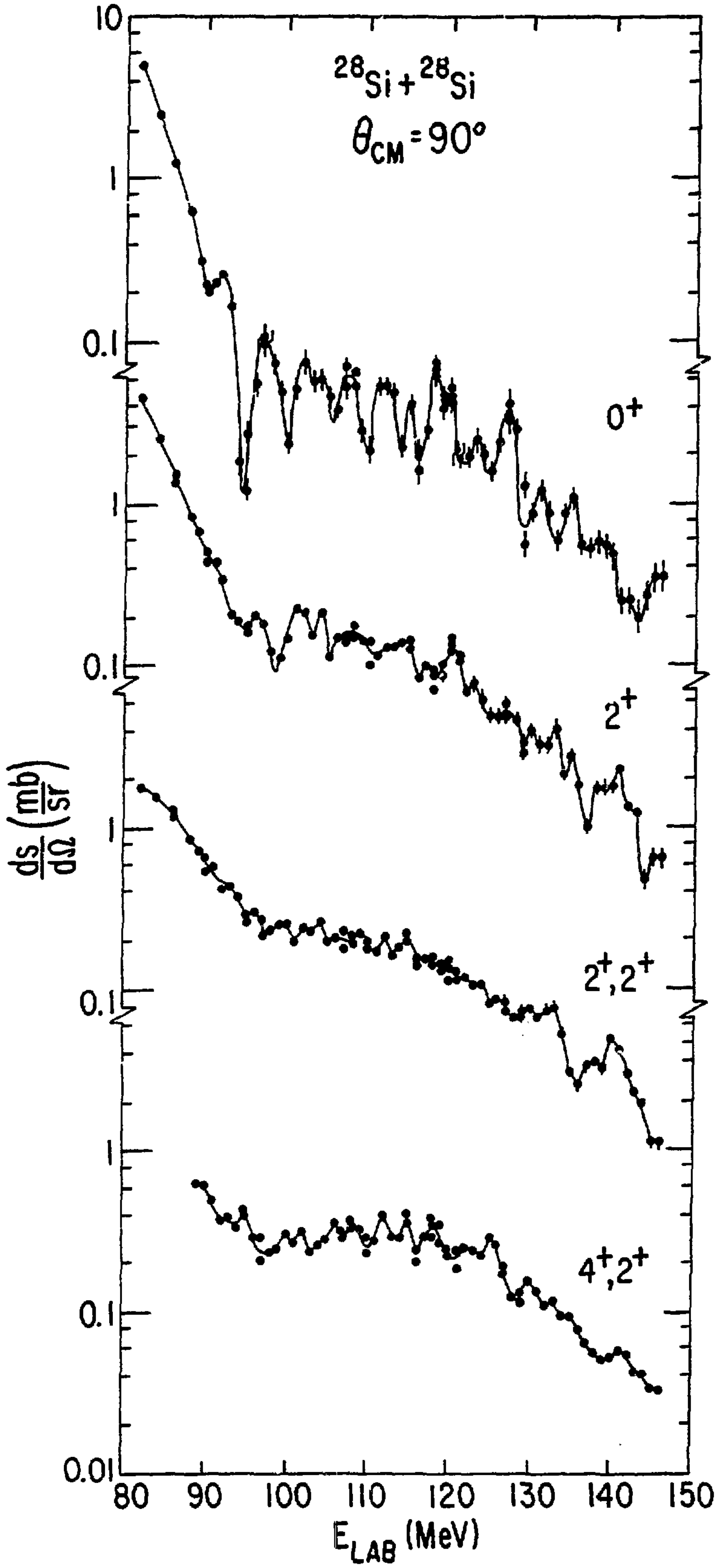
4. Angle-integrated cross-sections for $^{28}Si + ^{28}Si$ elastic scattering and reactions measured in 100 keV steps. The angular range over which the data were integrated is the same as for Fig. 3.

5. Elastic scattering angular distribution for $^{28}Si + ^{28}Si$ measured at a bombarding energy of 118 MeV. The three curves are P_L^2 (cosθ) for L = 38, 40 and 42 as indicated on the figure. For the sake of clarity only the last lobe of the L = 38 and 42 curves is shown.

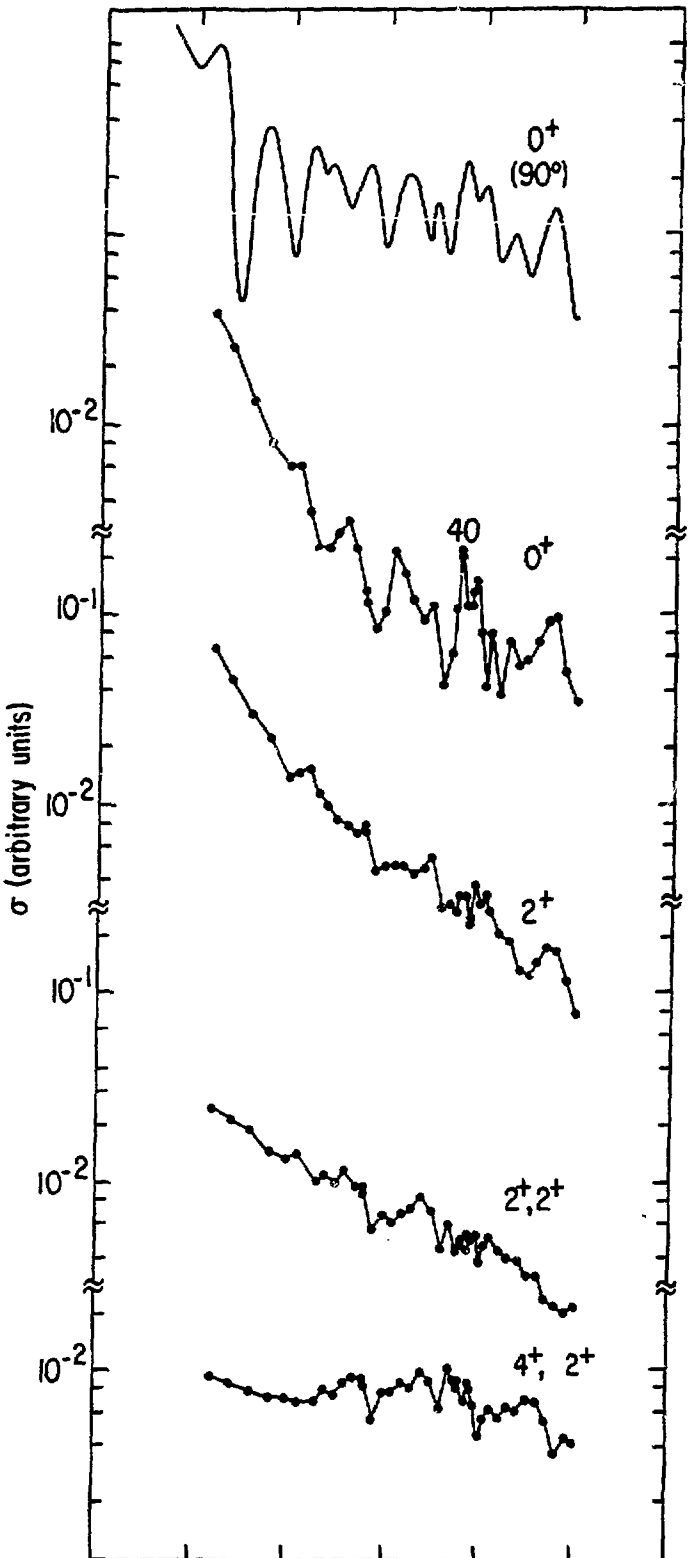
6. Potential energy surface for ^{56}Ni at $I = 40$ shown plotted as a function of deformation β and mass-asymmetry $M_r = M/56$ where M is the mass of one of the fragments. For details of the calculation see Ref. 9.

7. Summed elastic and inelastic scattering cross-sections for $^{28}Si + {}^{28}Si$, $^{28}Si + {}^{30}Si$ and $^{30}Si + {}^{30}Si$ plotted versus compound nucleus excitation energy. The cross-sections are averaged over a cm angular range of approximately 30°.

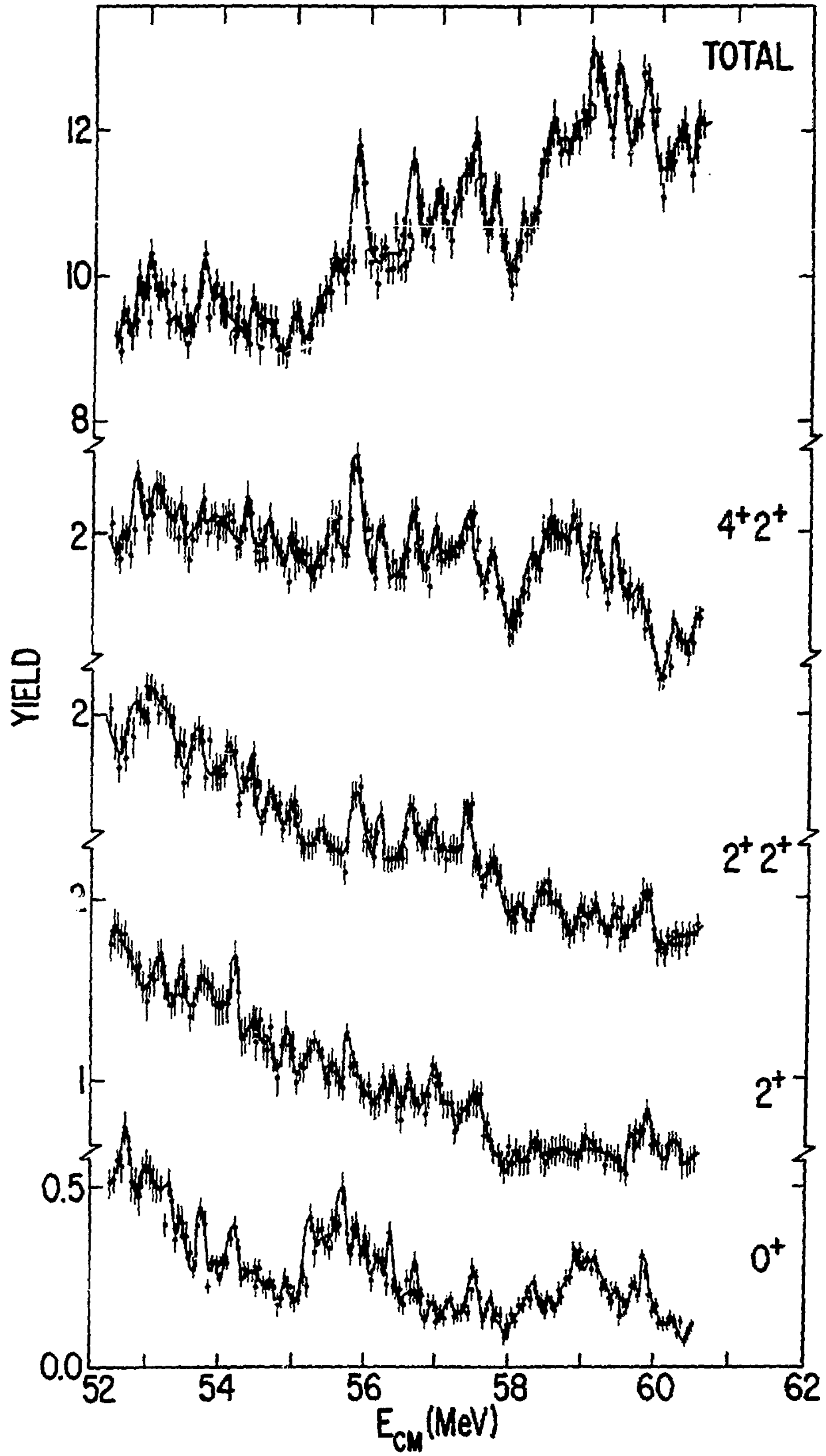

RELATIVE NUCLEAR STRUCTURE FACTOR
Ec.m. (MeV)
12C+12C
γ - RADIATION
○ YALE DATA
● MUNSTER DATA
3.17
3.35
3.75
0+
(4+)
2+
2+
2+
5.37
2+
0+
4+
2+
6.49
2+
4+
7.30
7.45
6+
4+
4+
4+
6+
6+
9.33
8+
8+

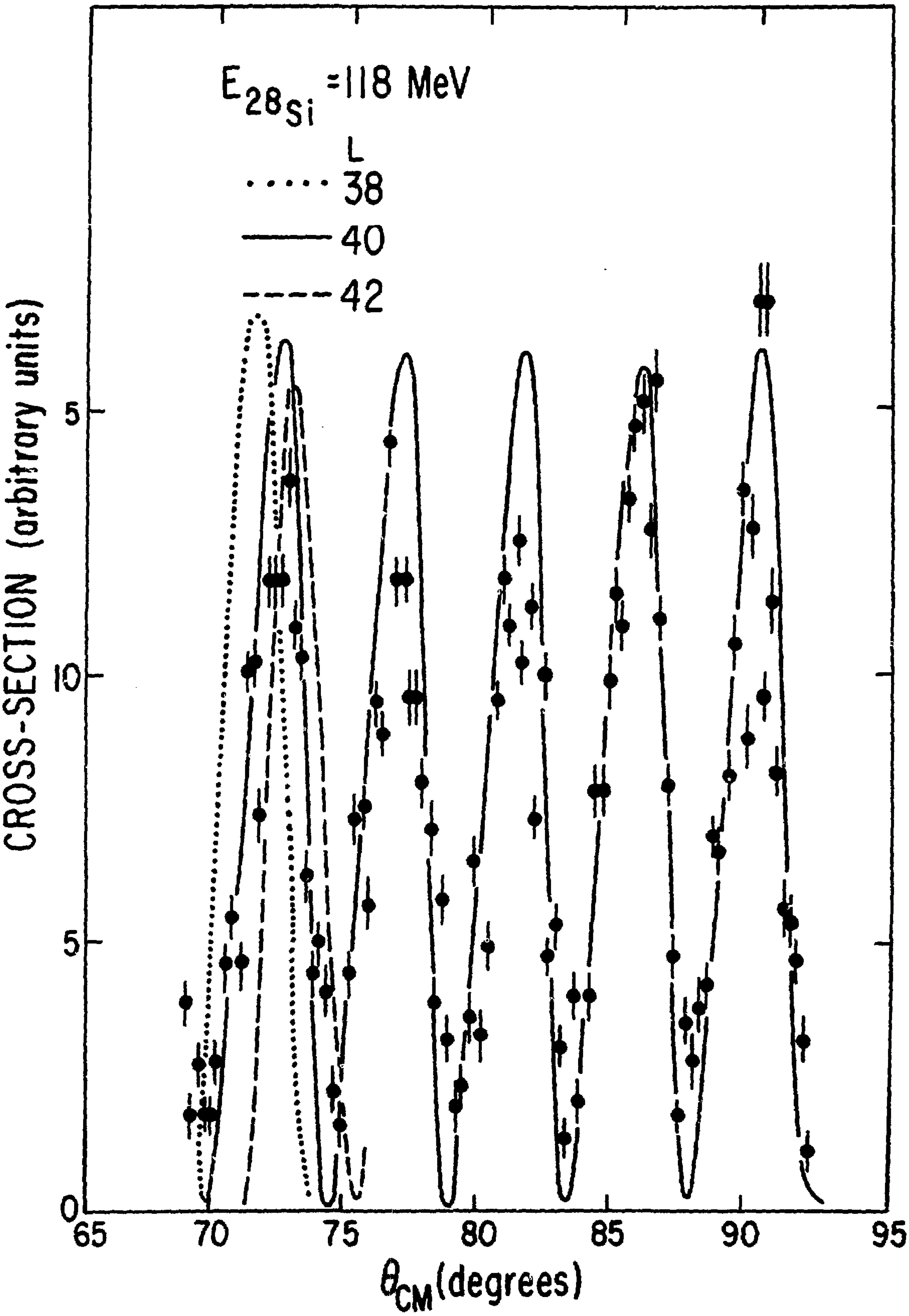


$^{28}Si + ^{28}Si$
$\theta_{CM} = 90°$
0+
2+
2+,2+
4+,2+
10
1
0.1
1
0.1
1
0.1
1
0.1
0.01
$\frac{d\sigma}{d\Omega}\left(\frac{mb}{sr}\right)$
80
90
100
110
120
130
140
150
E_{LAB} (MeV)

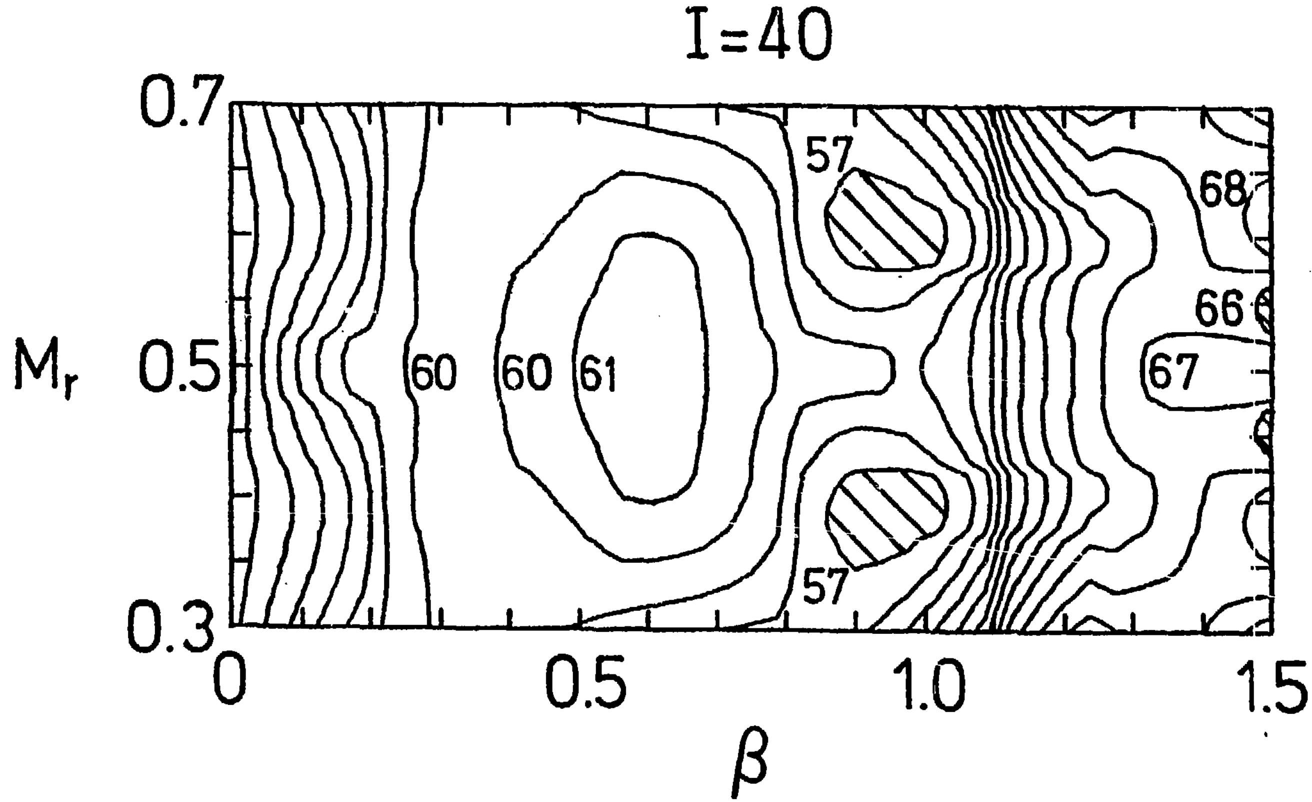


0+
(90°)
10-2
40
0+
10-1
10-2
2+
10-1
10-2
2+,2+
10-2
4+, 2+
σ (arbitrary units)
90
100
110
120
130
E_LAB (MeV)

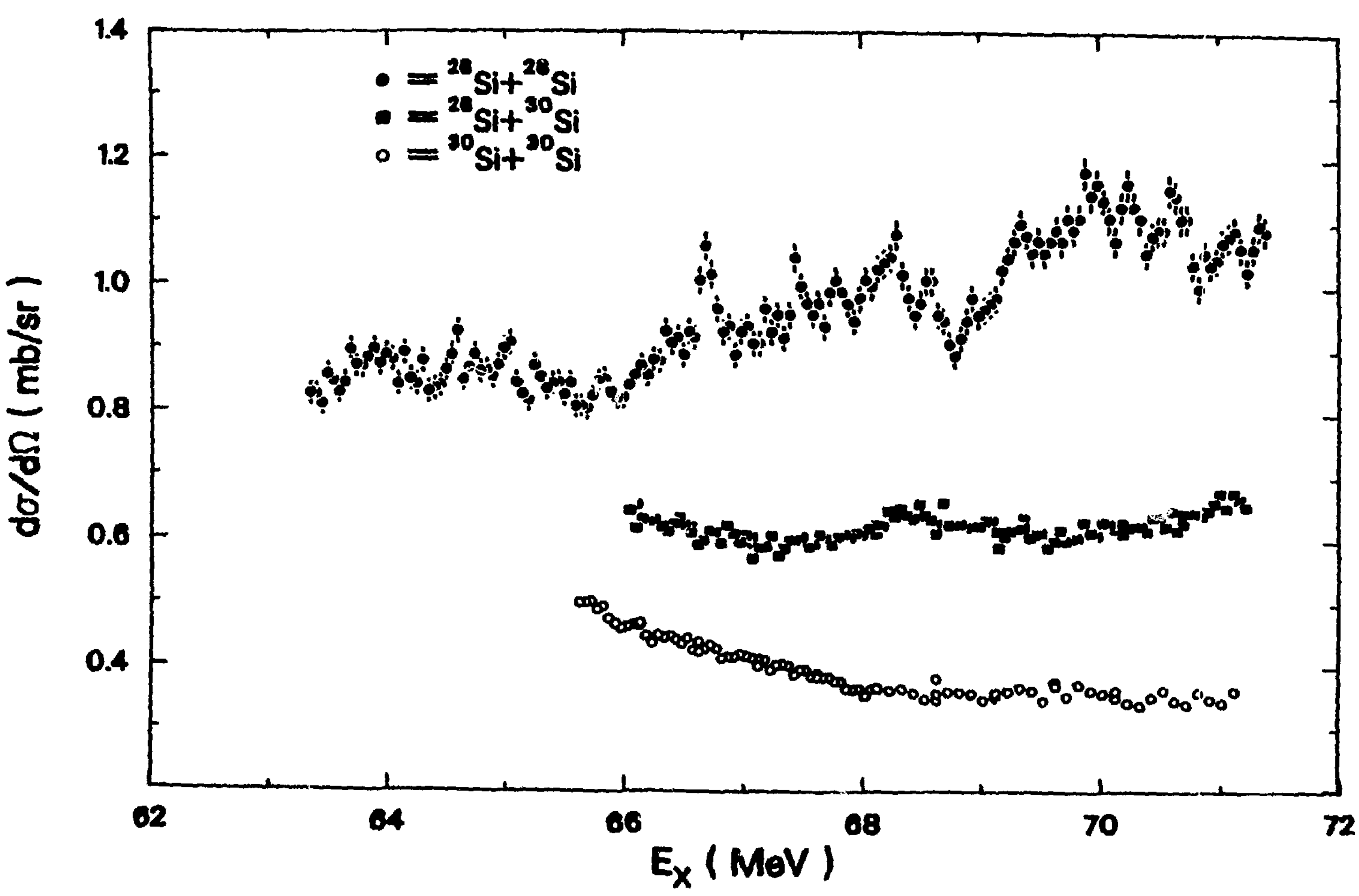

TOTAL
12
10
8
4+2+
2
YIELD
2
2+2+
1
2+
0.5
0+
0.0
52
54
56
58
60
62
E_CM (MeV)



E28Si =118 MeV
L
38
40
42
CROSS-SECTION (arbitrary units)
5
10
5
0
65
70
75
80
85
90
95
θCM (degrees)



I=40
0.7
0.5
0.3
M_r
0
0.5
1.0
1.5
β
60
60
61
57
57
68
66
67



● = 28Si+28Si
■ = 28Si+30Si
○ = 30Si+30Si
dσ/dΩ (mb/sr)
1.4
1.2
1.0
0.8
0.6
0.4
62
64
66
68
70
72
Ex (MeV)