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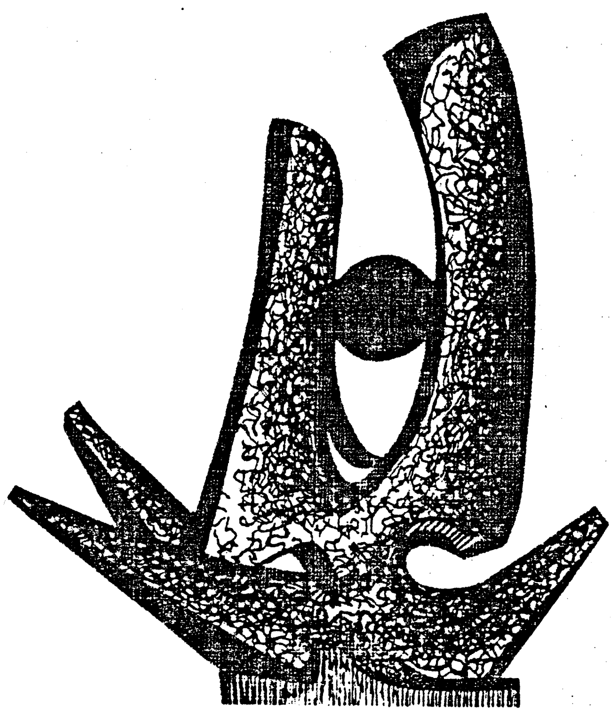

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Excitation of Resonance-like Structures in Low Energy Heavy Ion Collisions by Quasi-Free Scattering

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Abstract

We consider quasi-free scattering of the projectile with a cluster of a few nucleons as a possible origin of the gross structures observed in ^{40}Ca on ^{40}Ca and ^{63}Cu on ^{63}Cu reactions at 400 and 450 MeV incident energy. It is found that the model reproduces the structures by making reasonable assumptions concerning the heavy-ion trajectory under the influence of the Coulomb and nuclear potentials.

1. Introduction

Several recent experiments[1,2]) have shown gross structure in the energy spectra of outgoing projectile-like nuclei produced in ^{40} Ca on ^{40}Ca reactions at 284 MeV and 400 MeV. These structures are observed around the grazing angle and correspond to excitation energies in the residual system of approximately 25, 50, 80, and 120 MeV. Analogous results have been reported[1]) for ^{63}Cu on ^{63}Cu at 450 MeV.

Several theoretical models based on evaporation of particles after few nucleon pick up reactions[3,4]) and on giant resonances with high multipolarities[5-8]) have been proposed in order to explain these resonance-like structures. However, more recent experiments[9]) have indicated that the evaporation model cannot account for all of the data. Broglia et al.[5,6]) suggested the possible importance of the giant resonance excitations for energy dissipation in deeply-inelastic heavy-ion reactions. It is known that low lying giant resonances are indeed excited in heavy-ion reactions[10]). Although the harmonic oscillator model produces giant resonances with high angular momentum (L) at high excitation energies, the mean energies of the strength distribution do not increase with angular momentum, but rather converge to some small value, once a realistic potential is used[7]). Thus, in this description, the giant resonance picture can explain at best only the observed structure at 25 MeV excitation energy. Flocard and Weiss[8]) have suggested a dynamical model based on anharmonic nuclear vibrations, by making time-dependent Hartree-Fock (TDHF) calculations for ^{40}Ca on ^{40}Ca at 400 MeV.

In this paper, we investigate the possibility of quasi-free scattering of the incoming heavy-ion with light "clusters" in the target nucleus as the source of the resonance-like structures in the energy spectra. One feature of the experimental data is the fact that the excitation energies of the resonance structures are almost independent of the observed projectile-like nucleus. This fact seems to indicate that a quite simple mechanism might be responsible for the structures. Hence, we construct a model in terms of a quasi-free scattering process where the incoming heavy-ion collides with a cluster of nucleons and produces bumps in the excitation function at energies depending on the number of nucleons in the cluster. Other projectile-like nuclei are produced by a few nucleon transfer before and/or after quasi-free scattering with 'clusters'.

In the next section, we describe the quasi-free scattering process and present the calculated results. In section 3 we state the conclusions of our study and indicate future experiments which would serve to test the model.

2. Quasi-Free Scattering of the Projectile with Clusters in the Target Nucleus

We begin by describing the picture of heavy-ion collisions slightly above the Coulomb barrier. The relationship between the impact parameter and the scattering angle was studied by Koonin et al.[11]) for ^{40}Ca on ^{40}Ca collisions and for ^{16}O on ^{16}O collisions within the TDHF model. At a medium impact parameter the projectile sticks to the target nucleus and the system rotates for some time due to the nuclear attraction after which the nuclei separate at some finite scattering angle. We assume that the projectile collides with nucleons in the target and knocks out the nucleons, a process which might be considered as the fragmentation of the target nucleus. The number of nucleons with which the projectile collides depends on the impact parameter b, and increases with decreasing b. The more nucleons involved in the collisions, the more energy the projectile loses due to the energy-momentum conservation.

We shall describe the quasi-free scattering model for the projectile with "clusters" in the target nucleus using fig. 1. When the impact parameter b is given, the projectile is influenced by "the Coulomb and the nuclear" potential and ends up at the scattering angle θ_0, denoted by the dotted line. If the projectile collides with a cluster, then the trajectory changes by $\Delta\theta$ as indicated by the solid line due to quasi-free scattering.

We assume elastic scattering for the projectile and we neglect both the Coulomb and the nuclear forces, which are supposed to be taken into account in the semi-classical trajectory. By taking Fermi motion of clusters into account, the energy and momentum conservation before and after the quasi-free scattering gives;

$$\vec{P} + \vec{k} = \vec{P}' + \vec{k}' \tag{1}$$

$$\frac{P^2}{2M} - \text{B.E.} = \frac{P'^2}{2M} + \frac{k'^2}{2m} \tag{2}$$

where $\vec{P}$ and $\vec{P}'$ are the initial and final momenta of the projectile of mass M and m is the mass of the struck cluster. The momentum distribution of the quasi-free cluster $\vec{k}$ is assumed to have a Gaussian form.[12]

$$d_n(\vec{k}) = \exp\left(-\frac{\vec{k}^2}{2\sigma_n^2}\right) \tag{3}$$

$$\sigma_n^2 = \sigma_0^2 \, \frac{n(A-n)}{A-1} \tag{4}$$

where we take σ_0=80 MeV/c[13]. We assume an off-shell relation for the initial cluster motion, where B.E. denotes the binding energy of the cluster in the target nucleus.

The energy-momentum conservation, eqs. (1) and (2), provides the energy distribution of the outgoing projectile at each angle. This angle corresponds to $\Delta\theta$ in fig. 1 and

the actual angle is obtained by adding θ_0 due to the deflection in the Coulomb and the nuclear potential to this quasi-free scattering angle $\Delta\theta$.

Our problem now is to find θ_0 for each impact parameter, which is expected to have close correspondence with the number of nucleons in the cluster. Koonin et al.[11] have shown that changes of the impact parameter b can lead to drastic changes of the scattering angle. We therefore determine θ_0 for each cluster in order to reproduce the peak position with the experimental energy spectra. In addition, since the relation between b and the mass of cluster is not sharply defined, we allow an acceptance of a few degrees in the sum of θ_0 and $\Delta\theta$ for each scattering.

In order to derive the intensity (cross section) of the outgoing projectile-like nucleus, we have to know the spectroscopic factors of the clusters in the target nucleus. This information can be obtained from projectile fragmentation experiments at high energy. Furthermore, the recent study by Friedman[14] suggests the following expression for the spectroscopic factors of the clusters;

$$\gamma_F = S_F \, \frac{e^{-2\mu_F \chi_F b}}{\chi_F^3 (1-b)} \tag{5}$$

Here S_F is the normalized relative probability for finding a cluster of protons and neutrons; μ_F is given by $\frac{m_n m_F}{m_n + m_F}$ the reduced mass of the fragmented target and the removed cluster; x_F=1.2 $A^{1/3}$ fm is the distance between the cluster and the fragment; the parameter b is used to account for absorption effects with a value 0.4 in order to reproduce the fragmentation cross sections[14]). We use eq. 5 to calculate the spectroscopic factors of clusters instead of the experimental fragmentation cross sections, since the latter include contributions from secondary decay process of fragmented nuclei into more stable ones.

We first consider the case of ^{40}Ca on ^{40}Ca at 400 MeV. The results of our calculations as a function of the laboratory energy for ^{40}Ca are shown in fig. 2. The unit of cross section is arbitrary. Table 1 shows the range of integrated angles used for each cluster; the angles correspond to those of the quasi-elastic scattering. Since the angle of detection is fixed at $\theta=10^{\circ}$, the increase of $\Delta\theta$ with the number of nucleons in the cluster implies a decrease of 'the Coulomb and nuclear potential' scattering angle θ_0 in fig. 1 with the cluster mass. This decrease of θ_0 with A is consistent with our picture, in which the overlap of the projectile and the target nucleus increases as the cluster mass A increases. Hence, the quasi-elastic process considered here occurs in the region of the impact parameter, where the nuclear attraction wins the Coulomb repulsion and the scattering angle θ_0 decreases with decreasing impact parameter b (see fig. 7 of ref. [11])). The quasi-elastic peaks due to one (proton or neutron) and two nucleon knockout lies above 380 MeV. Thus, it is obscured by the "elastic" peak

in the experimental data and omitted in fig. 2. All peak widths are reasonably narrow and are commensurate with the experimental widths. This narrow width is due to the kinematical restriction in the use of the off-shell relation of eqs. (1) and (2). If we use the on-shell relation $\frac{k^2}{2m}$ instead of -B.E. in eq. (2) for the initial cluster, the widths come out to be much wider than the experimental values.

A similar resonance-like structure is reported at lower energy (E_{Lab}= 284 MeV) in the ^{40}Ca on ^{40}Ca system[1]). We show the calculated results in fig. 3, where the range of angles for each cluster taken is shown in table 1. In this case, we had to identify the lowest bump at E_x=25 MeV (E_{Lab}=240 MeV) as due to A=4 clusters. All the bumps due to $A\leq3$ seem to appear at higher laboratory energy and produce a large continuous bump together with the elastic scattering peak. The other resonance-like structures observed in ref. 1 seem to be reproduced by quasi-free scattering with A=5 and 7 clusters.

The quasi-free scattering is not limited to the ^{40}Ca + ^{40}Ca system. In fact, a similar structure is found also in the ^{63}Cu on ^{63}Cu system at E_{Lab}=450 MeV. Fig. 4 shows the calculated results for this system, where the angular range taken is summarized in table 1. We can reproduce the resonance-like structures at the energies corresponding to the excitation energy of 35, 50 and 80 MeV quoted in ref. 1.

3. Conclusion

In view of the results presented above, we conclude that the experimentally observed bump-structures in the excitation functions of the projectile-like nuclei may contain a contribution from the quasi-free scattering of the projectile with clusters in the target. It also seems plausible for this process to occur in heavy ion collisions, since the proposed process can be recognized as fragmentation of the target similar to the projectile fragmentation studied at higher energies. A weak point of our model is he variation of the scattering angle Θ_0 for each cluster. This may be solved with additional systematic experiments and theoretical calculations.

In order to test the validity of this model, one should perform further experiments not only for symmetric systems but also for asymmetric systems and at higher energies than the present energy range. Many questions and doubts remain to be settled, but one may hope that with new higher energy heavy-ion accelerators, the results will become less unambiguous. The process of quasi-free scattering should be expected to make some contribution in collisions of heavy nuclei. It may well be, however, that contributions from sequential excitation and decay, as well as giant resonance excitation, are also present. Experiments at different incident energies should therefore help to elucidate the nature of these gross structures.

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Table 1. The angular range for $\Delta\theta$ used in the calculation of excitation spectra

Particles (A) / Reaction	3	4	5	6	7
$^{40}Ca + ^{40}Ca$ 400 MeV	5.85-2.25	9.50-8.40	10.76 - 9.96	13.45-12.65	15.71-13.91
$^{40}Ca + ^{40}Ca$ 284 MeV	-	10.13-7.93	11.21-10.11	13.89-13.09	16.18-14.98
$^{63}Cu + ^{63}Cu$ 450 MeV	-	6.59-5.69	7.33 - 6.43	8.41 - 7.81	9.33 - 8.43

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Figure Captions

Fig. 1. Schematic picture of quasi-free scattering of the projectile with target clusters.

Fig. 2. Excitation function of ^{40}Ca at $\theta_{Lab}=10^{o}$ in $^{40}Ca + ^{40}Ca$ at 400 MeV.

Fig. 3. Excitation function of ^{40}Ca at $\theta_{Lab}=10^{o}$ in $^{40}Ca + ^{40}Ca$ at 284 MeV.

Fig. 4. Excitation function of ^{63}Cu at $\theta_{Lab}=10^{o}$ in $^{63}Cu + ^{63}Cu$ at 450 MeV.

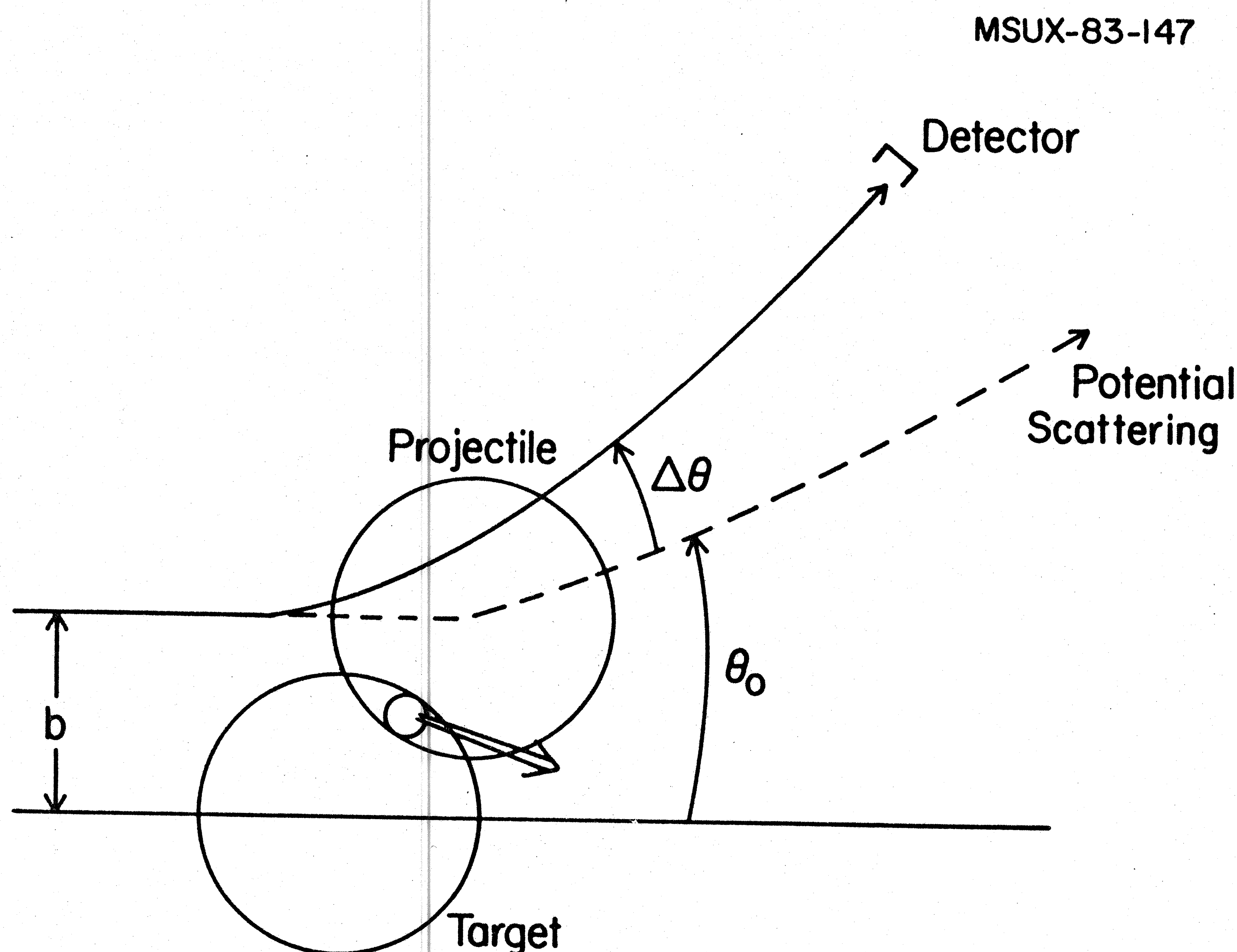
MSUX-83-147
Detector
Potential
Scattering
Projectile
$\Delta\theta$
θ_o
b
Target

Figure 1

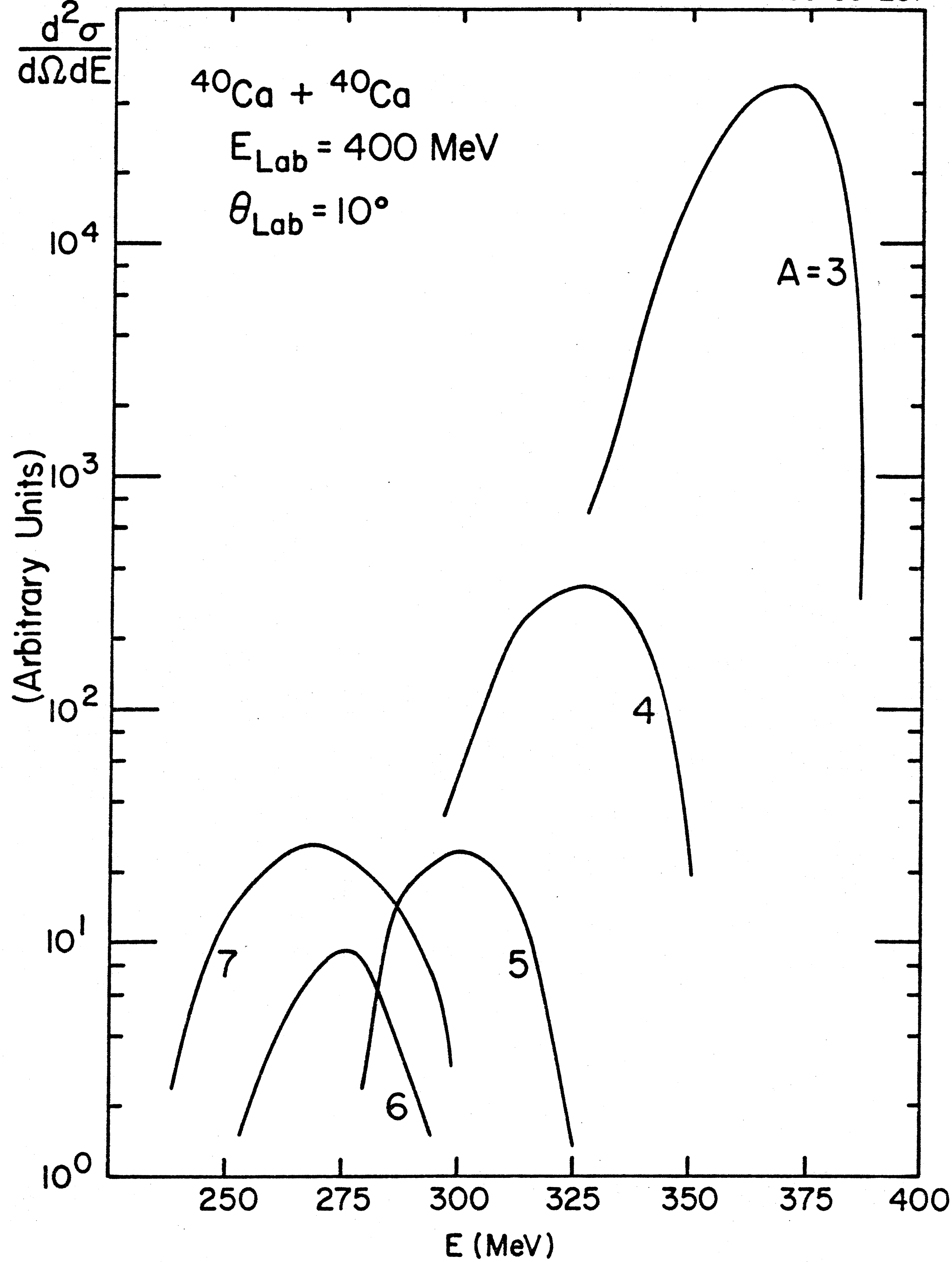
$\frac{d^2\sigma}{d\Omega dE}$
(Arbitrary Units)
^{40}Ca + ^{40}Ca
E$_{Lab}$ = 400 MeV
θ$_{Lab}$ = 10°
A=3
4
5
6
7
10^4
10^3
10^2
10^1
10^0
250
275
300
325
350
375
400
E (MeV)

Figure 2

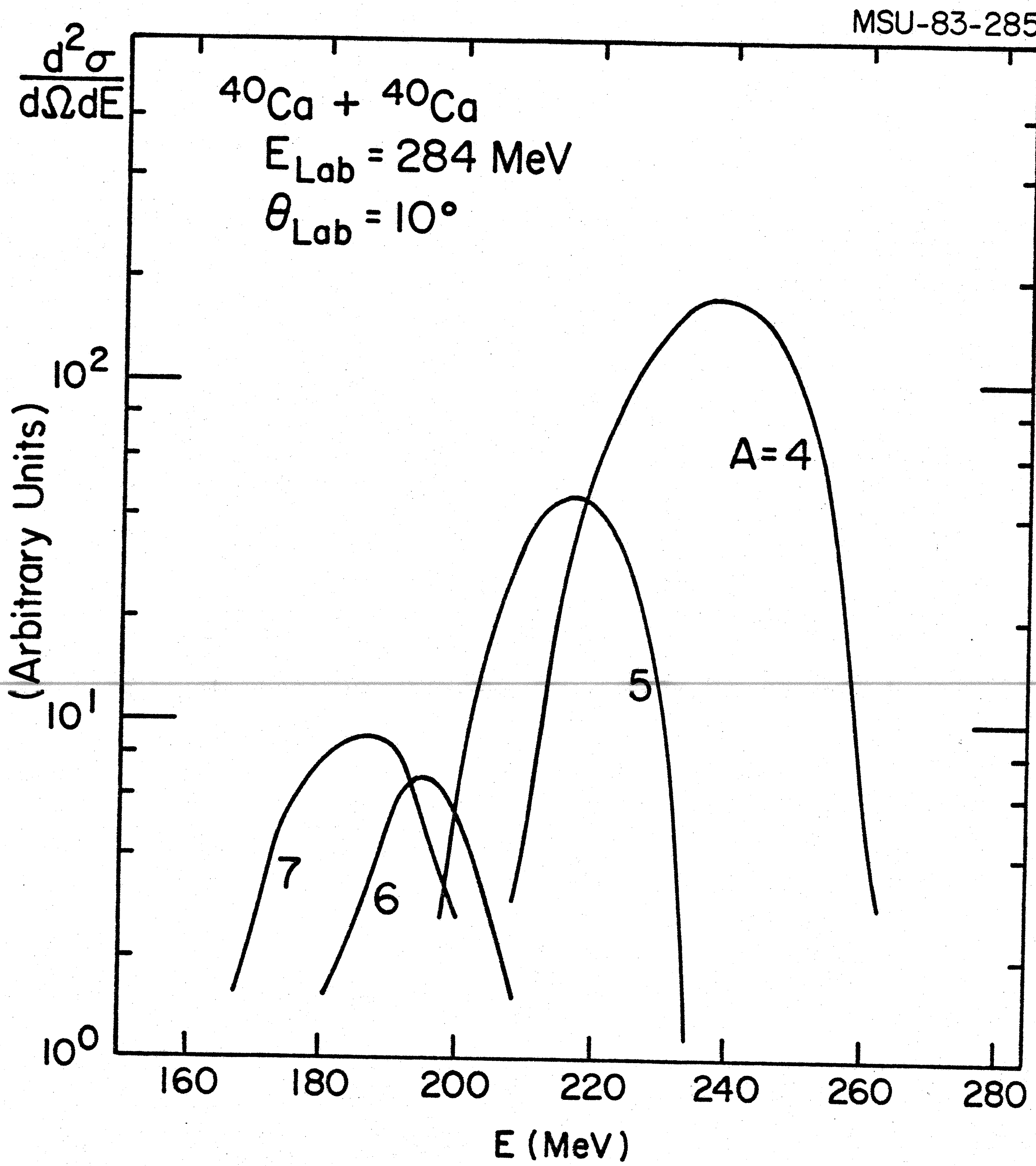
MSU-83-285
d²σ/dΩdE (Arbitrary Units)
40Ca + 40Ca
ELab = 284 MeV
θLab = 10°
10⁰
10¹
10²
A=4
5
6
7
160
180
200
220
240
260
280
E (MeV)

Figure 3

MSU-83-286

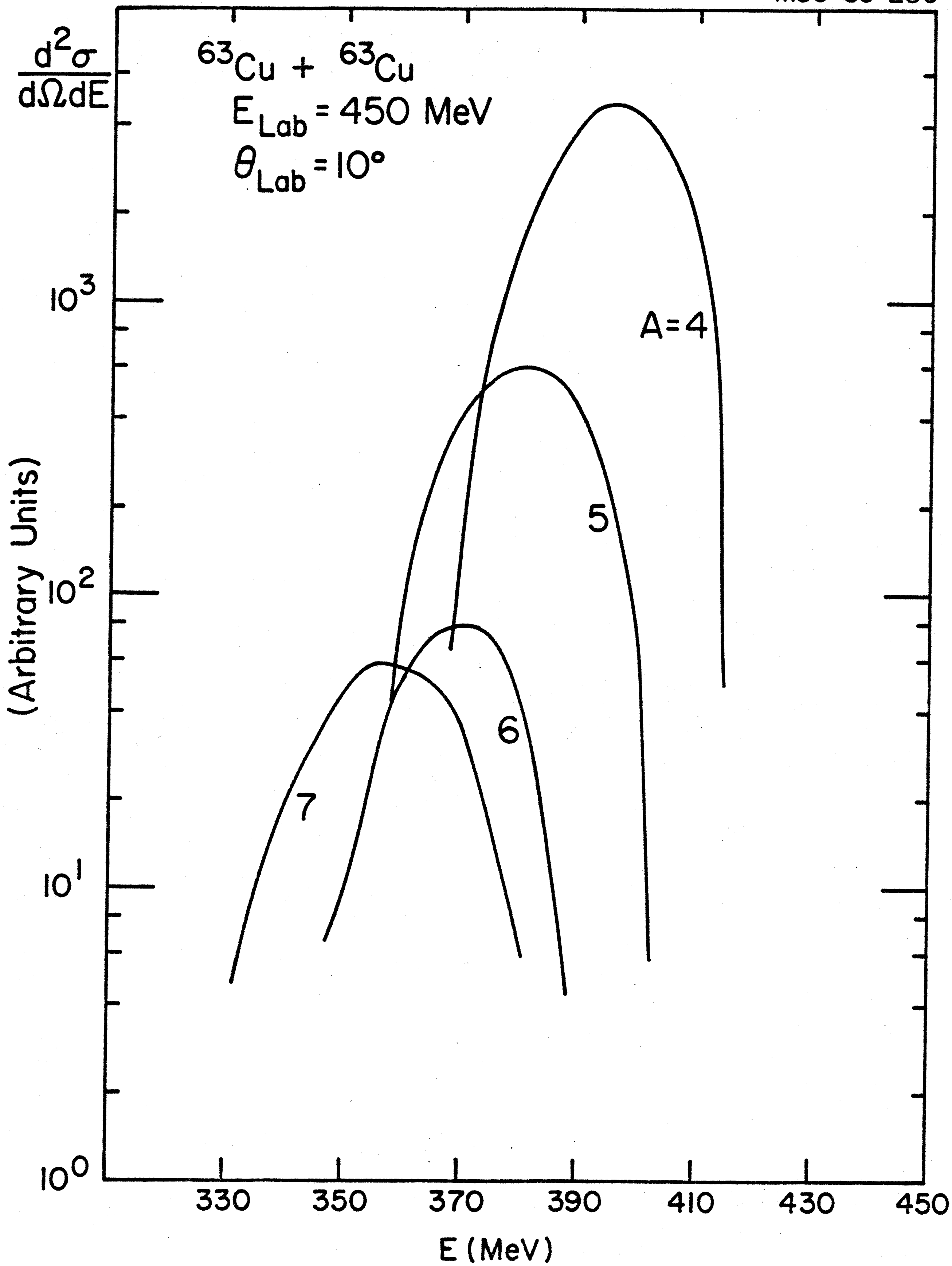

Figure 4