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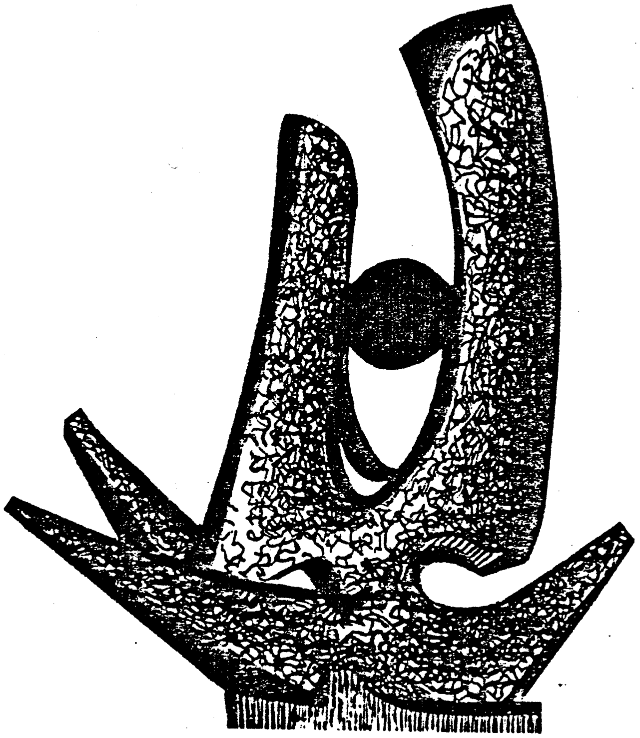

AUGUST 1983

MSUCL-432

MSUCL- #432
August, 1983

EVIDENCE FOR THE FORMATION AND DECAY OF SPATIALLY LOCALIZED AND HIGHLY EXCITED SUBSYSTEMS IN HEAVY ION INDUCED REACTIONS

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Abstract

Proton-proton correlations were measured in ^{16}O induced reactions on ^{197}Au at 400 MeV . Measurements at both small and large proton relative momenta indicate that a significant fraction of the correlated protons are emitted from a spatially localized region of high excitation.

Pacs Categories: 25.70-Z

Nonequilibrium particle emission in intermediate-energy nuclear collisions is a phenomenon whose description presents a clear challenge to our current understanding of nuclear reactions . Of the many differing theoretical approaches, the concept of a spatially localized region of high excitation ("hot spot")[1-4] has received support from the comparisons of inclusive light particle spectra and multiplicities with statistical predictions.[5,6] While these comparisons test the thermal assumptions of the "hot spot" picture, until now the particular aspect of spatial localization has lacked direct experimental verification. In this letter we report the first results from two-proton correlation measurements that provide evidence for particle emission from a spatially localized region of high excitation in qualitive agreement with the concept of a "hot spot".

The experiment was performed at the Holifield Heavy Ion Research Facility. A gold target of 9.7 mg/cm^2 was bombarded with ^{16}O ions of 400 MeV incident energy. Single and coincident protons were detected with 13 ΔE-E-telescopes consisting of silicon ΔE- and NaI E-detectors. Small angle correlations were measured with six telescopes with individual solid angles of 0.76 msr. The detectors were mounted in a closely packed hexagonal array that was centered at the scattering angle of 15°. The angular resolution and the angular separation between adjacent telescopes were 1.6° and 5.1°, respectively. Large angle correlations were measured with seven telescopes of solid angles between 13 and 41 msr.

Three of these telescopes were mounted in the plane of the small angle hodoscope ($\Phi=0^{o}$) at the scattering angles of $\Theta=40^{o}$, 70^{o}, and 130^{o}, where Θ and Φ denote the polar and azimuthal angles measured with respect to the beam axis. The remaining four telescopes were positioned at the polar angles of $\Theta= 40^{o}$, 70^{o}, 130^{o}, and 160^{o}; their azimuthal angle was varied between 50^{o} and 180^{o}. Absolute cross sections, accurate to 10%, were obtained from the integrated beam current, the target thickness and the solid angles of the telescopes. Energy calibrations accurate to 3% were obtained by measuring the energies of recoil protons backscattered from a Mylar target by a 200 MeV ^{16}O beam.

Consistent with previous observations, the singles light-particle cross sectons are rather well described in terms of thermal emission from a hot source of nucleons having an apparent temperature considerably higher than that of the compound nucleus and moving with slightly less than half the beam velocity6). Comparisons of the one- and two-particle energy spectra and angular distributions do not reveal any strong dynamical correlations in the two particle data7) which suggests that the one- and two-particle data share a common production mechanism consistent with a thermal interpretation. A detailed discussion of the energy spectra will be given in a forthcoming publication. Here we present those features of the two proton correlations that provide evidence for the spatial localization of the emitting region.

Information regarding the space-time extent of the emitting source is contained in the magnitude of the final state correlations between light particles emitted at small relative momenta. For the case of two protons emitted at close proximity in space and time, the strong attractive nuclear interaction in the singlet s partial wave causes a characteristic enhancemant in the two-proton correlation at relative momenta of about 20 MeV/c.$^{8)}$ Emission from a source of large dimensions or long source lifetimes will result in a reduced final state effect. Measurements of two proton correlations at small relative momenta have been used to determine the size of the nuclear fireball at relativistic beam energies$^{9)}$.

The two-proton correlation function, $R(\bar{p}_1,\bar{p}_2)$, is defined in terms of the singles cross sections, $\sigma(\bar{p}_1)$, $\sigma(\bar{p}_2)$ and coincidence cross sections $\sigma(\bar{p}_1,\bar{p}_2)$, by

$$\sigma(\bar{p}_1\bar{p}_2) = C\sigma(\bar{p}_1)\sigma(\bar{p}_2)(1 + R(\bar{p}_1,\bar{p}_2)) \qquad (1.)$$

where the $\bar{p}$'s denote the proton momenta and the normalization constant C is experimentally determined by the condition $R(\bar{p}_1,\bar{p}_2)=0$, for sufficiently large relative momenta, where final state interactions are not important. For a source of negligible lifetime, $R(\bar{p}_1,\bar{p}_2)$ depends principally upon the magnitude of the relative momentum $\Delta p=|\bar{p}_1-\bar{p}_2)|/2$.$^{8)}$ The experimental correlation function, shown in fig. 1, was obtained by inserting the cross sections, measured with the small angle hodoscope, into Eq.1 and by summing both sides of the equation over all energies and angles corresponding to a given relative momentum. The curves shown in the figure are the results of model calculations[8)] for the case of incoherent emission from a source of negligible lifetime and gaussian spatial distribution of rms radius $\sqrt{3/2}\ r_o$. The correlations observed experimentally are slightly larger than those calculated for a source with $r_o = 4$ fm. Nonnegligible decay times will reduce the correlations, therefore values for r_o deduced by comparison with the present calculations represent upper limits on the average source sizes.

Further insight may be gained by investigating the dependence of the measured correlation function $1+R(\Delta p)$ on the total energy of the two coincident protons. This energy dependence is shown in Fig.2 for the relative momentum intervals of $\Delta_1 p = 15\text{-}25$ MeV/c (where $R(\Delta p)$ is predicted to reach a maximum) and $\Delta_2 p = 50\text{-}80$ MeV/c (where $R(\Delta p)$ is predicted to be neglible). For the lowest proton energies, no substantial differences in the correlations of the two momentum intervals are observed, which indicates that these protons are predominantly emitted from a source of rather large space time extent, e.g. a long lived compound nucleus. With increasing proton energies the differences between the measured correlations become more pronounced, which indicates that high energy protons are emitted primarily from a short - lived and spatially localized region of high excitation, in qualitative agreement with the concept of formation and decay of a "hot spot". For proton energies above $E1+E2=90$ MeV the ratio $(1+R(\Delta_1 p))/(1+R(\Delta_2 p))$ yields an upper limit of $r_o=3.1$ fm. With the assumption that the gaussian source has a central density of normal or twice nuclear matter density (.015fm^{-3}), a maximum number of 25 or 50 participating nucleons is estimated, respectively.

In fig. 2, the correlation function corresponding to Δp = 50-80 MeV/c decreases slightly for increasing energy of the coincident protons. This decrease may be understood in terms of the phase space constraaints imposed by energy and momentum conservation. In order to assess these effects, we assume for simplicity that only a subset of nucleons have interacted strongly during the time in which the two protons are emitted. These protons are assumed to be emitted isotropically with a Maxwell-Boltzman distribution in the rest frame of this subset of nucleons. Following the emission of the first proton the subset recoils with a recoil velocity defined by momentum conservation and the number of nucleons in the source, A_s.7) This moving-source parameterization provides an adequate description of the inclusive data6) and is consistent with the overall features of the coincidence data.7) The solid line in Fig. 2 shows the correlation expected for a subset with apparent temperature of 7.1 MeV and average velocity of .087c consisting of A_s = 40 nucleons.

The phase space constraints imposed by momentum conservation may be used to assess the number of participating nucleons. Since the singles and coincidence cross sections depend strongly on the polar emission angle, these phase space constraints are best demonstrated by fixing the polar angles of the coincident protons and examining the ratio of cross sections for coplanar emission on opposite sides ($\Delta\Phi=180^{\circ}$) to coplanar emission on the same side of the beam axis ($\Delta\Phi=0^{\circ}$). In fig. 3, this ratio is shown for the polar angles of $\Theta_1=40^{\circ}$ and $\Theta_2=70^{\circ}$. For each data point of the figure, the cross sections have been integrated over an identical energy interval of 20 MeV width for each proton. The cross section ratio is plotted at the midpoint of this interval.

The correlations expected from momentum conservation with subsets consisting of A_s = 40,70,100,and 213 nucleons are shown by the solid curves in Fig. 3. These calculations were performed by assuming a fixed temperature of 7.1 MeV. (If one adopts a consistent thermal interpretation of this moving source parameterization, the emission of the first proton should cool the source. The effect of cooling was assessed for the case of A_s=40, see the dashed curve in Fig. 3. It can be seen from the figure that the energy conservation requirement has only a small effect on the asymmetry.) Since rescattering by any nearby cold nuclear matter can reduce the asymmetry expected for the smaller subsystems, estimates of A_s deduced by comparisons of data to these calculations can be viewed as upper limits to the number of strongly interacting nucleons. For low energy protons, the experimentally observed asymmetry is small and comparable to the calculation for 213 nucleons (the compound nuclear mass). For protons of higher energy, however, considerably larger asymmetries are observed corresponding to significantly smaller source sizes. This trend is in qualitative agreement with our conclusions from the analysis of the small angle correlations.

In summary, two proton correlations measured for ^{16}O induced reactions on ^{197}Au at 400 MeV provide evidence for the formation and decay of a localized region of high excitation in agreement with the physical picture of a "hot spot". High energy protons sample the early stages of the reaction characterized by a rather small space-time extent of the emitting source. Low energy protons, on the other hand, are primarily emitted at later stages of the reaction corresponding to an emitting source consistent with the compound nucleus.

This material is based upon work supported jointly by the National Science Foundation under Grant No. PHY 80-17605 and by the Department of Energy under Contract No. W-7405-eng-26 with the Union Carbide Corporation. One of us (C.K.G.) acknowledges the receipt of an Alfred P. Sloan Fellowship.

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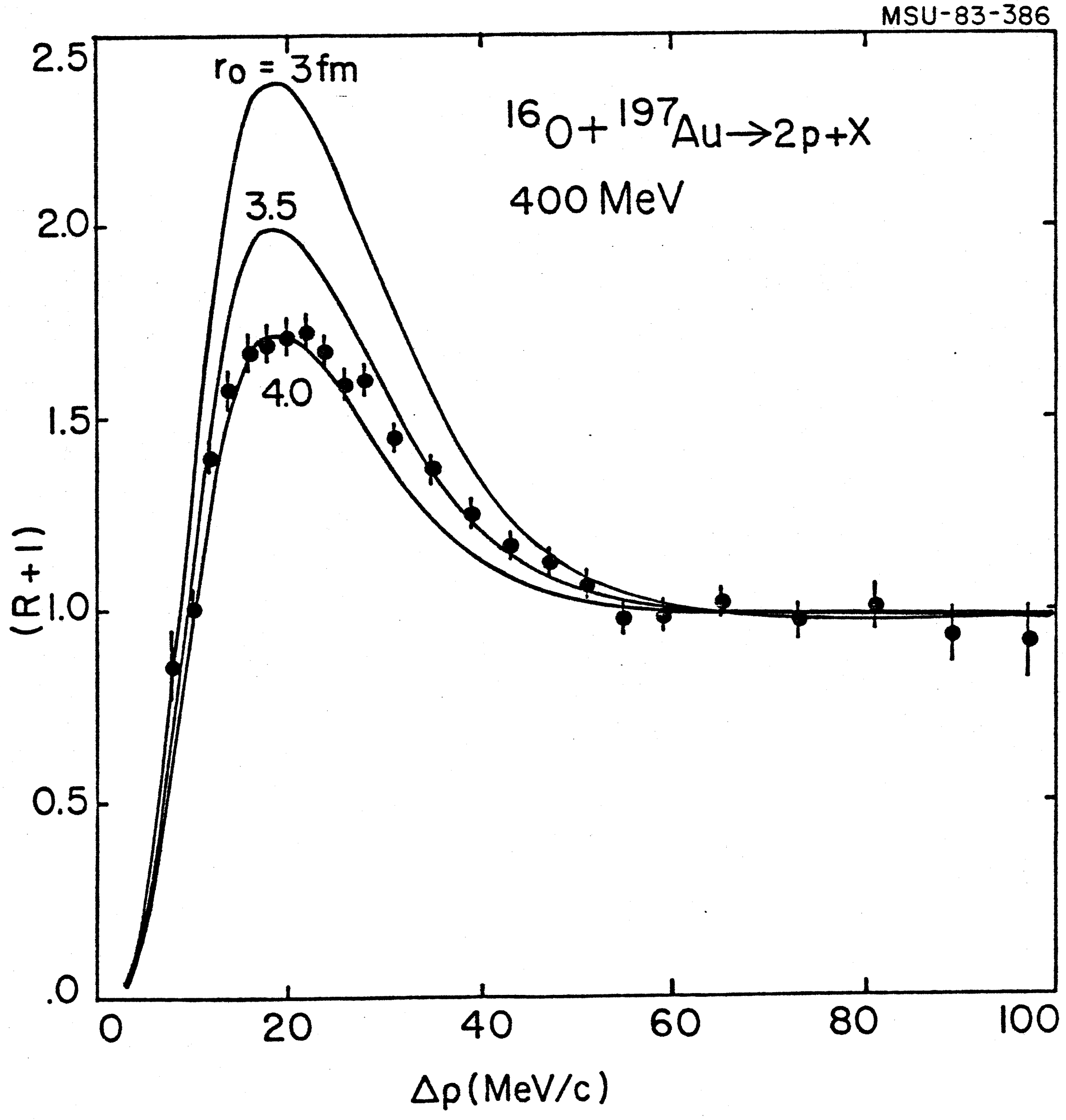
FIGURE CAPTIONS

Fig. 1. The experimental correlation function $1 + R(\Delta p)$ is plotted as a function of the proton relative momentum. The errors are purely statistical. See the text for a discussion of the curves.

Fig. 2. The correlation function $1 + R(\Delta p)$, gated on relative momentum intervals of 15-25 MeV/c and 50-80 MeV/c, is plotted as a function of the sum energy of the two protons. The errors are purely statistical. See the text for a discussion of the solid line.

Fig. 3. The ratio of the energy-integrated coincidence cross section for $\Delta\Phi = 180^\circ$ to that of $\Delta\Phi = 0^\circ$ is plotted as a function of the midpoint of the integration interval of 20-MeV width. The errors are purely statistical. See text for a discussion of the curves.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2.5
2.0
1.5
1.0
0.5
.0
(R+1)
0
20
40
60
80
100
Δp(MeV/c)
r_0 = 3fm
3.5
4.0
$^{16}O+^{197}Au \rightarrow 2p+X$
400 MeV

fig. 1

MSU-83-384

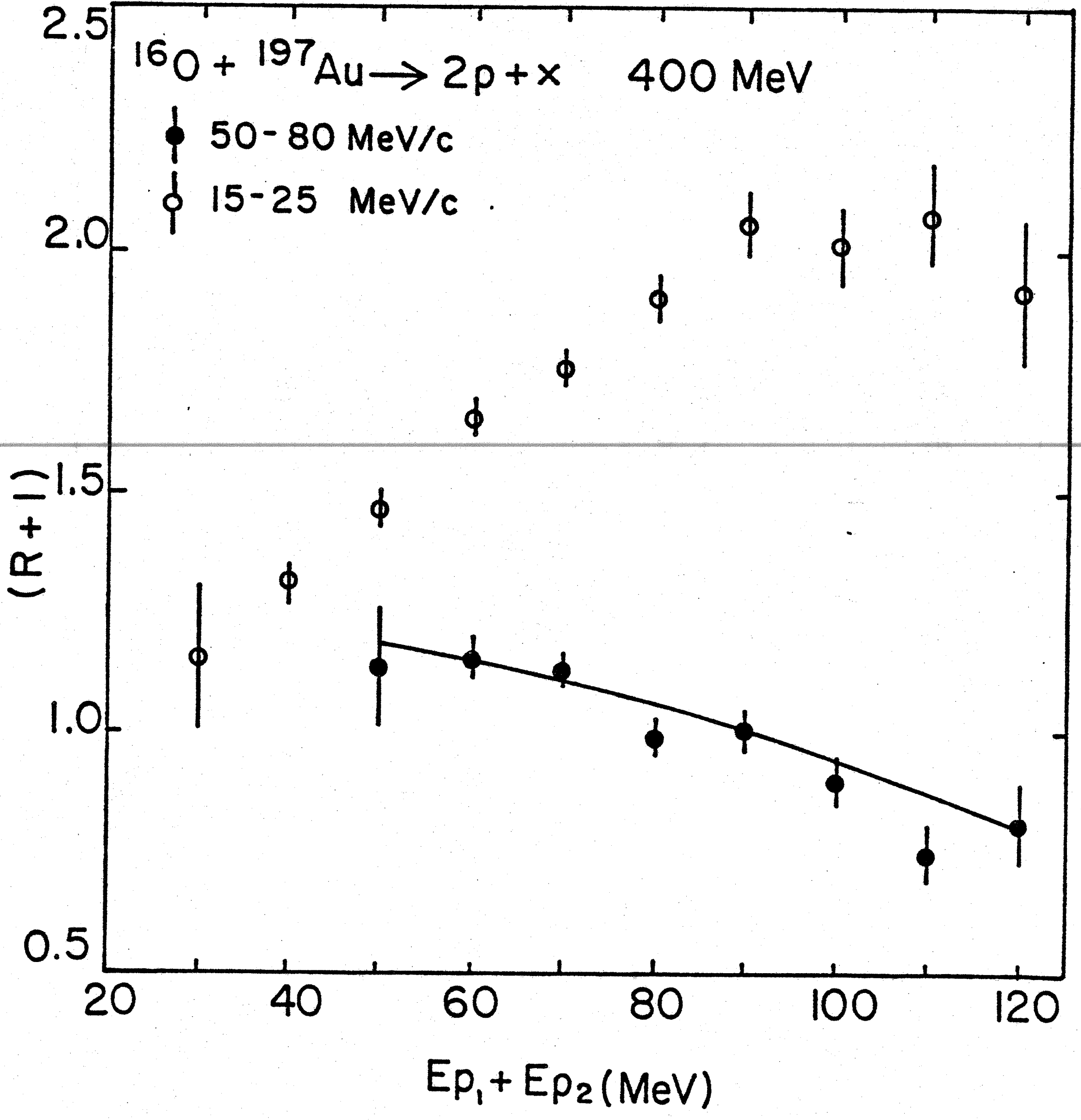

fig 2.

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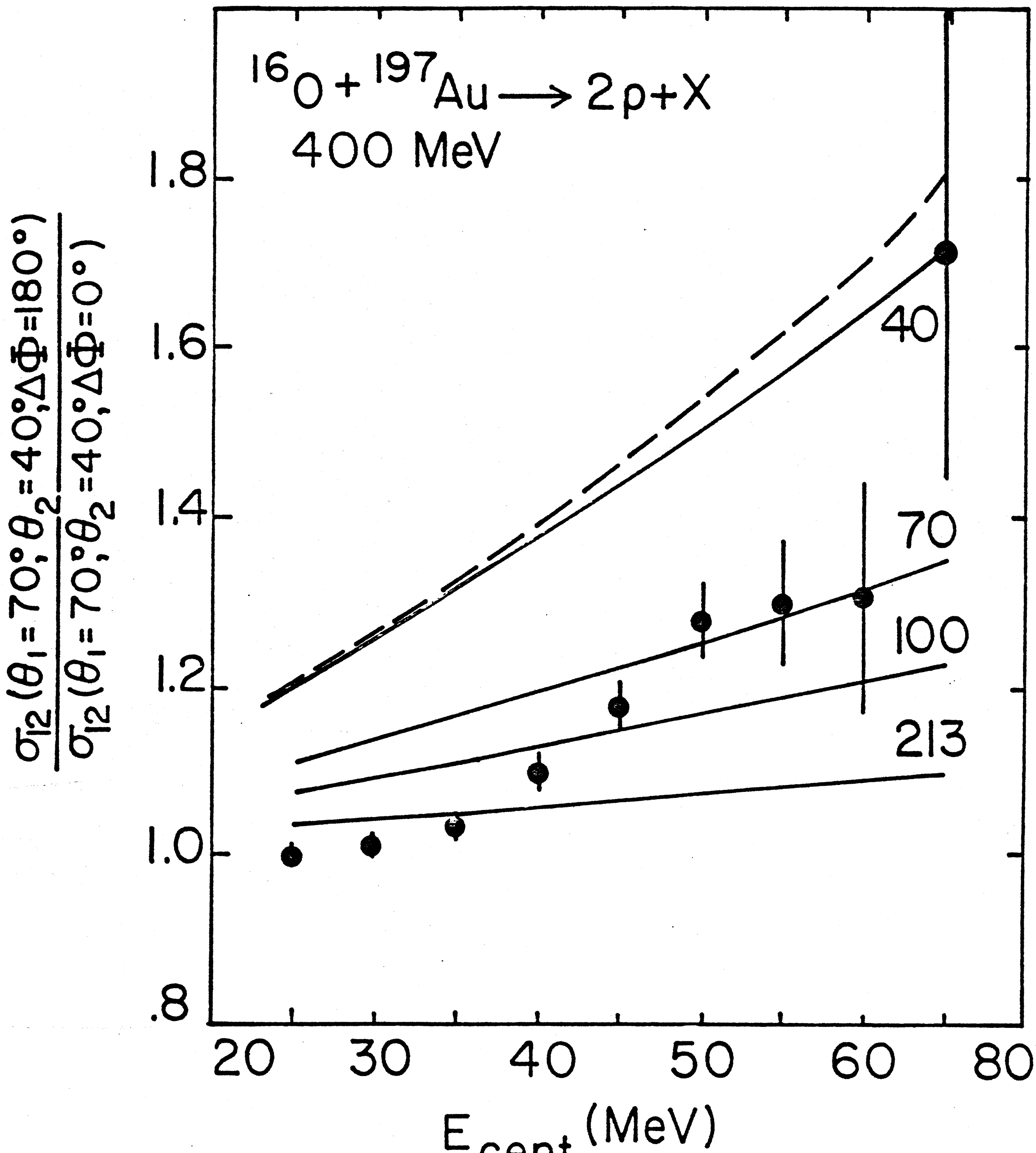

fig 3