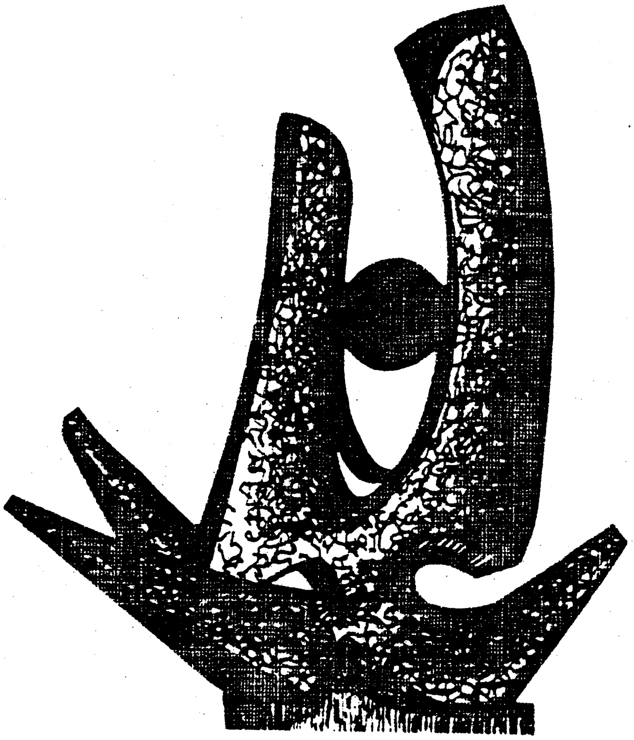
(136) 9/16/85

MICHIGAN STATE UNIVERSITY

CYCLOTRON LABORATORY

ENERGY DEPENDENT SOURCE RADII AND TEMPERATURES FOR ^{14}N INDUCED REACTIONS AT E/A = 35 MeV

C.B. Chitwood, C.K. Gelbke, J. Pochodzalla, Z. Chen, D.J. Fields, W.G. Lynch, R. Morse, M.B. Tsang, D.H. Boal and J.C. Shillcock



SEPTEMBER 1985

MSUCL-543

MSUCL 543
September, 1985

Energy Dependent Source Radii and Temperatures for ^{14}N Induced Reactions at E/A=35 MeV.

C.B. Chitwood, C.K. Gelbke, J. Pochodzalla*), Z. Chen, D.J. Fields,
W.G. Lynch, R. Morse, and M.B. Tsang

National Superconducting Cyclotron Laboratory
Michigan State University, East Lansing, Mi. 48824, USA

D.H. Boal and J.C. Shillcock
Department of Physics, Simon Fraser University
Burnaby, B.C. V5A 1S6, Canada

ABSTRACT

Correlations between coincident alpha particles and deuterons emitted in ^{14}N induced reactions on ^{197}Au at E/A=35 MeV were measured. Source radii ($r_0 \approx 3$-4 fm) and emission temperatures ($T \approx 9$-4 MeV) are extracted and shown to depend on the kinetic energy of the emitted particles.

PACS # 25.70Gh, 25.70 Np

The emission of complex particles prior to the attainment of full statistical equilibrium of the composite system is clearly established for intermediate energy nucleus-nucleus collisions.1,2) In the absence of a complete dynamical treatment, recourse is often taken to models based on the assumption of statistical particle emission from subsets of nucleons1-5) characterised by their average velocity, space-time extent, and excitation energy or "temperature". The experimental determination of the detailed characteristics of these subsets from single particle inclusive cross sections6) can be uncertain due to sensitivities to collective motion7) and the temporal evolution of the emitting system.2,8-10)

Information about the space-time extent of the emitting system can be obtained from the two-particle correlation function.11-13) "Emission temperatures" can be extracted from the relative population of states.14-17) To first order within the framework of equilibrium thermodynamics, the two-particle correlation function and the relative decay yields are independent functions of one variable each,13) the source volume and temperature, respectively. In this approximation, measurements of these two experimental quantities provide independent information on the temperature and the space-time evolution of the emitting system. In this letter, we simultaneously investigate source dimensions <u>and</u> emission temperatures for ^{14}N induced reactions at E/A = 35 MeV, by measuring correlations between coincident deuterons and alpha particles. Evidence is presented for a dependence of source radii and emission temperatures on the kinetic energy of the detected particles.

The experiment was performed at the National Superconducting Cyclotron Laboratory of Michigan State University. A gold target of 19 mg/cm^2 areal density was irradiated by a beam of ^{14}N of E/A=35 MeV incident energy. Light particles ($Z \leq 2$) were detected by a close-packed hexagonal array of 13 ΔE-E telescopes, each consisting of a 400 μm thick Si detector and a 10 cm thick NaI detector. Each telescope subtended a solid angle of 0.94 msr; the angular separation between adjacent telescopes was 6.1°. The energy calibrations of individual detectors are accurate to within 3%. Measurements were performed with the center of the hodoscope positioned at laboratory angles of 35° and 50°. Single particle inclusive cross sections of ^{6}Li were measured in a separate experiment using standard ΔE-E techniques.

The α-d correlation function, R(q), is defined in terms of the singles yields, $Y_\alpha(\vec{p}_\alpha)$ and $Y_d(\vec{p}_d)$, and the coincidence yield, $Y_{\alpha d}(\vec{p}_\alpha,\vec{p}_d)$:

$$Y_{\alpha d}(\vec{p}_\alpha,\vec{p}_d) = C \cdot Y_\alpha(\vec{p}_\alpha) Y_d(\vec{p}_d)[1+R(q)] \ . \qquad (1)$$

Here, $\vec{p}_\alpha$ and $\vec{p}_d$ are the laboratory momenta of alpha particles and deuterons, respectively; q is the momentum of relative motion; and C is a normalization constant. The experimental correlation functions were obtained by inserting the measured yields into eq. 1 and summing both sides of the equation over all energies and angles corresponding to a given constraint. In Figure 1 we show α-d correlation functions measured with the center of the hodoscope positioned at 35° (upper part) and 50° (lower part). The following constraints were applied: $E_\alpha \geq 40$ MeV, $E_d \geq 15$ MeV and: 55 MeV < $E_\alpha + E_d \leq 100$ MeV (left hand part), 100 MeV < $E_\alpha + E_d \leq 150$ MeV (center part), 150 MeV < $E_\alpha + E_d \leq 220$ MeV (right hand part). As observed previously,[16] the α-d correlation functions exhibit two maxima corresponding to the T=0 state in ^{6}Li at 2.186 MeV ($J^\pi = 3^+$, $\Gamma = 24$ keV, $\Gamma_\alpha/\Gamma_{tot} = 1.00$) and the overlapping T=0 states at 4.31 MeV ($J^\pi = 2^+$, $\Gamma = 1.3$ MeV, $\Gamma_\alpha/\Gamma_{tot} = 0.97$) and at 5.65 MeV ($J^\pi = 1^+$, $\Gamma = 1.9$ MeV, $\Gamma_\alpha/\Gamma_{tot} = 0.74$).[18]

Calculations of the α-d correlation function corresponding to a generalization of the final-state interaction model of ref. 11 are shown by the solid and dotted lines in Figure 1. A source of Gaussian spatial density, $\rho(r) = \rho_0 \cdot e^{-r^2/r_0^2}$, and negligible lifetime was assumed; corrections for the finite resolution of the hodoscope were included. Details of these calculations are given in ref. 12. The measured correlations do not exhibit a strong dependence on angle, but become more pronounced with increasing kinetic energies, $E_\alpha + E_d$, indicating that more energetic particles may originate from subsets of nucleons which are more localised in space-time. This feature is quantified by the estimated source radii summarized in Table 1.

Emission temperatures were obtained by comparing the experimental yield of particle unstable ^{6}Li nuclei with thermal calculations. The experimental yield of particle unstable decays $^6Li^* \rightarrow \alpha+d$, Y_c, was assumed to be given by $Y_c = Y_{\alpha d} - C \cdot Y_\alpha Y_d[1+R_b(q)]$, where $R_b(q)$ denotes the "background correlation function"[16) shown by the dashed lines in Figure 1. The resulting yields are shown in Figure 2 as a function of the kinetic energy, $T_{c.m.}$, in the ^{6}Li rest frame.

The theoretical yield of particle unstable decays $^6Li^* \rightarrow \alpha+d$, $Y_c(E^*,T)$, was calculated according to the equation:16)

$$Y_c(E^*,T) = \int dE\ \varepsilon_c(E^*,E) \cdot e^{-E/T} \cdot \left(\sum_i \frac{(2J_i+1) \cdot \Gamma_i/2\pi}{(E-E_i)^2+\Gamma_i^2/4} \cdot \frac{\Gamma_{c,i}}{\Gamma_i} \right) . \qquad (2)$$

The sum includes the excited states of ^{6}Li below 10 MeV excitation energy; the subscript c denotes the channel $^6Li^* \rightarrow \alpha+d$; E and $E^* = T_{c.m.} + 1.475$ MeV denote the actual and measured excitation energies of the decaying ^{6}Li nucleus, respectively; T is the emission temperature. (This operational definition of the emission temperature neglects the unknown effects of feeding from higher lying states.) The efficiency function, $\varepsilon_c(E^*,E)$, for the detection of the decay products was calculated for the precise geometry, detection thresholds and energy resolution of the experiment using the appropriate constraints on $E_\alpha+E_d$. Each resonance was assumed to decay isotropically in its center-of-mass frame. Spectra and angular distributions of excited ^{6}Li nuclei were taken to be identical to the measured spectra of particle stable ^{6}Li nuclei.

Calculations based on eq. 2 are shown in Figure 2 for emission temperatures of T = 1, 2.5, 5, and 10 MeV. The curves are normalised to reproduce the experimental yield integrated over the energy range of $T_{c.m.}$ = 0.3 - 1.2 MeV. In order to extract emission temperatures, we have integrated the decay yields over the energy ranges of $T_{c.m.}$ = 0.25-1.45 and 1.5-6.25 MeV and compared the ratio of these yields to the corresponding ratio calculated from eq. 2. The results are summarized in Table 1. Higher emission temperatures are extracted for higher kinetic energies, $E_\alpha+E_d$, of the emitted particles.

The temperatures extracted from the α-d coincidence yields can have a systematic error of the order of 25% due to uncertainties in the α-d the background correlation function and due to the saturation of the coincidence yields at higher temperatures; statistical uncertainties are negligible. Uncertainties of the absolute temperature scale may be caused by feeding from higher lying states. Quantum statistical calculations$^{19)}$ for infinite nuclear systems suggest that sequential decay corrections to the emission temperatures extracted with eq.2 from the $^6Li^* \rightarrow \alpha+d$ decay could result in temperatures 10-50% higher, depending on breakup density.

In general, the determination of temperatures from the populations of states becomes insensitive to secondary processes only in the limit that the level separation is much larger than the emission temperature. This limit is satisfied by the decays: $^5Li_{g.s.} \rightarrow \alpha+p$, $^5Li^*_{16.6} \rightarrow d+^3He$, for which statistical calculations indicate negligible feeding from higher lying states.[19] Mean emission temperatures for ^5Li of T=4.4±0.4 MeV are extracted at both angles from the energy integrated coincidence yields; they are consistent with the ones extracted from the decay of $^6Li^*$. Unfortunately, the angular separation (6.1°) between neighboring telescopes was too large to permit an exploration of the energy dependence of the relative population of these states in ^5Li.

The temperatures determined in the present experiment are about an order of magnitude larger than the ones reported in refs. 14 and 15. This discrepancy is probably caused by feeding of the ground state by sequential decay[14-17,19] rendering the method employed in refs. 14 and 15 inaccurate.[16,19]

In summary, higher emission temperatures and smaller source radii are extracted for higher kinetic energies of the emitted particles.

These findings are consistent with particle emission from a subsystem which is in the process of cooling and expanding. Cooling and expanding subsystems of high excitation could arise from the equilibration of participant matter with the surrounding cold target nuclear matter$^{2)}$ or from an isentropic expansion as expected from intranuclear cascade calculations.$^{20)}$

This article is based upon work supported by the National Science Foundation under grant PHY 83-12245 and by the Natural Sciences and Engineering Research Council of Canada.

References:

*) DFG fellow; on leave from the Max-Planck-Institut für Kernphysik, Heidelberg, W-Germany

1) B.V. Jacak, et al., Phys. Rev. Lett. 51, 1846 (1983)
2) D.J. Fields, et al., Phys. Rev. C30, 1912 (1984)
3) G.D. Westfall, et al., Phys. Rev. Lett. 37, 1202 (1976)
4) J. Gosset, et al., Phys. Rev. C18, 844 (1978)
5) J. Knoll, Phys. Rev. C20, 773 (1979)
6) G.D. Westfall, et al., Phys. Lett. 116B, 118 (1982)
7) P.J. Siemens and J.O. Rasmussen, Phys. Rev. Lett. 42, 880 (1979)
8) H. Stöcker, et al., Z. Phys. A303, 259 (1981)
9) W.A. Friedman and W.G. Lynch, Phys. Rev. C30, 16 (1983)
10) D.H. Boal, Phys. Rev. C30, 749 (1984)
11) S.E. Koonin, Phys. Lett. 70B, 43 (1977)
12) D.H. Boal and J.C. Shillcock, to be published in Phys. Rev. C
13) D.H. Boal, B.K. Jennings, and J.C. Shillcock, private communication
14) D.J. Morrissey, et al., Phys. Lett. B148, 423 (1984)
15) D.J. Morrissey, et el., Michigan State University preprint MSUCL-517, 1985
16) J. Pochodzalla, et al., Phys. Rev. Lett. 55, 177 (1985)
17) J. Pochodzalla, et al., Michigan State University preprint MSUCL-527, 1985
18) F. Ajzenberg-Selove, Nucl. Phys. A413, 1 (1984)
19) D. Hahn and H. Stöcker, private communication and to be published
20) G. Bertsch and J. Cugnon, Phys. Rev. C24, 2514 (1981)

Table 1:

Emission temperatures and source radii extracted from the decay $^6Li^* \rightarrow \alpha + d$.

constraint on	$\Theta = 35°$		$\Theta = 50°$	
$E_1 + E_2$	T(MeV)	r_0(fm)	T(MeV)	r_0(fm)
55 - 220 MeV	4	3.4	4	3.6
55 - 100 MeV	4	3.7	4	3.8
100 - 150 MeV	4	3.1	6	2.9
150 - 220 MeV	8	3.0	9	2.6

Figure Captions:

Fig.1: Correlation functions measured for coincident deuterons and alpha particles for ^{14}N induced reactions on ^{197}Au at E/A=35 MeV. A detailed discussion of the figure is given in the text.

Fig.2: Energy spectra resulting from the decay $^{6}Li^{*} \rightarrow \alpha+d$. A detailed discussion of the figure is given in the text.

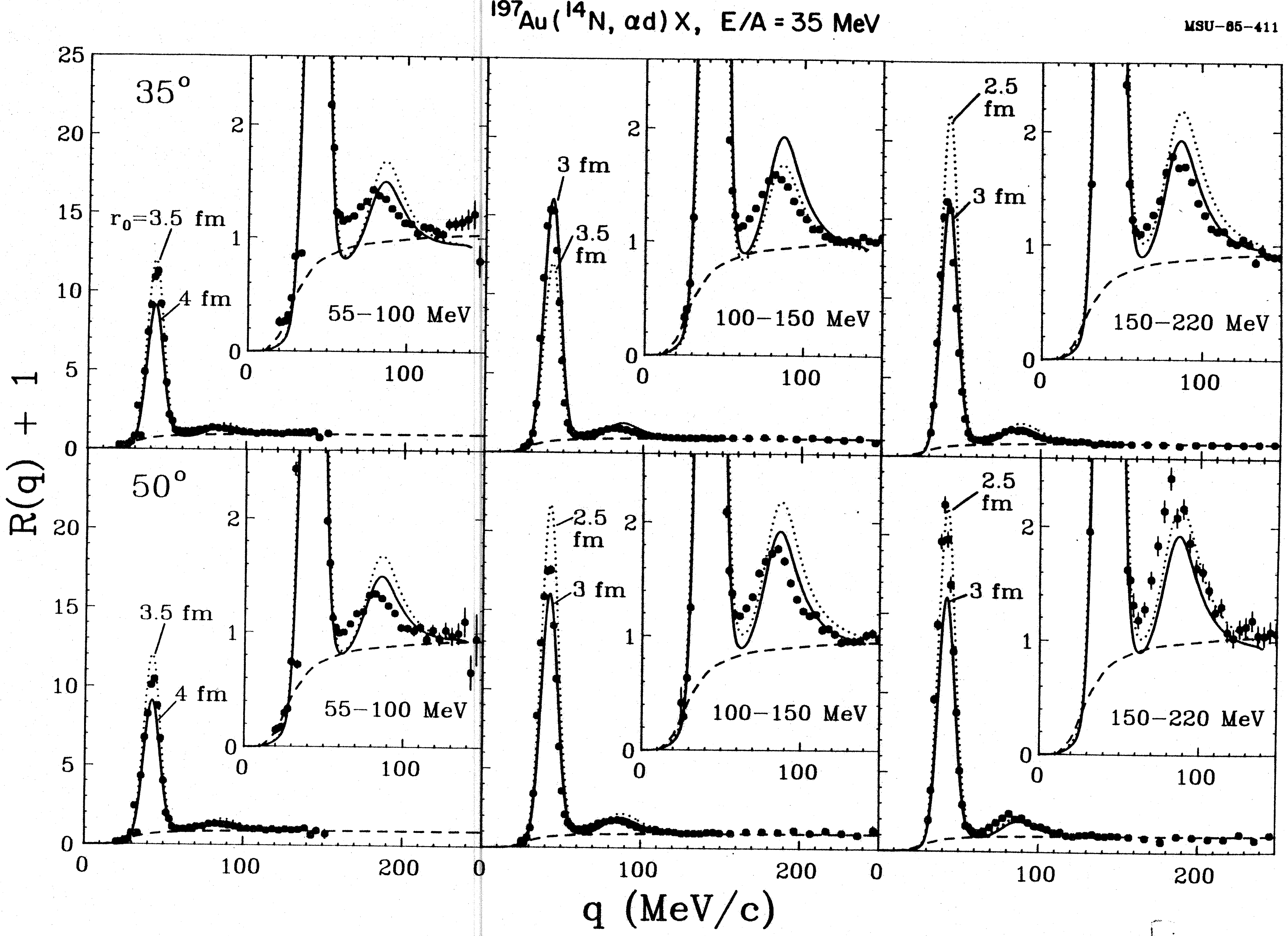

^{197}Au(^{14}N, αd)X, E/A = 35 MeV
R(q) + 1
q (MeV/c)
35°
50°
r_0=3.5 fm
4 fm
3.5 fm
3 fm
3.5 fm
2.5 fm
55–100 MeV
100–150 MeV
150–220 MeV
0
5
10
15
20
25
0
100
200
0
1
2

Fig 1

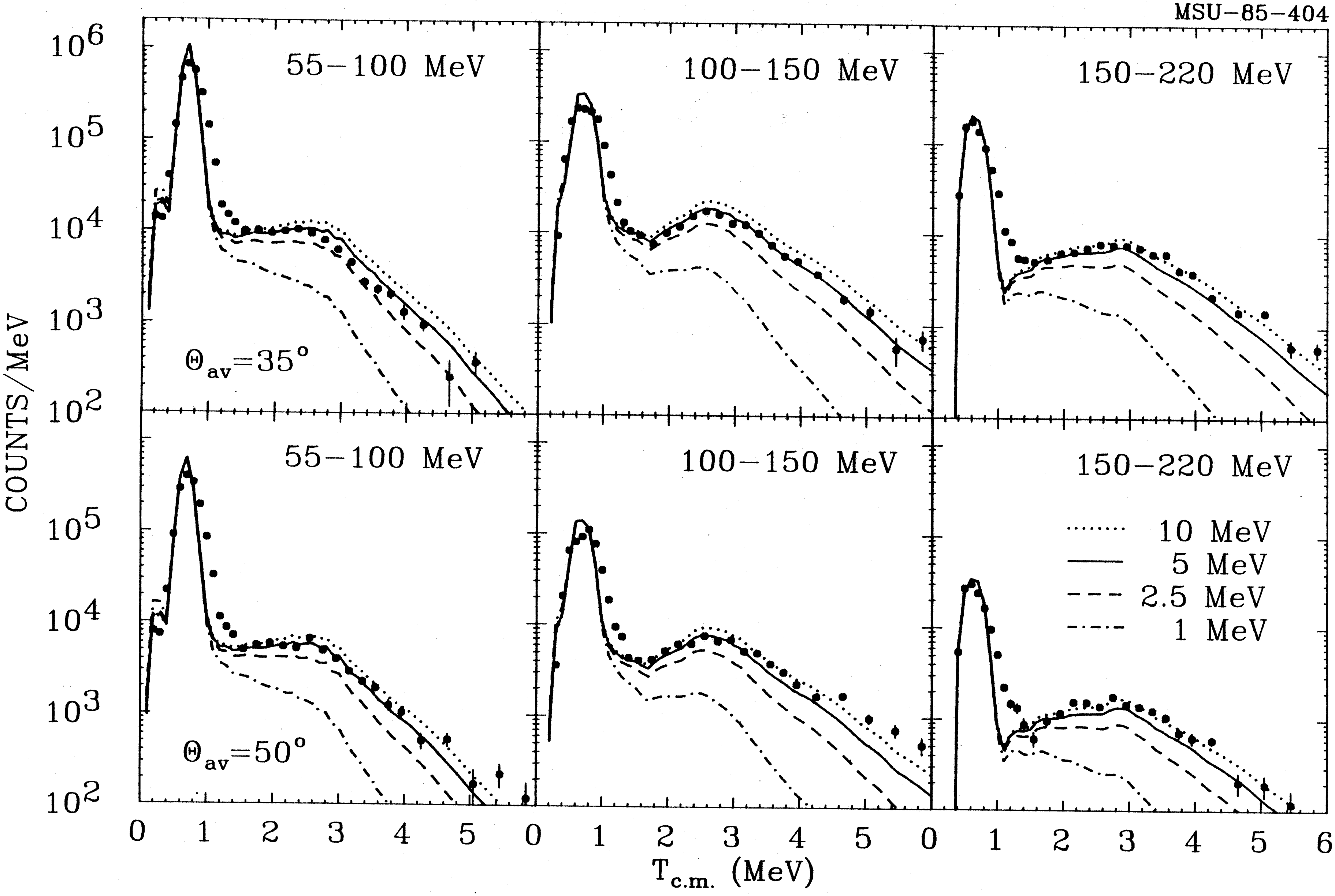

MSU-85-404
55–100 MeV
100–150 MeV
150–220 MeV
$\Theta_{av}=35^o$
$\Theta_{av}=50^o$
10 MeV
5 MeV
2.5 MeV
1 MeV
COUNTS/MeV
10^2
10^3
10^4
10^5
10^6
0
1
2
3
4
5
6
$T_{c.m.}$ (MeV)

Fig. [illegible]