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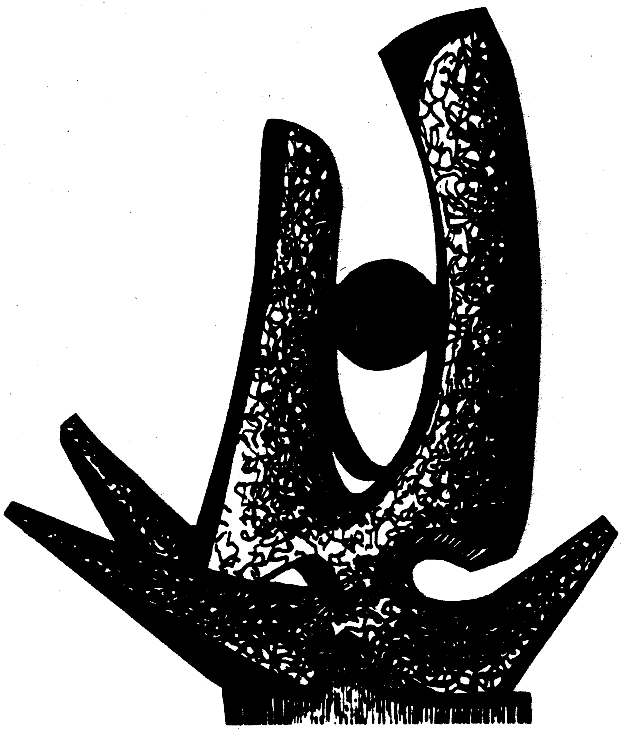

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Three - particle effects observed in two - particle correlation measurements+)

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ABSTRACT

Correlations between coincident alpha particles and protons were measured for ^{40}Ar induced reactions on ^{197}Au at E/A=60 MeV. The correlation function exhibits features not expected from free α-p interactions. These include a pronounced maximum at low relative momenta, $q \approx 15$ MeV/c, and a dependence of the ^{5}Li ground state peak on the total ^{5}Li energy and decay kinematics. These anomalies are explained by considering the contribution of the decay of ^{9}B, and the effects of the Coulomb field, due to the reaction residue, on the decay of ^{5}Li.

Small angle correlations between coincident alpha particles and protons were measured for ^{40}Ar induced reactions on ^{197}Au, at E/A=60 MeV. The correlation function exhibits two pronounced maxima located at values of the relative momentum near 15 and 50 MeV/c. The peak near 15 MeV/c is totally unexpected from properties of the mass 5 system. A peak near 50 MeV/c is expected from the free decay of ^{5}Li; however, the precise location of this peak was observed to depend on the relative magnitude of the proton and alpha particle velocities. In this letter we examine these surprising features and provide an explanation for each in terms of simple three-body effects.

The experiment was performed at the Laboratoire GANIL at Caen. A gold target of 10 mg/cm^2 areal density was irradiated by a beam of ^{40}Ar of E/A=60 MeV incident energy. The size of the beam spot on target was approximately 1×2 mm^2. Light particles ($Z \leqq 3$) 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. The center of the hodoscope was positioned at a laboratory angle of 30°. Each telescope subtended a solid angle of 0.46 msr; the angular separation between adjacent telescopes was 4.2°. The energy calibrations of the hodoscope, established for all isotopes with $Z \leqq 3$, are accurate to within 2%. A complete description of the experimental details will be given elsewhere.

Figure 1 shows a contour diagram of the α-p coincidence yield as a function of the energies of the two particles. This yield represents the sum over all adjacent detector pairs. The figure shows the anomalies mentioned above. Four ridges corresponding to two pairs of kinematic branches can be discerned. The two center ridges correspond to kinetic energies of relative motion of $T_{c.m.} \approx 0.15$ MeV; these do not correspond to any known resonance of the p-α system. The two outermost ridges are near the location of the two kinematic branches expected for the free decay of ^{5}Li. Close inspection of these two ridges reveals, however, that they correspond to different relative kinetic energies. (As a visual aid, the two kinematic loci corresponding to $T_{c.m.} = 1.5$ MeV are shown by dashed lines.)

For a more quantitative discussion of the data, we define the α-p correlation function, R(q), in terms of the singles cross sections, $\sigma_\alpha(\vec{p}_\alpha)$ and $\sigma_p(\vec{p}_p)$, and the coincidence cross section, $\sigma_{\alpha p}(\vec{p}_\alpha,\vec{p}_p)$:

$$\sigma_{\alpha p}(\vec{p}_\alpha,\vec{p}_p) = C\cdot\sigma_\alpha(\vec{p}_\alpha)\sigma_p(\vec{p}_p)[1+R(q)] \ . \qquad (1)$$

Here, $\vec{p}_\alpha$ and $\vec{p}_p$ are the laboratory momenta for alpha particles and protons, respectively; $\vec{q}$ is the proton momentum in the center-of-momentum frame of the α-p system; C is a normalisation constant which was determined by requiring R(q)=0 for q=100-150 MeV/c for the experimental correlation function shown in the upper part of the figure. The experimental correlation functions were obtained by inserting the measured cross sections into Eq. (1) and summing both sides of the equation over all energies and angles corresponding to a given momentum q. For the correlation functions shown in the lower part of the figure, the summation was performed with the constraints $v_\alpha < v_p$ (open points) and $v_\alpha > v_p$ (solid points), where v_α and v_p denote the laboratory velocities of alpha particles and protons, respectively. Consistent with the qualitative features shown in Figure 1, the experimental correlation functions exhibit two pronounced maxima located at $q \approx 15$ and 50 MeV/c. While the location of the first maximum ($q \approx 15$ MeV/c) is the same for both branches, the location of the second maximum ($q \approx 50$ MeV/c) is not.

The peak near $q \approx 15$ MeV/c is not related to resonances in the mass five system. However, its position and width are consistent with the detection of two of the three fragments from the two stage decay of ^9B: $^9B \rightarrow p + {}^8Be \rightarrow p + (\alpha + \alpha)$.

The peak near $q \approx 50$ MeV/c is clearly related to the unbound ground state of ^5Li. This state has a width of about 1.5 MeV and consequently has the short mean life of about $\tau = 130$ fm/c. For short lived states, the Coulomb interaction with the target residue can be important [1,2]. We suggest that the anomalies observed for the second peak arise, indeed, from the interaction of the ^5Li decay products with the background Coulomb field. Since the charge-to-mass ratio of protons is greater than that of alpha particles the former will experience a greater acceleration from the reaction residue. Qualitatively, the velocity difference between protons and alpha particles should be decreased if $v_p < v_\alpha$ at the time of decay, while the difference should be increased if $v_p > v_\alpha$. If the life time were long, as is the case of the the decay of the ^{9}B, this effect would be negligible.

To test these hypotheses we have performed detailed calculations which are described next. We assume that the coincidence cross section consists of three terms: $\sigma_{\alpha p}=\sigma_{^9B}+\sigma_{^5Li}+\sigma_b$, where $\sigma_{^9B}$ and $\sigma_{^5Li}$ denote the contributions from the decay of ^{9}B and ^{5}Li nuclei and σ_b denotes the "background" cross section. A detailed calculation of the background cross section is beyond the scope of the present paper, since it is expected to depend on the space-time characteristics of the emitting source and would suffer distortions similar to the ones observed for the second maximum of the correlation function. We, therefore, choose an empirical background shown by the dashed lines in Figure 2, and then test the consequences of this choice. The singles cross sections for protons, alpha particles, ^{5}Li and ^{9}B nuclei were parameterised with a simple moving source parameterisation,

$$d\sigma/dE \cdot d\Omega \propto E^{1/2}\exp[-(E+E_0-2(E \cdot E_0)^{1/2}\cos\Theta)/T] , \qquad (2)$$

with $E_0=mv^2/2$; m denotes the mass of the emitted particle; v and T denote the velocity and effective temperature of the source. The calculations were performed with the parameters v/c=0.2 and T= 20 MeV. It was found that the shape of the correlation function was not sensitive to the specific choice of source parameters. The calculations took into account the measurement efficiency by including the exact detector geometries and detection thresholds. The decays of ^{9}B (and ^{8}Be) and ^{5}Li were assumed to be isotropic in the rest frames of the corresponding parent nuclei. For the case of ^{5}Li decay, the Coulomb interaction with the reaction residue was treated classically. Each ^{5}Li nucleus was assumed to decay at the time $t=\tau$, where $t=0$ denotes the instant of emission of the ^{5}Li parent nucleus. The energy gain in the Coulomb field of the residue was found to have a major effect on the peak position; angular deflections were found to be of minor importance. The energy gain was approximated as

$$E_{\alpha,p} = E^{o}_{\alpha,p} + e^2\, Z_{eff} \cdot Z_{\alpha,p} / (R_0 + \beta \cdot \tau) \ , \qquad (3)$$

where E^o and E denote the kinetic energy at the point of decay and the asymptotic kinetic energy; β is the velocity of the ^{5}Li nucleus and Z_{eff} is the charge number characterising the Coulomb field of the residual matter. We have set $Z_{eff}=80$, $R_0=8$ fm. The line shape of ^{5}Li was approximated as [3]

$$dN/dE \propto \sin^2\delta_R \,/P_1 \ , \qquad (4)$$

where δ_R is the resonant phase shift [4] and P_1 is the $l=1$ penetration factor, $k/(F_1(k,a)^2 + G_1(k,a)^2)$; k is the wave number; F and G are the Coulomb wave functions evaluated at the radius a= 3 fm.

The results of our calculations are shown by the solid lines in Figure 2. The agreement with the experimental correlation function is good.

According to Eq. (3), the line shape distortion caused by the Coulomb interaction with the reaction residue should become less important at higher energies $E_\alpha+E_p$, i.e. higher velocities β. This effect is illustrated in Figure 3, where the energy dependence of the peak location is shown for the two kinematic branches of the correlation function. In order to obtain sufficient statistics, the data were sorted into 50 MeV wide bins of $E_\alpha+E_p$. The calculations are shown by the solid and dashed histograms; they reproduce the observed trend in each branch rather satisfactorily. (The systematic deviation between theory and experiment could arise from uncertainties in the theoretical line shape or different decay processes contributing to the background.)

We have examined the angular distribution for the decay of ^{5}Li nuclei. Figure 4 shows the angular distribution of the experimental yield, $dY/d\Psi$, integrated over the range dominated by the second peak in the correlation function, 25 MeV/c $\leqq q \leqq$ 100 MeV/c. The angle Ψ denotes the angle between the vectors $\vec{q}$ and $(\vec{p}_\alpha+\vec{p}_p)$. The size of the vertical bars corresponds to the uncertainties associated with the background, which was assumed to lie within the boundaries shown by the dashed lines in Figure 2. The yields calculated for the case of isotropic emission are shown by the solid histogram. Considering the uncertainties which have to be attributed to the background, the data are consistent with the assumption of isotropic decay. The angular distribution for data in the vicinity of the peak at $q \approx 15$ MeV/c was also studied and found to be consistent with the isotropic distribution expected for the two stage decay of ^{9}B.

In summary, the $\alpha+p$ correlation measured for ^{40}Ar induced reactions on ^{197}Au at E/A=60 MeV cannot be understood by only considering the final state interactions between the two coincident particles. The sharp peak of the correlation function at $q \approx 15$ MeV/c does not correspond to a resonance in the $\alpha+p$ system. It results from the decay $^{9}B \rightarrow 2\alpha + p$. The second peak observed in the correlation function at $q \approx 50$ MeV/c can be understood as due to the isotropic decay of ^{5}Li. However,the variation of this peak for different kinematic regions of E_α and E_p suggests the influence of the Coulomb force from the heavy reaction residue.

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+) Experiment performed at Laboratoire National GANIL

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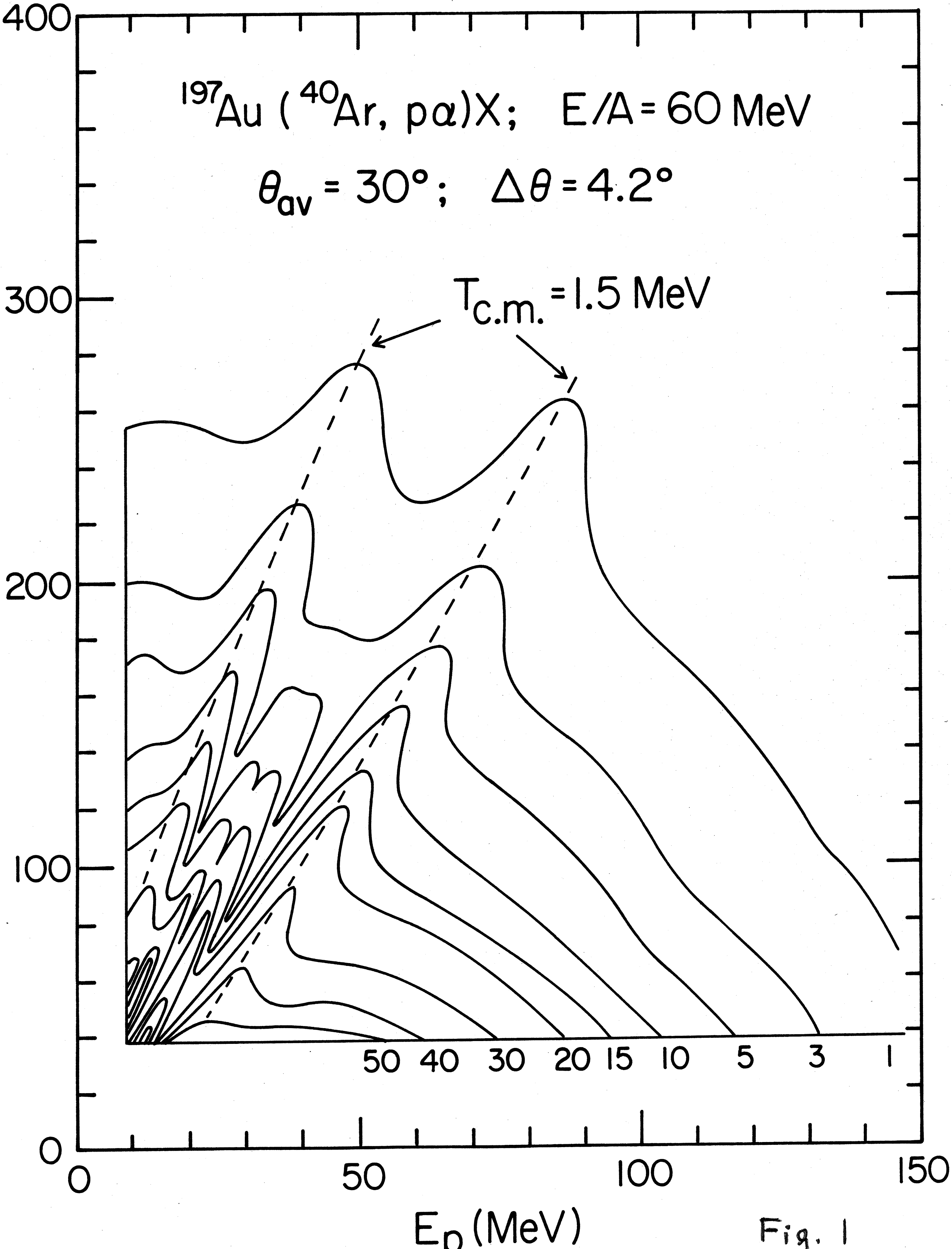
Figure Captions:

Fig.1: Contour diagram of the α-p coincidence yield as a function of the energies of the two particles. The yield has been obtained by summing over all adjacent detector pairs.

Fig.2: Correlation function for coincident protons and alpha particles for ^{40}Ar induced reactions on ^{197}Au at E/A=60 MeV. The upper part of the figure shows the correlation function corresponding to the sum over all particle velocities. The lower part shows the correlation functions corresponding to $v_\alpha < v_p$ (open points) and $v_\alpha > v_p$ (full points). The curves are explained in the text.

Fig.3: Location of the maximum of the experimental and theoretical correlation functions corresponding to $v_\alpha < v_p$ (open points, solid histogram) and $v_\alpha > v_p$ (full points, dashed histogram) as a function of the summed energy $E_\alpha + E_p$.

Fig.4: Dependence of the experimental yield above background on the angle Ψ between $\vec{q}$ and $(\vec{p}_\alpha + \vec{p}_p)$. The yields were integrated over the range 25 MeV/c $\leq q \leq$ 100 MeV/c. The background was assumed to lie within the boundaries corresponding to the dashed lines in Figure 2. The histogram corresponds to the yield calculated for the isotropic decay of ^{5}Li.



^{197}Au (^{40}Ar, pα)X; E/A = 60 MeV
θ_{av} = 30°; Δθ = 4.2°
$T_{c.m.}$ = 1.5 MeV
E_α (MeV)
E_p (MeV)
0
100
200
300
400
0
50
100
150
50
40
30
20
15
10
5
3
1

Fig. 1

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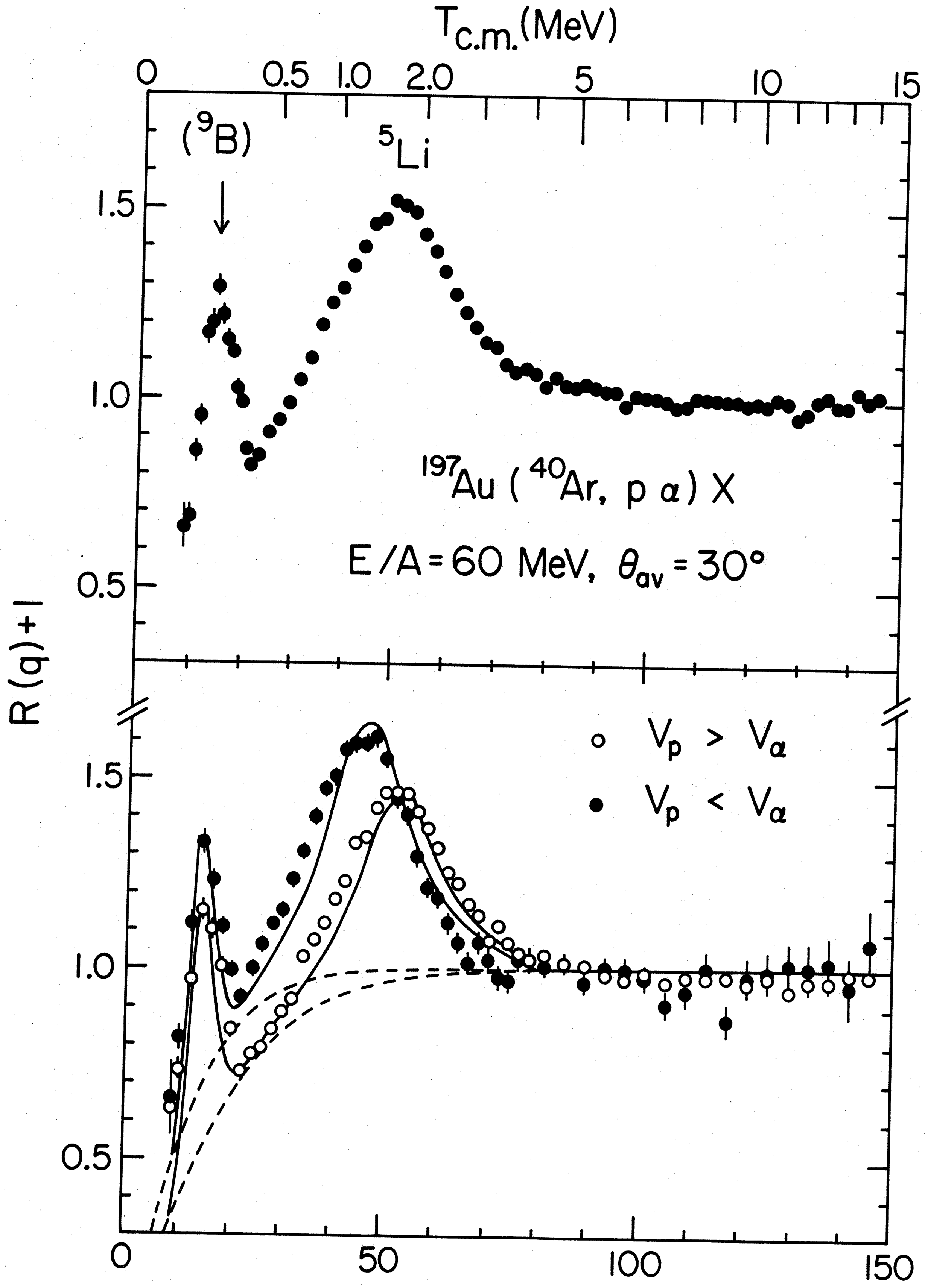

Fig. 2

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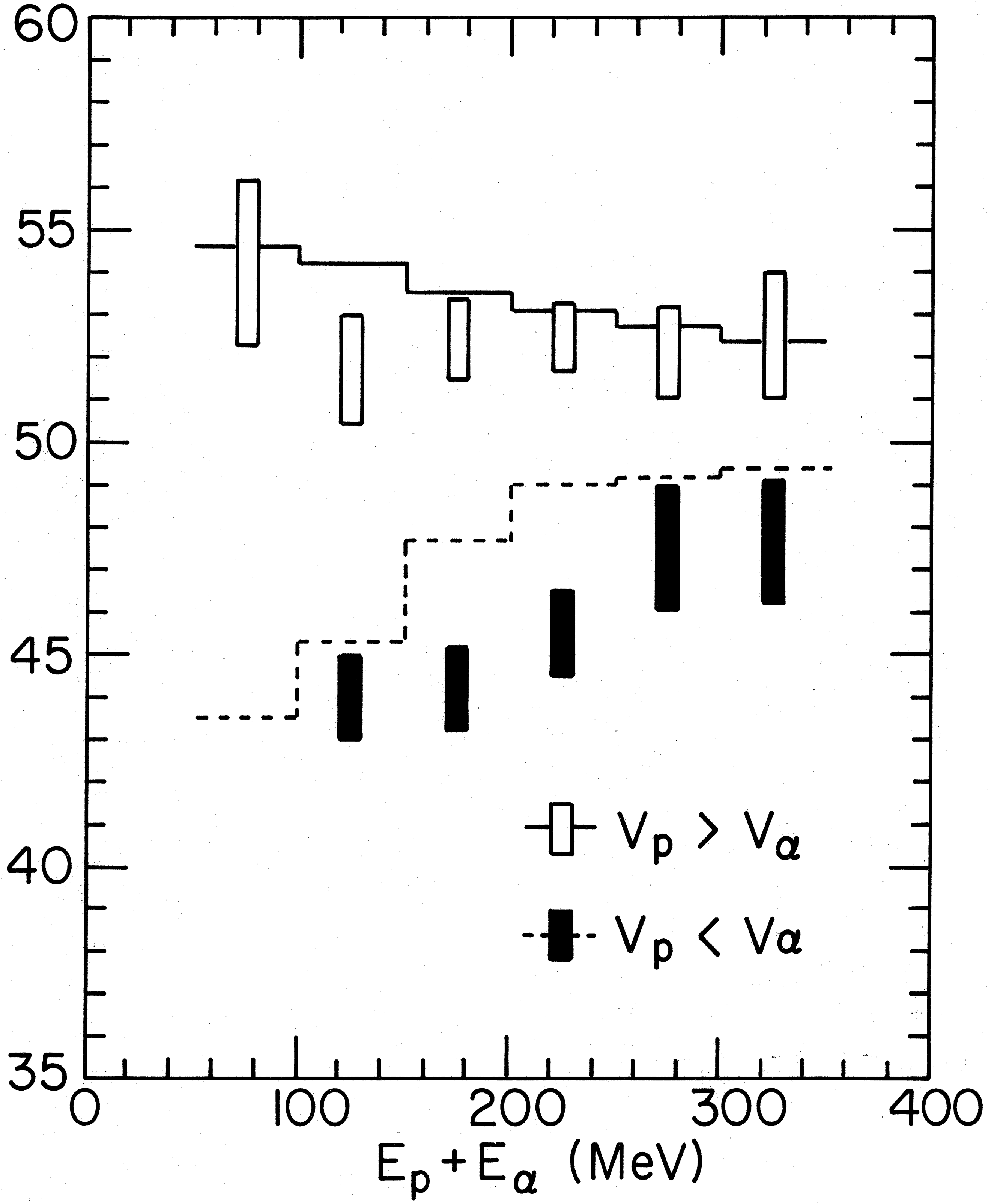
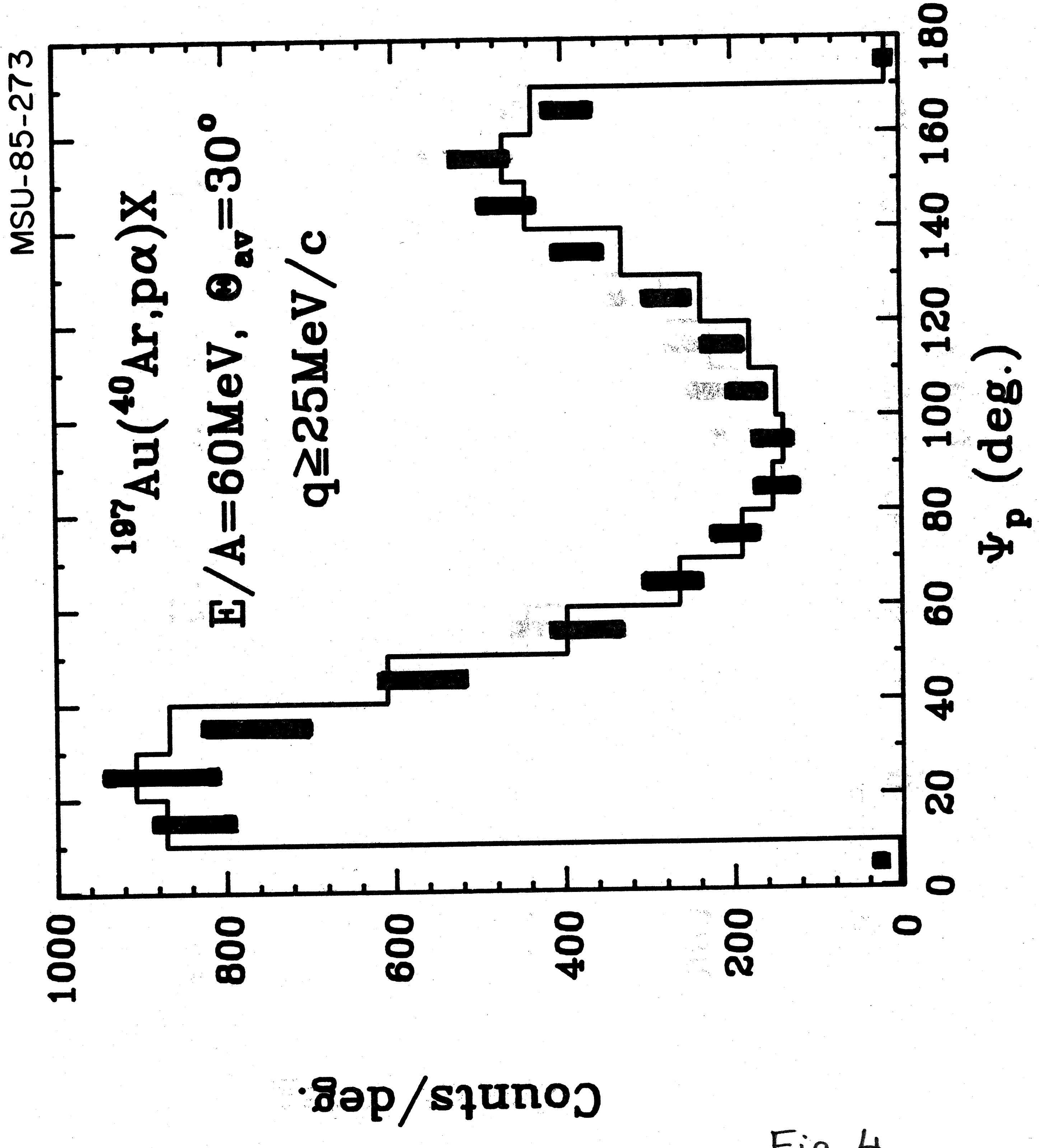


Fig. 3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^{197}Au(^{40}Ar,pα)X
E/A=60MeV, Θ_{av}=30°
q≧25MeV/c
Counts/deg.
0
200
400
600
800
1000
Ψ_p (deg.)
0
20
40
60
80
100
120
140
160
180

Fig. 4