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INELASTIC SCATTERING OF  $^{16}\text{O}$  FROM  $^{208}\text{Pb}$ \*

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Abstract:

The inelastic scattering of  $^{16}\text{O}$  from  $^{208}\text{Pb}$  has been studied at an incident  $^{16}\text{O}$  energy of 104 MeV. The angular distributions to the  $3^-$ ,  $5^-$ , and  $2^+$  levels at 2.62, 3.20, and 4.10 MeV excitation in  $^{208}\text{Pb}$  show interference patterns characteristic of those expected from the destructive interference of Coulomb and nuclear excitation. The results are analyzed using DWBA. The phase,  $\alpha$ , of the nuclear excitation form factor, is determined to be  $\alpha = 30 \pm 15^\circ$ , in good agreement with the collective model. Values of the transition probabilities deduced from the potential deformation parameters are found to be smaller by a factor of  $\sim 2$  than the electromagnetic transition probabilities measured in  $(e, e')$  or Coulomb excitation.

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The interference of nuclear and Coulomb excitation has been observed using alphas,<sup>1,2</sup>  $^3\text{He}$  particles,<sup>3</sup> and recently, heavy ions.<sup>4,5</sup> It has been suggested that the interference effect can be used to obtain information about the nuclear interaction since one knows the properties of Coulomb excitation.<sup>6-9</sup> Satchler

has shown,<sup>9</sup> for example, that one can determine the absolute phase of the nuclear interaction. Most inelastic scattering experiments using light ions are not sensitive to either the sign or phase of the nuclear interaction since the Coulomb forces are much weaker at the interaction radius than nuclear forces. The information easily obtainable by studying the interference effect using light ions is, therefore, limited. In contrast, the Coulomb and nuclear forces for heavy ion projectiles are often comparable and, as we shall show, the inelastic angular distributions are dominated by interference effects and are a sensitive probe of the interactions inducing inelastic transitions.

The experiments were performed at the LBL 88 inch cyclotron. A beam of 104 MeV  $^{16}\text{O}$  ions was scattered from enriched  $^{208}\text{Pb}$  targets (100-300  $\mu\text{g}/\text{cm}^2$ ) on 20  $\mu\text{g}/\text{cm}^2$  carbon backing. The reaction products were identified in the focal plane of a magnetic spectrometer using a position sensitive proportional counter.<sup>10</sup> This counter measures the position ( $B\rho$ ), energy loss ( $dE/dx$ ), and time of flight of the products and permits mass separation up to  $A \sim 20$ . A position spectrum (summed over six horizontal wires,  $\sim 6$  cm vertical height) is shown in Fig. 1.

Levels in  $^{208}\text{Pb}$  at 2.62 ( $J^\pi = 3^-$ ), 3.20 ( $5^-$ ), 4.10 ( $2^+$ ), and 4.31 ( $4^+$ ) MeV could be identified and cross sections extracted. The group at  $E_x \sim 6$  MeV (Fig. 1) is tentatively ascribed to excitation of the  $3^-$  state in  $^{16}\text{O}$  which is at 6.13 MeV. The peak centroids and shapes for such groups will be shifted and Doppler-broadened due to the gamma decay of the  $^{16}\text{O}^*$  in flight.

The apparent excitation of states in  $^{16}\text{O}$  has been observed<sup>11</sup> for a number of other targets,  $A \sim 90$ . Several  $^{16}\text{O}$  spectra were taken extending up to 20 MeV in excitation of  $^{208}\text{Pb}$ . No evidence for a predicted<sup>12</sup> isoscalar giant quadrupole state was obtained, although the cross section may be too small to be seen above the background.<sup>13</sup>

The angular distributions for the elastic and inelastic transitions are shown in Fig. 2. The inelastic data show structure which depend on the spin of the final state (also  $Q$  value). This is in contrast to the data obtained for nucleon transfer reactions which exhibit structureless angular distributions.<sup>15-17</sup>

The elastic scattering data were fit with the optical model using a potential

$$U(r) = (V + iW) f(r) \quad (1a)$$

where

$$f(r) = (1 + \exp \frac{r-R}{a})^{-1} \quad (1b)$$

with

$$R = r_0 (A_1^{1/3} + A_2^{1/3}) \quad (1c)$$

Initial parameters were taken from Ref. 5 and adjusted to fit the data. The final parameters are given in Table I and the fit is shown in Fig. 2.

The DWBA form factor for inelastic scattering is given by the collective model as<sup>6,7,8,18</sup>

$$F_L(r) = F_L^C(r) + F_L^N(r) \quad (2)$$

where

$$F_L^C(r) = \frac{Z_1 e^{4\pi} \sqrt{B(EL)}}{2L + 1} \frac{1}{r^L + 1}, \quad (3)$$

and

$$F_L^N(r) = U e^{i\alpha} \beta_L^N R \frac{df(r)}{dr}, \quad (4)$$

where  $B(EL)$  is the electromagnetic transition probability for Coulomb excitation of the target,  $Z_1 e$  is the projectile charge, and  $\beta_L^N$  is the deformation of the optical potential (1) of multipolarity  $L$ .

The term  $U e^{i\alpha}$  allows for an arbitrary phase between the Coulomb and nuclear parts,  $F_L^C(r)$  and  $F_L^N(r)$ . The collective model has

$$U e^{i\alpha} = V + iW \quad (5)$$

where  $V$  and  $W$  are taken from the analysis of the elastic scattering. The potentials listed in Table I correspond to  $U \doteq -42.8$  MeV and  $\alpha \doteq 20^\circ$ .

In Fig. 3 (top) we show the contributions to the cross section of the  $3^-$  state arising from Coulomb excitation (with distorted waves) and nuclear excitation separately. The  $B(E3)$  value measured in  $(e, e')$  was used.<sup>19</sup> The DWBA calculations were made using the program DWUCK<sup>14</sup> with 140 partial waves and radial integrations out to 40 fm. The calculations were found to be accurate ( $\pm 20\%$ ) for all but the most forward angle points ( $\theta < 40^\circ$ ).

The phase,  $\alpha$ , was determined in the following manner: At large angles, where nuclear excitation dominates, one can determine the modulus of the effective interaction since the calculations are relatively insensitive to the phase.

Having done this, one can then determine  $\alpha$  by fitting the interference pattern over the entire angular range. The results are shown in Fig. 3 for the transition to the  $3^-$  state. The best fit was obtained with  $\alpha \approx 30^\circ$  but reasonable fits could be obtained with

$$15^\circ \lesssim \alpha \lesssim 45^\circ \quad , \quad (6)$$

i.e.  $0 < W \lesssim V$  with  $V$  and  $W$  both negative (attractive and absorptive, respectively). The calculations with  $\alpha = 0$  (purely real interaction) show too much structure compared to the data (see Fig. 3) and could be excluded, at least for the model and form factors used here. The value  $\alpha = 30^\circ$  is close to the value given by the collective model, Eq. (5), for the optical potential listed in Table I ( $\alpha \approx 20^\circ$ ).

In Fig. 2 we show calculations for the  $3^-$ ,  $5^-$ , and  $2^+$  angular distributions. The  $B(EL)$  values were fixed at values taken from  $(e, e')$  measurements.<sup>19</sup> The collective model form factor was used ( $\alpha \approx 20^\circ$ ) and  $\beta_L^N$  was adjusted to fit the data. The resulting values of  $\beta_L^N$  are listed in Table I. In contrast to the analysis of light ion scattering, the parameter  $\beta_L^N$  affects both the shape and magnitude of the angular distribution, owing to the interference with Coulomb excitation. Furthermore, since the DWBA calculations can be normalized by  $B(EL)$  values taken from pure Coulomb excitation, the absolute phase and magnitude of the nuclear part of the form factor can be determined.

We have deduced target mass deformations,  $\beta_L$ , from the potential deformations,  $\beta_L^N$ , using the deformation lengths<sup>25</sup>

$$\beta_L R_m = \beta_L^N R_{OM} \quad , \quad (7)$$



where  $R_m$  is the target mass radius ( $R_m = 1.3 A_m^{1/3}$ ) and  $R_{OM}$  is the optical potential radius [ $R_{OM} = 1.3 (A_1^{1/3} + A_2^{1/3})$ ]. Thus one has  $\beta_L^N < \beta_L$ . Equation (7) is only approximate since one should use radii appropriate to the multipolarity of the transition however this requires a more detailed model.<sup>23,24</sup> The values of  $\beta_L$  deduced using Eq. (7) are probably upper limits. In Table I we list values of  $\beta_L^N$ ,  $\beta_L$  and  $G_L \equiv B(L)/B_{sp}(L)$  and compare them with values deduced from other measurements.<sup>19-27</sup> Our results are in good agreement with the (p,p') results of Ref. 20 and the ( $^3\text{He}$ ,  $^3\text{He}'$ ) results of Ref. 3, which give  $G_L$  values much smaller than the  $G_{EL}$  values deduced from the B(EL) measurements.

It has been pointed out that the  $G_L$  values one measures may differ between various reactions since the transition probabilities depend on isospin.<sup>25</sup> Thus (e,e') measurements and Coulomb excitation determine properties of the target charge deformation whereas (p,p'), ( $\alpha$ , $\alpha'$ ), etc. are primarily measures of the total mass deformation. Bernstein has compared<sup>25</sup>  $G_L$  values obtained from ( $\alpha$ , $\alpha'$ ) with those obtained from B(EL) measurements and has not found any systematic differences, however.

The (e,e') and Coulomb excitation measurements listed in Table I for the  $3^-$  state in  $^{208}\text{Pb}$  indicate  $G_{EL} \sim 35 \pm 5$  whereas the  $G_L$  values obtained from light ion inelastic scattering are scattered over a range  $19 < G_L < 41$ . Our results, which are sensitive to both  $G_{EL}$  and  $G_L$  are consistent with  $G_{EL} = 40$  and  $G_L = 20$ . If we constrain  $G_{EL} = G_L$ , we obtain  $G_L = 25 \pm 4$  (see Table I). The fit is poorer than that shown in Fig. 2 for  $G_{EL} > G_L$ , however.

The interpretation of the  $G_{EL}$  values obtained from Coulomb excitation is complicated by the possibility<sup>26</sup> of corrections due to reorientation and

other higher order effects. These corrections will depend on the projectile used, and can lead to apparent differences in the  $G_{EL}$  values one obtains using first order theory only (see Table I). Thus the differences in the  $G_{EL}$  and  $G_L$  values shown in Table I may be due to neglect of higher order terms in the transition matrices rather than differences between the  $B(EL)$  and  $B(L)$  transition probabilities. The utilization of the interference between nuclear and Coulomb excitation promises to yield much additional information about transition probabilities and the higher order corrections terms.

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#### FOOTNOTES AND REFERENCES

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## FIGURE CAPTIONS

Fig. 1. A  $^{16}\text{O}$  spectrum from  $^{16}\text{O} + ^{208}\text{Pb}$ . The spectrum was obtained by summing over six wires of a position sensitive proportional counter in the focal plane of the magnetic spectrometer.

Fig. 2. Angular distributions for  $^{208}\text{Pb}(^{16}\text{O}, ^{16}\text{O})$ . The spins and parities are taken from Ref. 20. The excitation energies ( $\pm 50$  keV) measured in the present experiment are listed in parentheses. The curves are DWBA calculations (see text and Table I).

Fig. 3. Top: DWBA calculations for excitation due to Coulomb forces ( $F_L(r) = F_L^C(r)$ ) or nuclear forces ( $F_L(r) = F_L^N(r)$ ). Bottom: DWBA calculations for combined Coulomb and nuclear excitation as a function of the phase factor  $\alpha$  (see Eq. (4)).

Table I. Transition probabilities for states in  $^{208}\text{Pb}$

Ex(MeV) <sup>i</sup>	J <sup>π</sup> <sup>j</sup>	This work <sup>a</sup>			(e,e') <sup>b</sup>		Coul. Ex. <sup>c</sup>	(p,p') <sup>d</sup>	(p,p') <sup>e</sup>	( <sup>3</sup> He, <sup>3</sup> He') <sup>f</sup>	(α,α')
		$\beta_L^{Nk}$	$\beta_L^k$	$G_L^l$	$G_{EL}$	$G_{EL}$	$G_L$	$G_L$	$G_L$	$G_L$	$G_L$
2.62	3 <sup>-</sup>	0.060	0.085	20±4 <sup>m</sup> (25±4) <sup>n</sup>	39.5±2	32±2 (24±2) <sup>o</sup>	19.5	35.8	19.2	41.1±4.1 <sup>g</sup> 19.6 <sup>h</sup>	
3.20	5 <sup>-</sup>	0.036	0.051	8±2 <sup>m</sup>	14±5		8.1	10.7	3.5	14.1±1.6 <sup>g</sup>	
4.10	2 <sup>+</sup>	0.030	0.043	5±1 <sup>m</sup>	8.1±0.5		4.6	9.4	4.9	8.0±0.8 <sup>g</sup>	
4.31	4 <sup>+</sup>				26±2		6.4		5.2	14.8±1.6 <sup>g</sup>	

<sup>a</sup>Collective model analysis with optical potential:  $U(r) = (V+iW)(1+\exp(\frac{r-R}{a}))^{-1}$  with  $V = -40$  MeV,  $W = -15$  MeV,  $R = 1.31 (A_1^{1/3} + A_2^{1/3})$  fm,  $a = 0.45$  fm.

<sup>b</sup>Ref. 19.

<sup>c</sup>Ref. 26; Coulomb excitation including reorientation,  $E_{16_0} = 69.1$  MeV,  $E_\alpha = 17.5 - 19$  MeV ( $Q = -1.3$  b).

<sup>d</sup>Ref. 20,  $E_p = 24.6$  MeV.

<sup>e</sup>Ref. 22,  $E_p = 40$  MeV.

<sup>f</sup>Ref. 3,  $E_{^3\text{He}} = 43.7$  MeV.

<sup>g</sup>Ref. 21,  $E_\alpha = 42$  MeV.

<sup>h</sup>Ref. 27,  $E_\alpha = 44$  MeV.

<sup>i</sup>Measured in this experiment ( $\pm 50$  keV).

<sup>j</sup>From Ref. 20.

(continued)

Table I. (continued)

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<sup>k</sup> $\beta_L^N$  is the potential deformation and  $\beta_L$  is the target mass deformation, as deduced from the deformation lengths (see text).

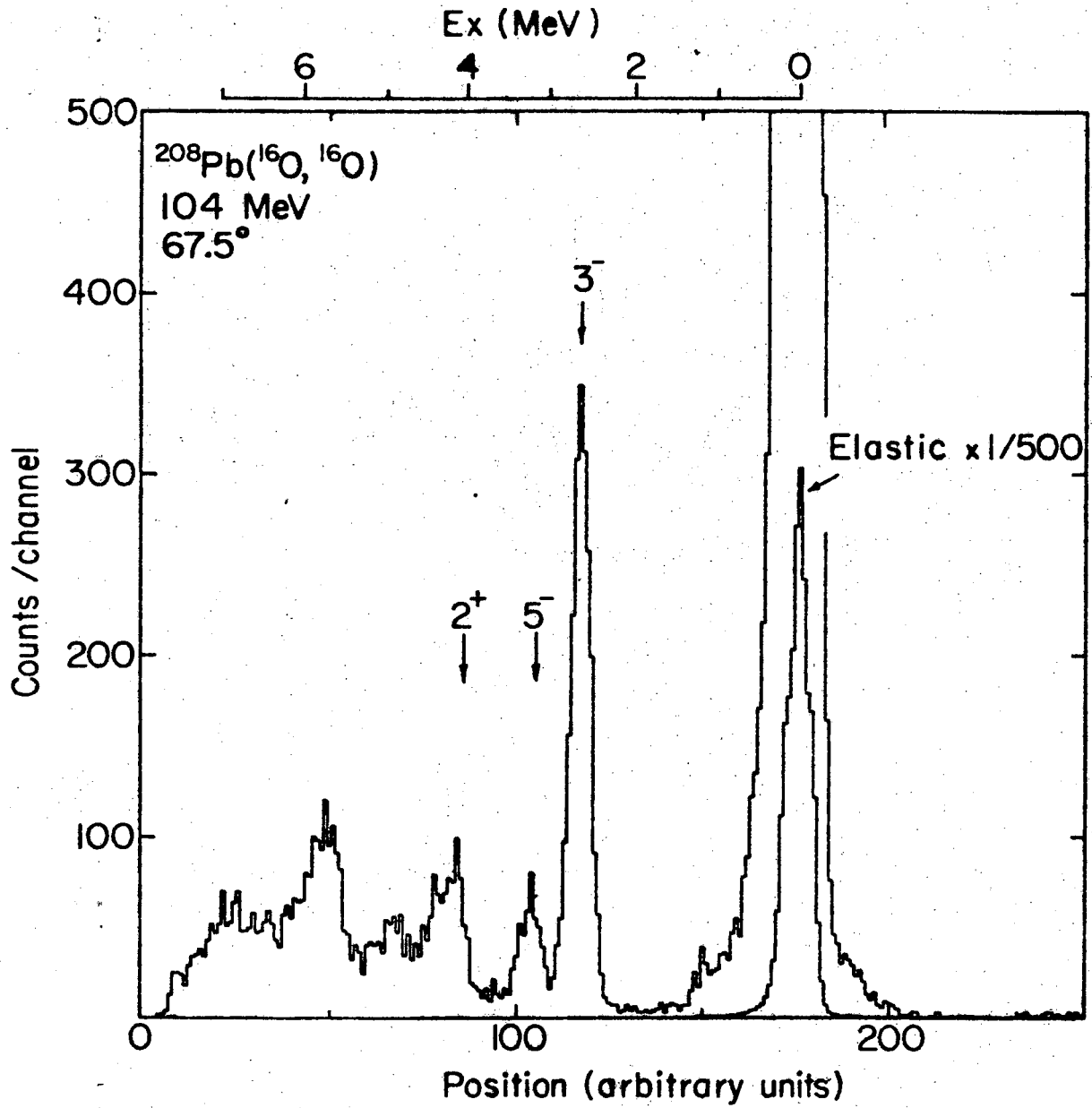
<sup>l</sup> $G_L \equiv B(L)/B_{sp}(L)$ . Estimated errors are shown.  $G_L = Z^2(3+L)^2\beta_L^2/4\pi(2L+1)$  where  $\beta_L$  is the mass ( $G_L$ ) or charge ( $G_{EL}$ ) deformation of the target

<sup>m</sup> $B(EL)$  from (e,e') of Ref. 19 (see Eq. (3)).

<sup>n</sup> $B(EL)$  from  $G_{EL} = G_L$  and adjusting  $G_L$  to fit the data.

<sup>o</sup>Deduced from the  $^{16}O + ^{208}Pb$  data presented in Ref. 26 but neglecting reorientation terms ( $Q = 0$  b).

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Fig. 1

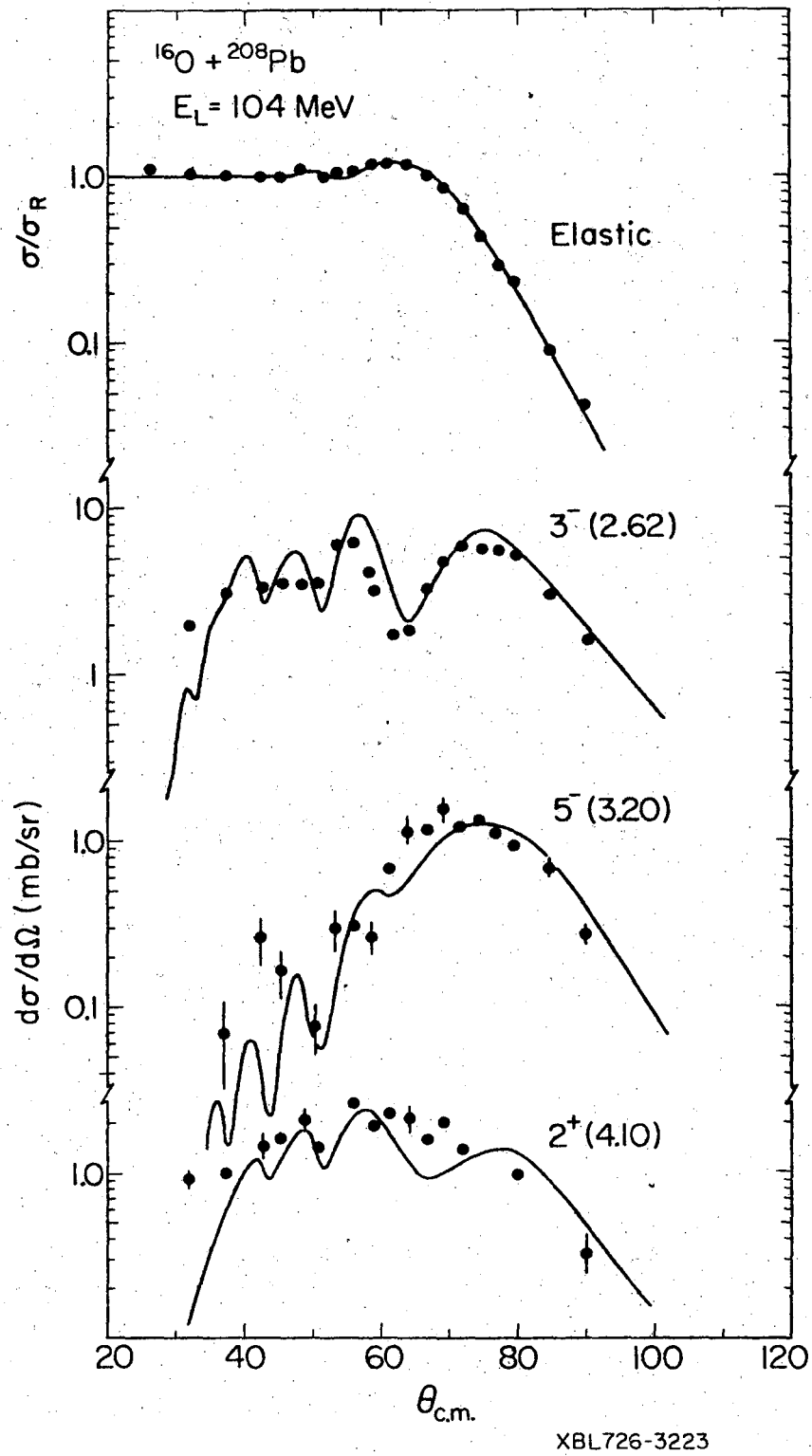


Fig. 2



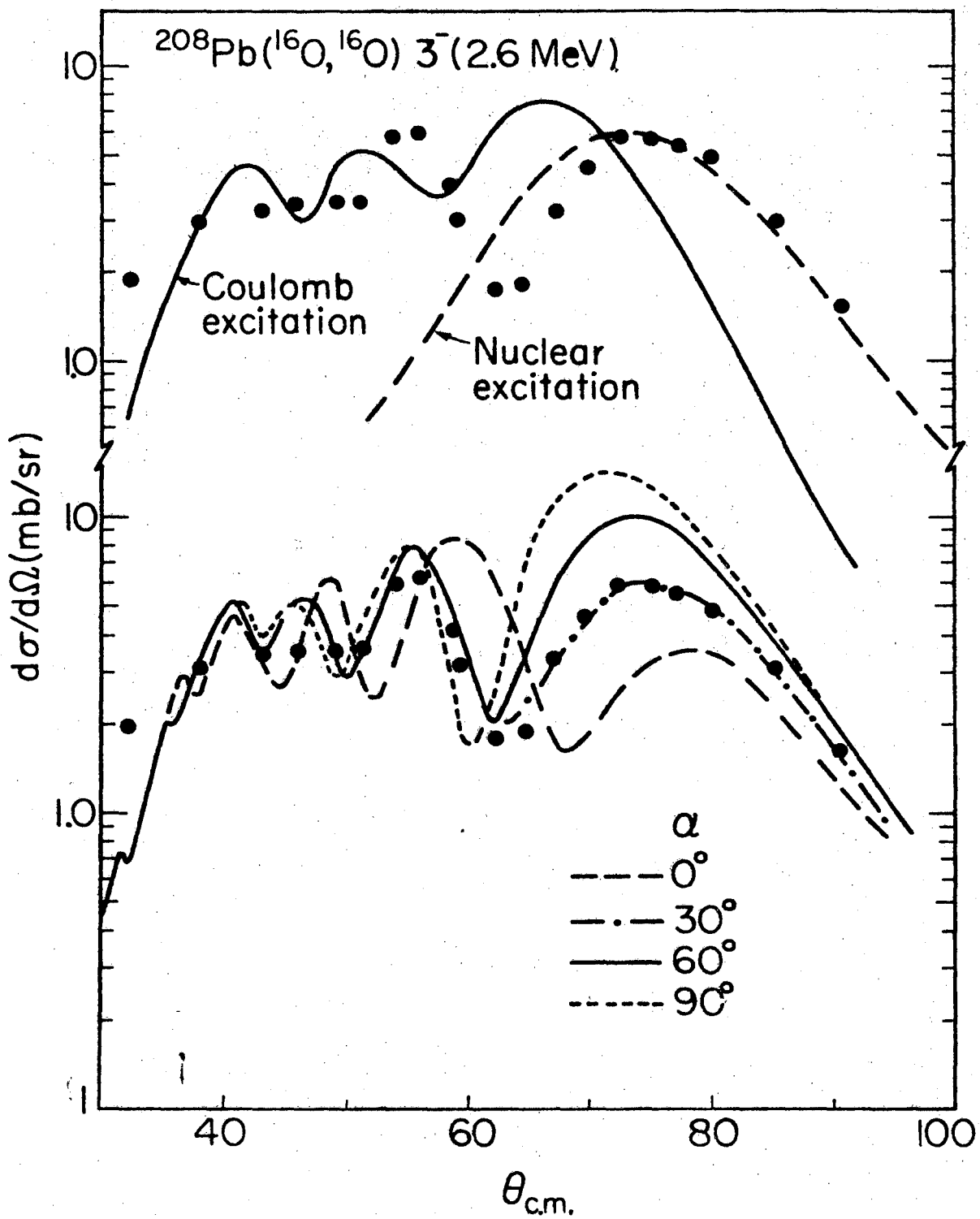


Fig. 3

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