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ABSTRACT

In the inelastic scattering of 65 MeV helium ions by O^{16}, the following levels of O^{16} were excited: 6.134, 6.918, 7.118, 8.876, 9.850, 10.363, 11.083, 11.52, 12.02, 12.443 + 12.528 (unresolved), 12.968 + 13.101 (unresolved), 13.981 and 14.94 MeV. Angular distributions were obtained for the particle groups corresponding to nearly all these O^{16} levels.

The levels at 8.876, 11.083, 12.528, 12.968, 13.981 are of unnatural parity (i.e. parity $(-)^{J+1}$). At small angles the angular distributions of the 8.876 MeV 2- level oscillates in phase with the elastic angular distribution as a negative parity level should, but at angles greater than 45^{o}, it behaves more like a positive parity level.

The T = 1 levels at 12.968 and 13.101 MeV were excited about as strongly as neighboring T = 0 levels, but the T = 1 level at 13.260 MeV was not observed.

All negative parity levels of the $p^{-1}(s,d)$ configuration were observed where not forbidden by selection rules or obscurred by their great width. The 9.59 MeV 1- level was not observed; this confirms that it is a level of three-particle excitation.

The 3- level at 6.134 MeV showed collective enhancement of its cross section.

SCATTERING OF 65 MeV HELIUM IONS FROM O^{16*}

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Introduction

Successful operation of the 224 cm (88-inch) spiral ridge cyclotron has enabled us to study the elastic and inelastic scattering of 65 MeV helium ions from C^{12}, N^{14}, and O^{16}. We wish to report only the results obtained from O^{16}, since this target was the most completely investigated, but the elastic particle angular distributions for C^{12} and N^{14} are given for purposes of comparison.

The scattering of helium ions has a longer history than any other type of measurement in nuclear physics. Our results are not as striking as those obtained by the first investigators[1], but the experiment permitted us to establish an historical continuity with their work which should guarantee that our new cyclotron has the support of an ancient tradition. The choice of experiment was not uninfluenced by its comparative simplicity: such considerations are important when using an accelerator and its associated equipment for the first time.

Angular distributions for the elastic and a few inelastic groups from O^{16} have previously been measured for incident helium ion energies of 6-19 MeV[2], 18 MeV[3], 20 - 22 MeV[4], 38 MeV[5] and 40 MeV[6]. Like the earliest investigators, we used a solid state device for the detection of the scattered particles; in our experiment it was a lithium-drifted silicon diode rather than a zinc sulfide screen. With this detector, and by the use of a momentum analyzed incident beam, we were able to resolve more inelastic groups than has previously been possible.

Experimental

Figure 1 shows the beam optical system. The quadrupole doublet created an image of the cyclotron effective source about half way between the quadrupole lens and the analyzing magnet. In the vertical plane, the beam was everywhere approximately parallel. A circular pole uniform field magnet deflected the beam through 57° and threw a radial image on the analyzer slit. The vertical height of the beam was usually limited to 2.5 cm by means of a graphite plate with a rectangular hole placed at the entrance to the analyzer magnet.

The water-cooled tantalum jaws of the vertical analyzer slit could be opened and closed and the whole slit could be moved to any radial position in the beam pipe; both operations were performed by remote control. A slit opening of 0.15 cm was used. First order calculations of the energy resolution (including the effect of dispersion in the cyclotron fringing field) showed that it should be possible to obtain a full width at half maximum (FWHM) in energy of 0.5%, or about 70 keV. Aberrations ensure that the actual value will be worse than this, but we have obtained a resolution of 140 keV FWHM in the spectrum of elastic particles scattered from gold leaf. This figure includes the energy resolution of the beam and of the detector as well as the small broadening due to target thickness and angular resolution.

After the slit, the beam passed through the main shielding wall of the cyclotron vault, consisting of about 80 cm of steel and 170 cm of concrete. The particles were re-focused by a second quadrupole doublet to a radial focus at the target position in the center of a 90 cm diameter scattering chamber. A vertical collimating slit and anti-scattering slit were placed in the beam pipe at a distance of 56 cm from the target. The tantalum slit had an opening 0.203 cm wide by 1.25 cm high. Rather tight collimation of the beam spot was necessary to obtain good resolution because the energy of the helium ions scattered from light target nuclei varies so rapidly with angle. The full angle of convergence of the beam at the target position was 0.2°.

The target was O_2^{16} or CO_2^{16} gas contained in a 7.6 cm diameter cell at a pressure of about 10 cm Hg. The particles entered and left the cell through windows of 0.00025 cm thick nickel foil. The gas pressure was maintained constant by means of a simple mercury bubbler manostat which was necessary because the thin nickel windows frequently developed slow gas leaks. After passing through the gas cell, the beam current was measured in a magnet-protected Faraday cup and beam integrating electrometer. The scattering chamber and Faraday cup have been described before[7].

The beam current reaching the Faraday cup was typically 0.1 μA, but as the experiment progressed the cyclotron crew improved the operation of the machine until at the end we obtained 0.4 μA. At all times the internal beam current was limited to 20 μA in order that the cyclotron should not become too radioactive to permit further engineering work. Subsequently, changes of the shape of the deflector entrance septum and of the cyclotron field configuration have raised the extraction efficiency from its initial value of 20% to 50%. The effective radial particle source in the deflector channel was about 0.2 cm wide for particles of the full beam energy spectrum[8]. For a selected energy group it must have been substantially narrower since there is much dispersion in the fringing field, and we have used a value of 0.04 cm[9] in beam optics calculations. The maximum angle of divergence of particles from the radial source was measured as 0.018 radians on either side of the optic axis[10]. In the vertical plane, the beam appeared to originate from a source whose calculated height and full angle of divergence were 1.2 cm and 0.0088 radians respectively[9]. That the beam is not very tall in the vertical direction was confirmed when it melted a slot only 0.16 cm high in a tantalum deflector entrance septum.

The scattered particles were detected by a lithium-drifted silicon surface barrier diode[11] whose depletion layer thickness was sufficient to stop 65 MeV helium ions. Best resolution was obtained at a reverse bias of 500 volts. At lower bias voltages, the detector noise was lower, but the charge collection was too slow. The lithium drifted zone extended all the way to the front surface of the silicon wafer. The contact on this surface was a gold surface barrier, which gave no appreciable "dead layer" or window. Tests with natural α-particle sources showed that the detector was capable of a resolution (FWHM) of about 70 keV. The counter assembly is shown in fig. 2.

Pulses from the detector were amplified by a charge-sensitive nuvistor pre-amplifier placed outside the scatter chamber vacuum system. From the pre-amplifier, pulses passed through shielded cable to the counting area where they were further amplified by a Mod VI amplifier[12] operating in the RC mode with time constants of 1 μsec (rise) and 5 μsec (clipping). Energy spectra were obtained from a 400 channel RIDL analyzer.

To avoid electrical pick-up, particularly from the cyclotron oscillator, care was taken to maintain a one-point ground system. The metal box surrounding the counter was insulated from the scattering chamber itself, as were the signal cable shields and the pre-amplifier. Detector bias and pre-amplifier power were supplied from the counting area. All cables connecting the two areas were installed in a single metal tray and they and the tray were connected to ground only in the counting area racks. This system gave such excellent results that it was impossible to tell from the noise level whether or not the cyclotron oscillator was operating. A spectrum is shown in fig. 3. The line was drawn freehand through only those peaks which were observed at all angles.

The counter solid angle and the effective gas target thickness were defined by means of a pair of tantalum slits. The slit nearest the target was 0.1773 x 0.7120 cm; its distance from the target was 13.85 cm. At a distance of 34.75 cm from the target, there was a second slit 0.1582 x 0.7099 cm. Distances were measured to the front surfaces of both slits.

The differential cross section was calculated for each angle Θ from the equation

$$\sigma(\Theta) = \frac{(T + 273) \sin\Theta \, (\ell_1 + \ell_2)^2 \times N \times 3.320 \times 10^{-6}}{BPnW_1W_2h_2 \quad [1 + \ell_1/\ell_2]} \text{ mb sterad}^{-1} \qquad (1)$$

where T is the gas target temperature in degrees centigrade, ℓ_1 and ℓ_2 are the distances from the front collimator to the gas target center and from the front collimator to the rear collimator, N is the number of events recorded for the passage of B μcoulombs of doubly charged particles, P is the gas pressure (cms Hg), n is the number of target atoms in each molecule of the gas, W_1 and W_2 are the widths of the front and rear slit and h_2 is the height of the rear slit. All linear dimensions are measured in centimeters.

Energy resolution of particle groups scattered from the gas target was never as good as that obtained from a solid foil target such as Au^{197}, for which the energy changes much more slowly as a function of scattering angle. With the gas target, the resolution (FWHM) was typically 250 keV.

The excited states of O^{16} were identified by measurement of the energies of the inelastic particle groups. Immediately after recording each spectrum, pulses from a pulse generator were fed into the front end of the pre-amplifier through a small capacitor. The pulse heights from the generator were varied in about twenty steps by means of a Dekapot potentiometer linear to 0.01%, and in this way a relationship was established between Dekapot dial reading and pulse height analyzer channel number. By interpolation, the channel numbers corresponding to the peaks in the helium ion spectra were converted to their equivalent Dekapot dial reading.

The cyclotron beam energy, obtained from the resonance magnetic field, the frequency and the extraction radius, was 65.3 ± 0.3 MeV[10]. At the center of the gas target, the helium ion energy was 65.0 ± 0.3 MeV. The energies of elastically and inelastically scattered ions were calculated as a function of angle by means of a computer program using relativistic kinematics. At ten angles between 33° and 66°, the energy of elastically scattered particles incident on the counter was calculated by subtracting the small energy loss in leaving the target from the computed energy at the center of the target. In this way, a relationship was obtained between the energy of particles incident on the counter surface and the equivalent pulse generator Dekapot dial reading. This relationship was used to obtain the energies of particles belonging to groups which were believed to correspond to the 6.134 and 8.876 MeV excited states of O^{16}. The excitation energies thus obtained were 6.110 and 8.887 MeV. Having thus unambiguously identified these groups in the spectrum, their computed particle energies and equivalent Dekapot readings were incorporated into the energy scale. This scale was very nearly linear; the ratio (particle energy at counter) $\div$ (Dekapot reading) varied from 1.0312 at 40 MeV to 1.0227 at 60 MeV.

From this final energy scale, the energies of the other inelastic groups were calculated at seven angles between 33° and 46°. The values thus obtained were compared with the computed values to obtain the excitation energy of each level. As a check on the accuracy of the energy scale, the energy of the He^3 ions from O^{16} (α, He^3) O^{17} was measured by the use of the He^4 energy scale, and the Q-value for the reaction was calculated. The experimental result was -16.465 MeV, different from the accepted value of -16.436 MeV[13] by 0.029 MeV. Energy losses in nickel and oxygen for both He^3 and He^4 were obtained from the compilation of Williamson and Boujot[14]. The reproducibility of the level energy measurements varied somewhat with the intensity of the peak. For the more intense peaks, the average deviation from the mean was about 30 keV, but for the less intense levels it was about 50 keV. The accuracy of measurement of the energies of excited states is very insensitive to the value adopted for the beam energy. For example, the computed energy difference between the elastic and 8.876 MeV groups at 20° (lab) is 8.8545 MeV for a beam of 64.5 MeV and 8.8538 MeV for a beam of 65.0 MeV.

Results

Energy Levels Observed.

The levels of O^{16} that were observably excited are summarized in Table I.

The peak at 6.137 MeV may contain a small amount of the 6.052 MeV 0+ level, but the proportion cannot be large. The peak was no wider than the elastic peak, and the level energy measured on the preliminary scale established from the elastic peak along agreed extremely well with the known 3- level at 6.134 MeV.

Excitation of the unnatural parity 2- level at 8.876 MeV has been observed previously in inelastic helium ion scattering[3]. We also observed the 2- level at 13.981 MeV and the 3+ level at 11.083 MeV. The peak at an observed excitation of 12.989 MeV was broad and probably contains both the 13.101 MeV 1- level and the 12.968 MeV unnatural parity 2- level. Both these levels have been assigned isotopic spin 1[20], and even if we have misassigned our peak, the known levels below and above this pair have also been assigned isotopic spin 1. The broad levels at 11.26 and 11.63 MeV were not observed, though they may be responsible for the rise in the height of the valleys in the energy spectrum in this region. There is a close correspondence between the levels listed in Table 1 and those that were observed by Hornyak and Sherr in the scattering of 19 MeV protons[16]. Agreement is complete up to an excitation energy in O^{16} of 13.1 MeV. Beyond that, they observed a T = 1 level at 13.39 MeV which we did not see, whereas we observed the levels at 13.981 and 14.94 MeV, which were beyond the end of their spectra.

Angular Distributions and Cross Sections.

Figure 4 shows the angular distribution of helium ions of various energies elastically scattered from O^{16}. At 65 MeV, the diffraction pattern is not strong at angles beyond the maximum at 31°, but the similarity both in shape and in absolute cross section value at the first maximum is remarkable.

In preliminary experiments, we measured the elastic angular distribution of 65 MeV helium ions scattered from N^{14} and C^{12}. Figure 5 shows these angular distributions, and that for O^{16}, plotted as a function of the parameter $(\underset{\sim}{k}_i - \underset{\sim}{k}_f) \times R$, where $\underset{\sim}{k}_i$ and $\underset{\sim}{k}_f$ are the wave numbers of the incident and scattered particles and R is the interaction radius. Values of R were calculated from the quation.

$$R = 1.25\ (A_1^{1/3} + A_2^{1/3}) \times 10^{-13}\ \text{cm} \qquad (2)$$

where A_1 and A_2 are the target and projectile mass numbers. The general shapes of the three angular distributions are very similar except for large values of $(k_i - k_f) \times R$, where the C^{12} curve drops while the others show a broad maximum.

The inelastic angular distributions are shown in fig. 6 and 7. The individual contributions of the imperfectly resolved 6.918 and 7.118 MeV levels were obtained by means of a computer program which made a fit to the experimental spectrum, using two gaussian curves whose width and relative amplitudes were varied to obtain the lowest value of χ^2. Only in spectra with large numbers of recorded counts was this procedure sufficiently reliable to be worth recording the results.

At small angles, the Blair phase rule[17)] is clearly obeyed in several cases. The angular distribution for the 3- octupole level at 6.134 MeV oscillates in phase with that of the elastic group. The differential cross sections of the 12.443 + 12.528 MeV unresolved pair (both negative parity) drop rapidly between 30° and 40°, like the elastic angular distribution. The 11.52 MeV 2+ level oscillates out of phase with the elastic group, while the cross section for the 10.363 MeV 4 + level rises between 30° and 40°. In this region, the cross sections for negative parity states are falling.

The unnatural parity levels are particularly interesting. The angular distribution of the 8.876 MeV 2- level behaves very clearly like a negative parity level at small angles, but becomes out of phase with the 3- octupole level beyond 40°. The 12.02 MeV level behaves very like the 12.968 + 13.101 MeV negative parity levels; it was plotted in fig. 6 with the positive parity levels only because, according to the α-particle model[18], it is probably 1+. The observation by Hornyak and Sherr[16] of a γ-ray from the decay of this level to the ground state shows that it probably has unnatural parity, for a natural parity state should α-decay. The angular distribution for the 13.981 MeV 2- level drops rapidly between 30° and 40°, like the elastic cross section; it is very similar to the angular distribution of the 12.443 (1-) and 12.528 MeV (2-) unresolved pair. The angular distribution of the 3+ level at 11.083 MeV was not sufficiently accurate to permit any conclusions to be drawn from it, and it is not plotted in fig. 6. Thus in three cases, it appears that the angular distribution of levels of even spin and negative parity obeys the normal phase rule at small angles. In the doubtful case of the 12.02 MeV level, the angular distribution has no clear oscillations.

Eidson and Cramer[19] have shown that excitation of an unnatural parity state can occur only a) by compound nucleus formation, b) through a velocity dependent potential such as a spin orbit interaction, c) an exchange interaction such as knockout or target stripping. Process a) seems highly improbably at 65 MeV, and in any case would not be consistent with the observed diffraction maxima and minima. Process b) should give a cross section increasing with incident particle velocity. In the excitation of the 3+ level of Mg^{24} at 5.22 MeV, the average cross section dropped from 0.7 mb/sr at 19.3 MeV (CM) to 0.2 mb/sr at 36.9 MeV[19]. For the 8.876 MeV level of O^{16}, the average cross section at 14.7 MeV (CM) was 2.5 mb/sr[3], whereas at 52 MeV (CM) we find it to be only about 0.2 mb/sr. These results both suggest that the spin-orbit interaction is not important.

The rather slow decrease in the differential cross section for the 8.876 MeV level with increasing angle is suggestive of a target stripping mechanism. The change of phase of the oscillations at about 40° suggests that two mechanisms are operating, one mainly responsible for small angle scattering and the other for large angle scattering. A similar phase change was observed by Eidson and Cramer[19]. In the excitation of the 8.876 MeV level of O^{16} by 18 MeV helium ions, however, Corelli, Bleuler and Tendam[3] found minima in phase with the elastic cross section, but at twice the frequency. This observation is also suggestive of two interfering mechanisms.

The unresolved pair of T = 1 levels at 12.968 and 13.101 MeV was quite strongly excited. Their spins are 2- and 1- respectively. The angular distribution is rather featureless, but the broad maximum at about 38° is reminiscent of positive parity. These two levels can be made only through a T = 0 admixture. Since both levels α-decay to T = 0 levels of C^{12}, Wilkinson has suggested that they both contain a strong T = 0 admixture[20]. The integrated cross sections shown in Table II support this view; the value for the sum of the two T = 1 levels is about twice the values for adjacent single T = 0 levels. The nonappearance of the T = 1 level at 13.260 MeV, coupled with its formation by (p,p')[16], suggests that it contains relatively little T = 0 admixture.

The integrated cross sections given in Table II show that the 8.876 MeV level was quite strongly excited in spite of its unnatural parity. Since the excitation can take place only through second order processes or by a velocity dependent (spin-orbit) term in the potential[19], this result is quite surprising. The 11.083 MeV 3+ level was, however, quite weakly excited, but the 13.981 MeV 2- level was quite normal.

It is interesting to compare the integrated cross sections with the various theories of the nature of the O^{16} levels. The inelastic helium ion scattering process should excite single particle levels, but show collective enhancement[21]. The large cross section for excitation of the 6.134 MeV 3- level is in qualitative agreement with the known collective nature of this level[22, 23, 24]. The elaborate particle-hole calculations of Gillet and Vinh-Mau[25] show that about 80% of the E3 relative radiation transition probability should appear in the 6.134 MeV 3- level, and substantially less in the 13.260 MeV T = 1 level and the 11.63 MeV T = 0 level, neither of which were observed. By comparison of the differential cross section at the first diffraction maximum (25° and 30° respectively for positive and negative parity levels) with the value calculated from the Blair plane wave theory[17], an approximate value can be obtained for β_{ℓ}, the nuclear deformation parameter. Values thus derived are shown in Table III, which includes results of a preliminary study of inelastic scattering of 65 MeV helium ions by N^{14}. Warburton and Pinkston[26] have produced arguments to show that the E3 decay of the 5.10 and 5.83 MeV levels of N^{14} to the ground state is enhanced by a factor of about 10. The E3 transition from the 6.134 MeV level of O^{16} to the ground state is enhanced by a factor of about 7[22]. With these enhancement factors, it is possible to obtain crude estimates of the value of β appropriate to single particle transitions. The values thus obtained are shown in the last column of Table III.

Assuming that a value of 0.04 for β represents a pure single particle transition, it appears that the 11.520 MeV level is enhanced by a factor of approximately 3 (the enhancement being proportional to β^2). The unnatural parity levels at 8.876 and 13.981 MeV, and in fact most of the levels whose angular distributions appear in figs. 6 and 7, have β values substantially below the single particle value. However, the meaning of the β value is quite unclear in the case of the unnatural parity states. A value of β equal to 0.4 gives a cross section of about 0.7 mb/sr at the appropriate maximum for ℓ equals 2 and ℓ equals 3 transitions.

An attempt was made to resolve the large peak containing the 6.918 and 7.118 MeV levels into its two components. A computer program fitted gaussian curves to the peak at 6.134 MeV and the double peak at about 7 MeV varying the width of the gaussians, the positions of their maxima and the ratios of the individual components. The resulting angular distribution of the 6.918 MeV level shows the oscillations that might be expected for a positive parity state; it resembles the angular distribution of the 2+ level at 11.52 MeV both in shape and magnitude, giving a very similar β-value.

The angular distribution of the 7.118 MeV (1-) level shows some of the features expected of a negative parity level. The results are shown in fig. 7. No error bars are given on the angular distribution curves for the 6.918 and 7.118 MeV levels since it is difficult to assess the accuracy of the computer fitting program.

With the exception of the 9.59 MeV level, all the negative parity states of O^{16} up to 13.5 MeV can be accounted for by the configuration

$p^{-1}(sd)$[23,24,25]. They would thus be made from the O^{16} ground state by the promotion of a single 1p nucleon. The 9.59 MeV level is apparently of more complex nature, involving three excited nucleons[24,27]. It is therefore not surprising that it was very definitely not observed in the present experiment. The failure to observe the 10.953 MeV level is presumably due to difficulties with spin and parity conservation in the excitation of a 0- level from a 0+ target by 0+ incident and outgoing particles. The failure to observe the 11.63 MeV 3- level of the $p^{-1}(sd)$ configuration is probably due to its width (1.2 MeV). Thus all the $p^{-1}(sd)$ levels that could have been observed, were observed.

The positive parity levels of O^{16} are less well understood. The shell model would require either single excitation from the 1s to the 2s or $1d_{5/2}$ shells, from the 1p to the 1f or 2p shells, or else a two particle excitation such as $1p^2 \rightarrow (s,d)^2$. Levels of this type should be more weakly excited than the single particle $1p \rightarrow (sd)$ negative parity states unless collective enhancement of the cross section occurs. Experimentally however, some positive parity levels, such as the 2+ levels at 6.918 MeV and 11.52 MeV, were rather strongly excited while others, such as the levels at 9.850 MeV (2+) and 11.083 MeV (3+) were only weakly excited. The 9.850 MeV level was found by Meads and MacIldowie not to be collective[28]; its γ-ray width is only 1/16 of the E2 single particle value. The 11.52 MeV level, however, was found to have an E2 width slightly greater than the single particle value, which is in qualitative agreement with the β value reported in Table III.

The positive parity levels of O^{16} are usually discussed in the language of the cluster model[29,30]. Most of them have been accounted for as $(C^{12} + He^4)$ clusters in various states of relative motion. In some levels, the C^{12} core is presumed to be in an excited state. An inelastic scattering event in which the incident helium ion changed the internal motion of the (C^{12} + He^4) clusters and at the same time excited the C^{12} core should have a lower probability than an event in which only one of these two changes occured. In fact there appears to be no correlation of this type between the observed cross sections and the cluster configurations. The ground state of O^{16} is represented[30] as a 3s motion of the He^4 cluster. The 11.52 MeV level, quite strongly excited, is represented as a 3d motion of the He^4 cluster around an excited C^{12} core, but the 11.083 MeV level of the same configuration was particularly weak. No level represented as a relative s-motion of the He^4 and either C^{12} or C^{12*} was strongly excited. The levels of this type are: 6.052, 9.850 and 11.26 MeV[30]. The 11.26 MeV level, however, is too broad to have been observed. A level at about 14.7 MeV (probably the 4+ 14.94 MeV level) has been assigned a strong deuteron-like cluster configuration[31] with the odd proton and neutron in the $d_{5/2}$ shell, coupled to a spin of 5. The core is an unexcited J = 1 N^{14} nucleus, which couples to the deuteron cluster to produce levels of spin 4,5 and 6. It seems unlikely that the 14.94 MeV level should be excited in inelastic helium ion scattering through this particular component of its wave function. An analogous J = 5 level in N^{14} was not excited by (α,α')[31]. However, this N^{14} level should be quite pure $(d_{5/2})^2$, whereas the J = 4 level of O^{16} could be quite mixed with other configurations. The 6+[32] level of the $\left[N^{14} + (d_{5/2})^2\right]$ configuration at 16.2 MeV was not observably populated. Unfortunately it would fall very close to the strong He^3 group from $O^{16}(He^4, He^3)O^{17}$ g.s. This group moved in energy as a function of angle exactly as though it were pure He^3, and the peak was very narrow at all angles.

Hence it is very probable that the 16.2 MeV level was not populated as strongly as the 14.94 MeV level. There was no evidence for strong population of the third member of the $\left[N^{14} + (d_{5/2})^2\right]$ triplet, which lies at about 17.2 MeV[31].

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Table I. Levels of O^{16} excited by $O^{16}(\alpha,\alpha')O^{16}$[a]

Level energy, MeV		
This work	Previous work[15)]	J Π, T[15)]
6.137[a]	6.134	3-, 0
6.903	6.918	2+, 0
6.973	7.118	1-, 0
8.876[a]	8.876	2-, 0
9.797	9.850	2+, 0
10.308	10.363	4+, 0
11.069	11.083	3+, 0
11.480	11.520	2+, 0
11.997	12.02	?
12.492	12.443 12.528	1-, 0 2-, 0
12.989	12.968 13.101	2-, 1 1-, 1
13.966	13.981	2-, ?
14.975	14.94	4+, ?

a. Used to establish energy scale

Table II. Integrated cross sections for $O^{16}(\alpha,\alpha')O^{16}$

Level energy (MeV)	Cross section integrated From (degrees,	To lab. system)	Cross section (mb)
0	16	80	39.8
6.134	16	80	8.1
6.918	16	46	2.4
7.118	16	46	2.4
8.876	16	60	0.65
9.850	25	46	~0.16
10.363	25	46	0.33
11.083	25	46	~0.15
11.52	16	60	2.16
12.02	25	46	0.23
12.443 12.528	25	46	0.36
12.968 13.101	25	46	0.52
13.981	25	46	0.31
14.94	25	46	0.74

Table III. Deformation parameters obtained by comparison of measured cross sections with plane wave theory.

Nucleus	Level energy, MeV	$J\pi$	ℓ Assumed	β exp.	Enhancement (assumed)	β sp
N^{14}	5.104	2-	3	0.096	~10	0.030
	5.832	3-	3	0.090	~10	0.029
O^{16}	6.134	3-	3	0.12	7	0.046
	6.918	2+	2	0.091		
	8.876	2-	3	0.014		
	11.520	2+	2	0.067		
	13.981	2-	3	0.014		

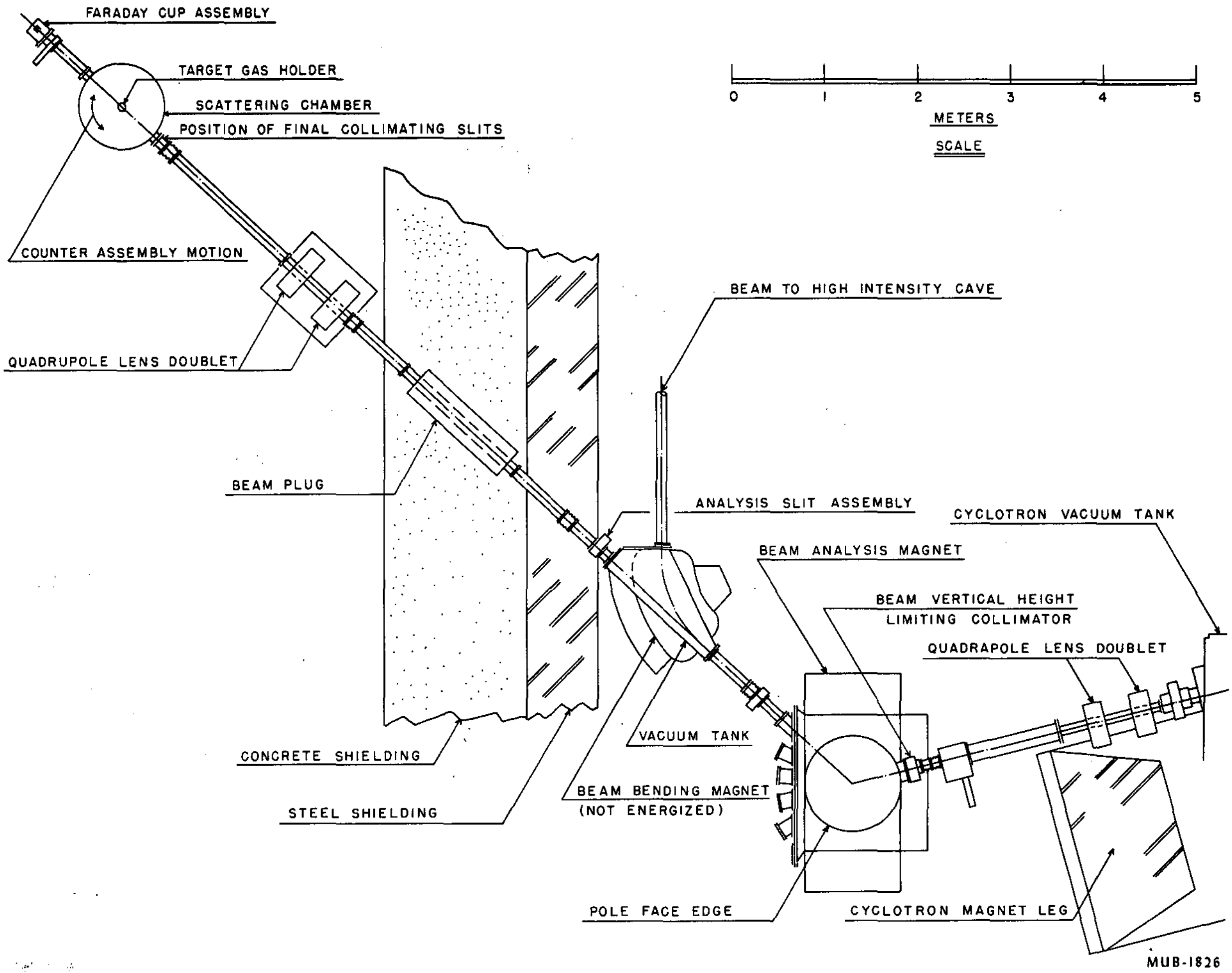

Fig. 1. Arrangement of experimental equipment.

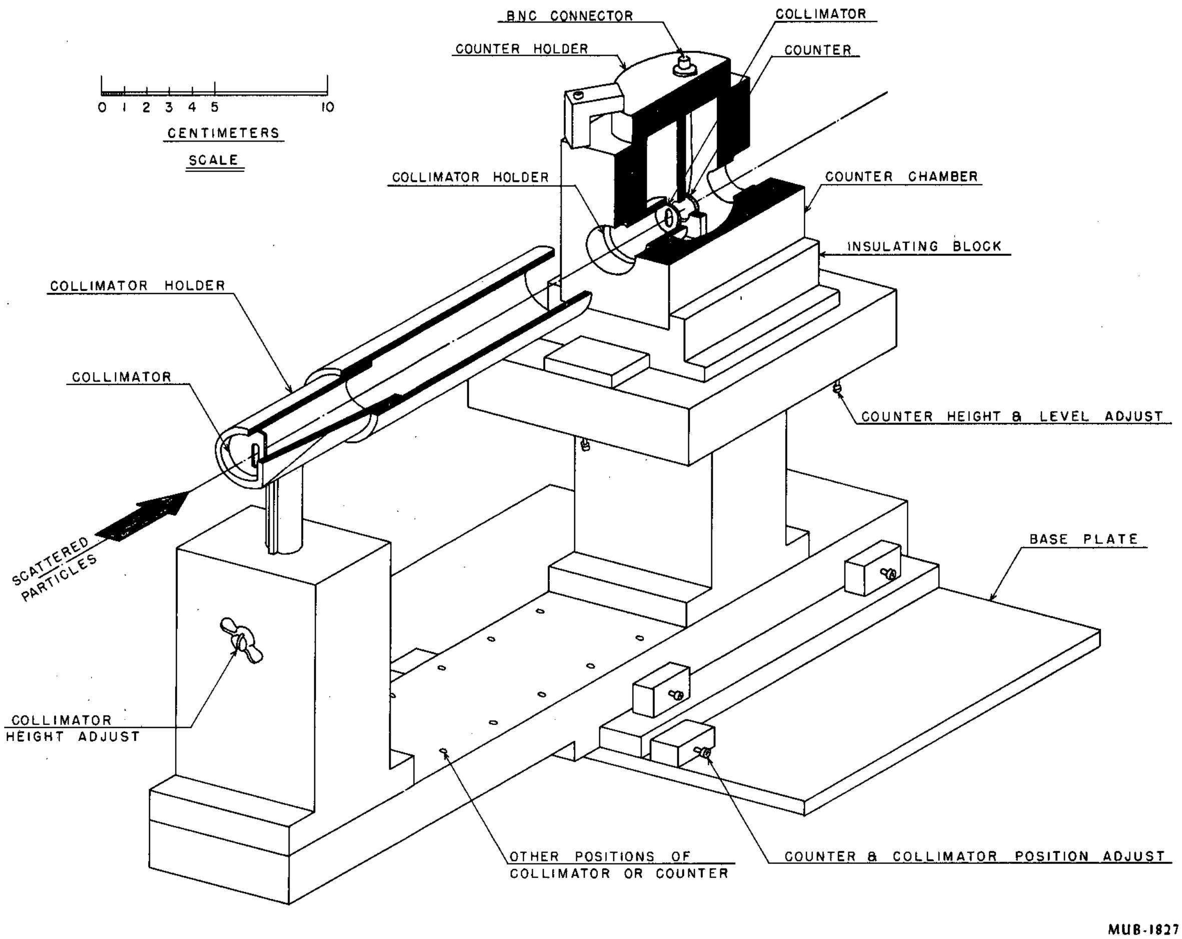

Fig. 2. Counter assembly with collimators for use with gaseous targets.

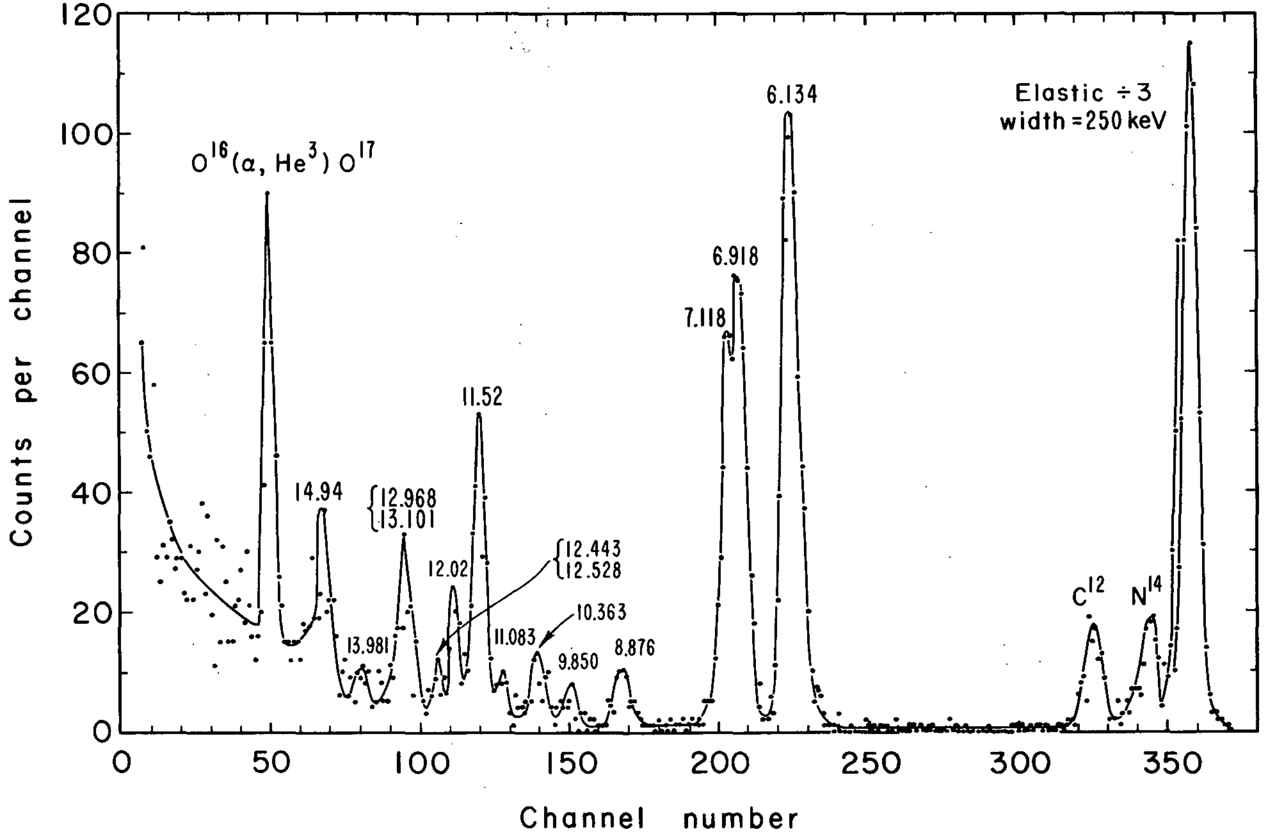

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Fig. 3. Energy spectrum of elastic and inelastic groups from the scattering of 65 MeV helium ions by O^{16} at 31° (lab. system).

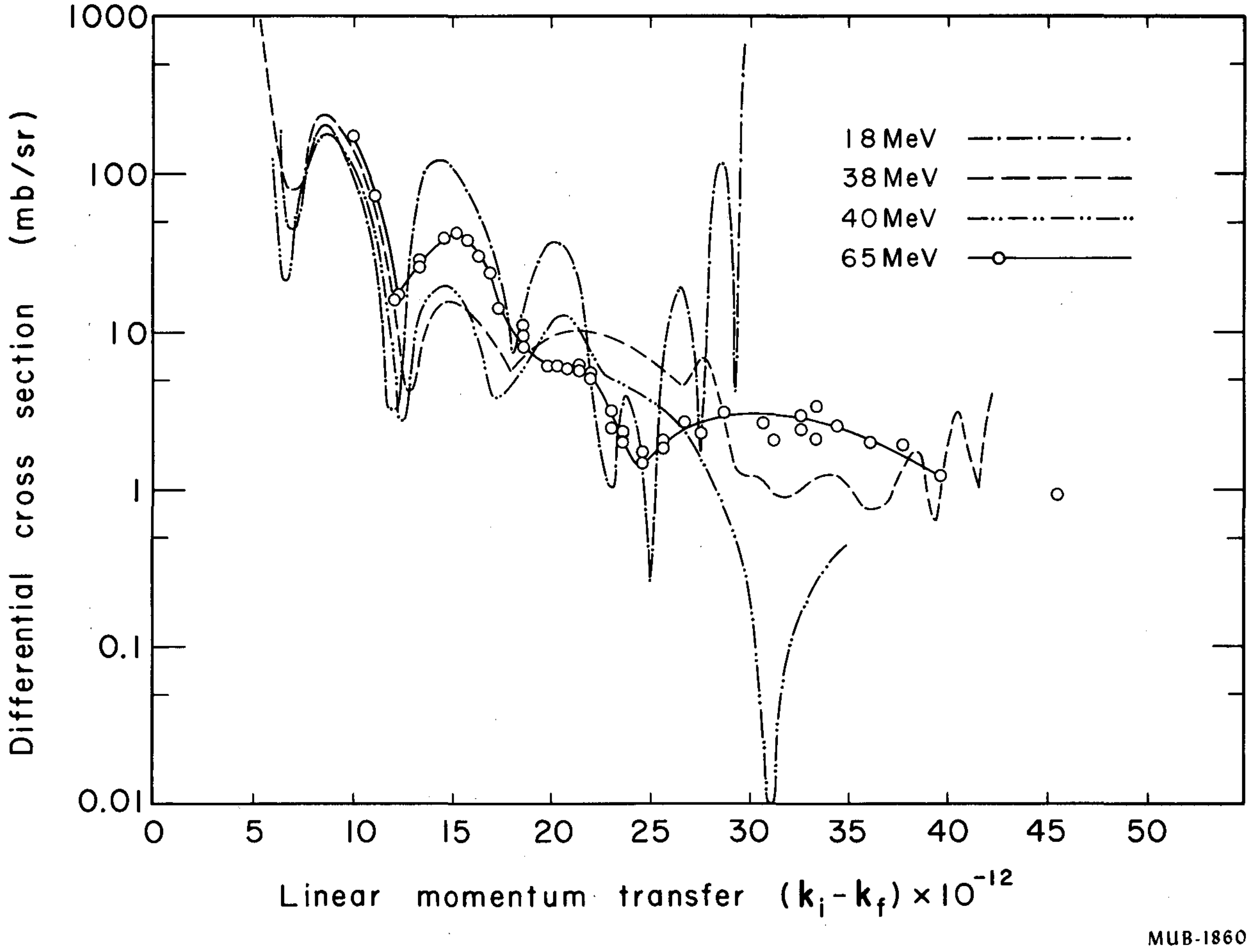

Fig. 4. Differential cross section for elastic scattering from O^{16} of helium ions of various energies, as a function of linear momentum transfer $(k_i - k_f)$.

18 MeV -·-·-·
38 MeV ----
40 MeV -·····-·····-
65 MeV —⊙—

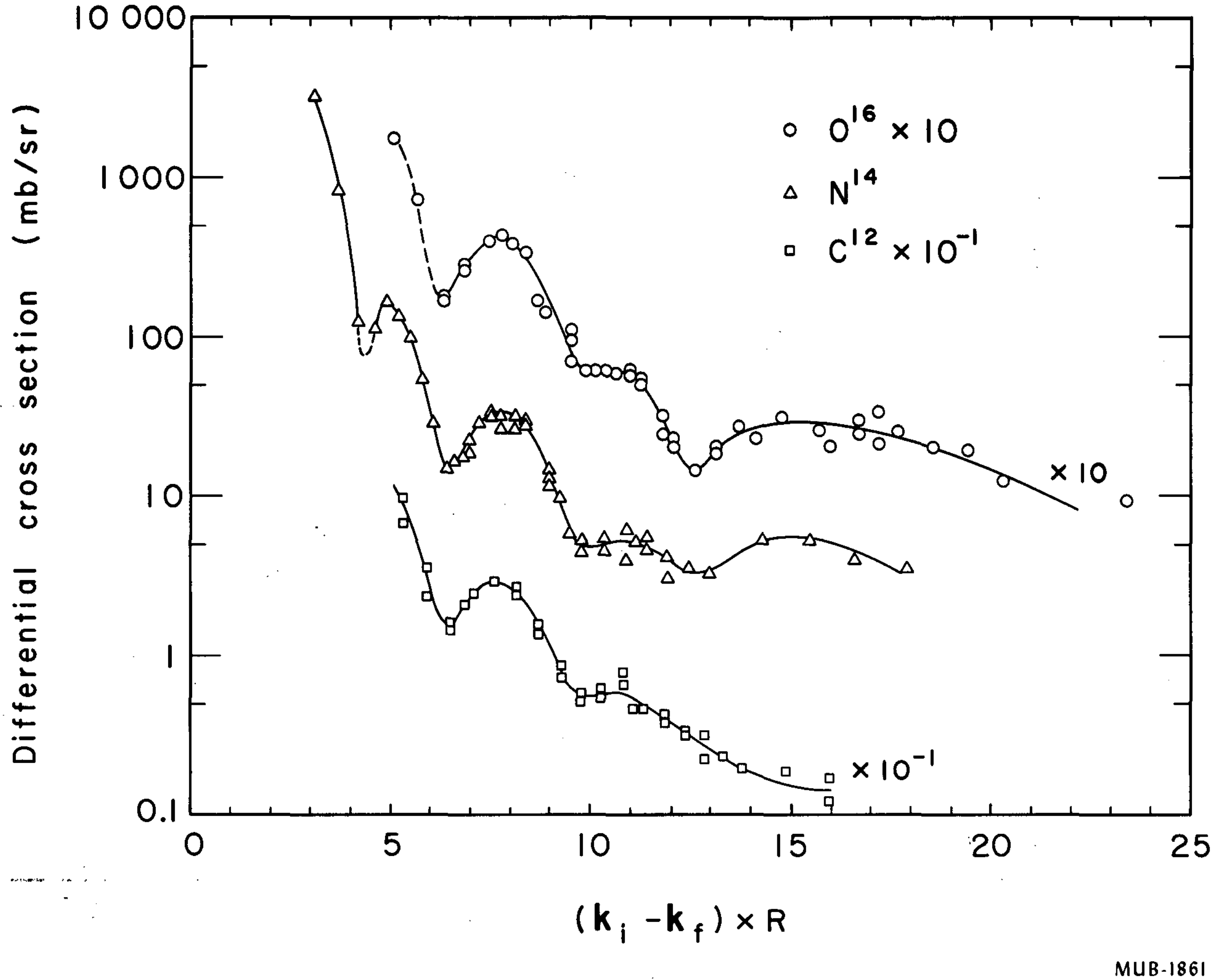

Fig. 5. Differential cross section for elastic scattering of 65 MeV helium ions from C^{12}, N^{14} and O^{16}, as a function of angular momentum transfer $(\underset{\sim}{k}_i - \underset{\sim}{k}_f) \times R$.

C^{12} —⊡—
N^{14} —△—
O^{16} —⊙—

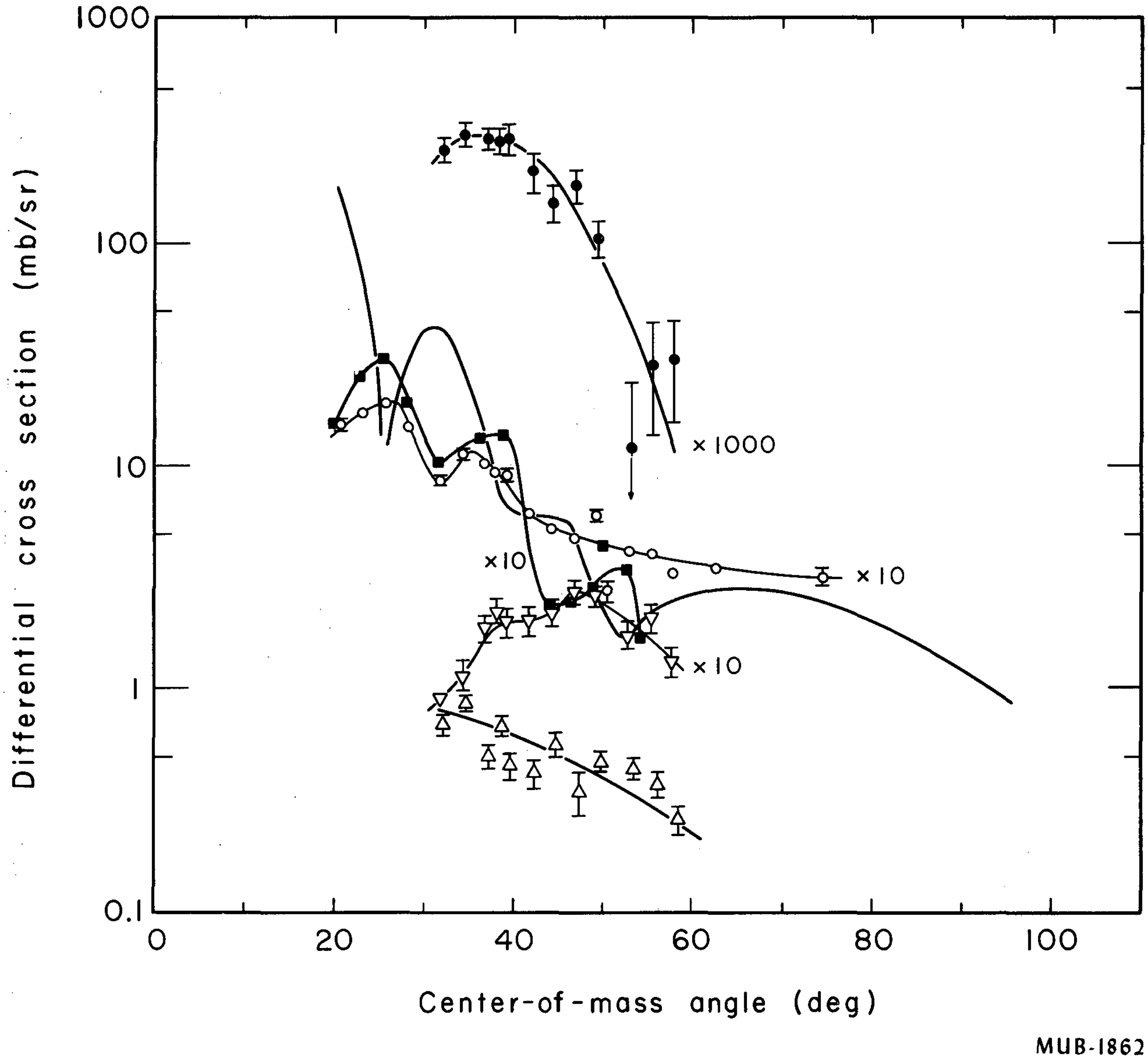

Fig. 6. Angular distributions for inelastic scattering of 65 MeV helium ions from positive parity levels of O^{16}. The elastic angular distribution is shown for comparison.

Elastic	———
6.918 MeV	—■—
10.363	—▽—
11.52	—⊙—
12.02	—●—
14.94	—△—

Fig. 7. Angular distributions for inelastic scattering of 65 MeV helium ions from negative parity levels of O^{16}. The elastic angular distribution is shown for comparison.

Elastic	———
6.134 MeV	—⊙—
7.118	—●—
8.876	—△—
12.443 12.528	—▲—
12.968 13.101	—▽—
13.981	—X—

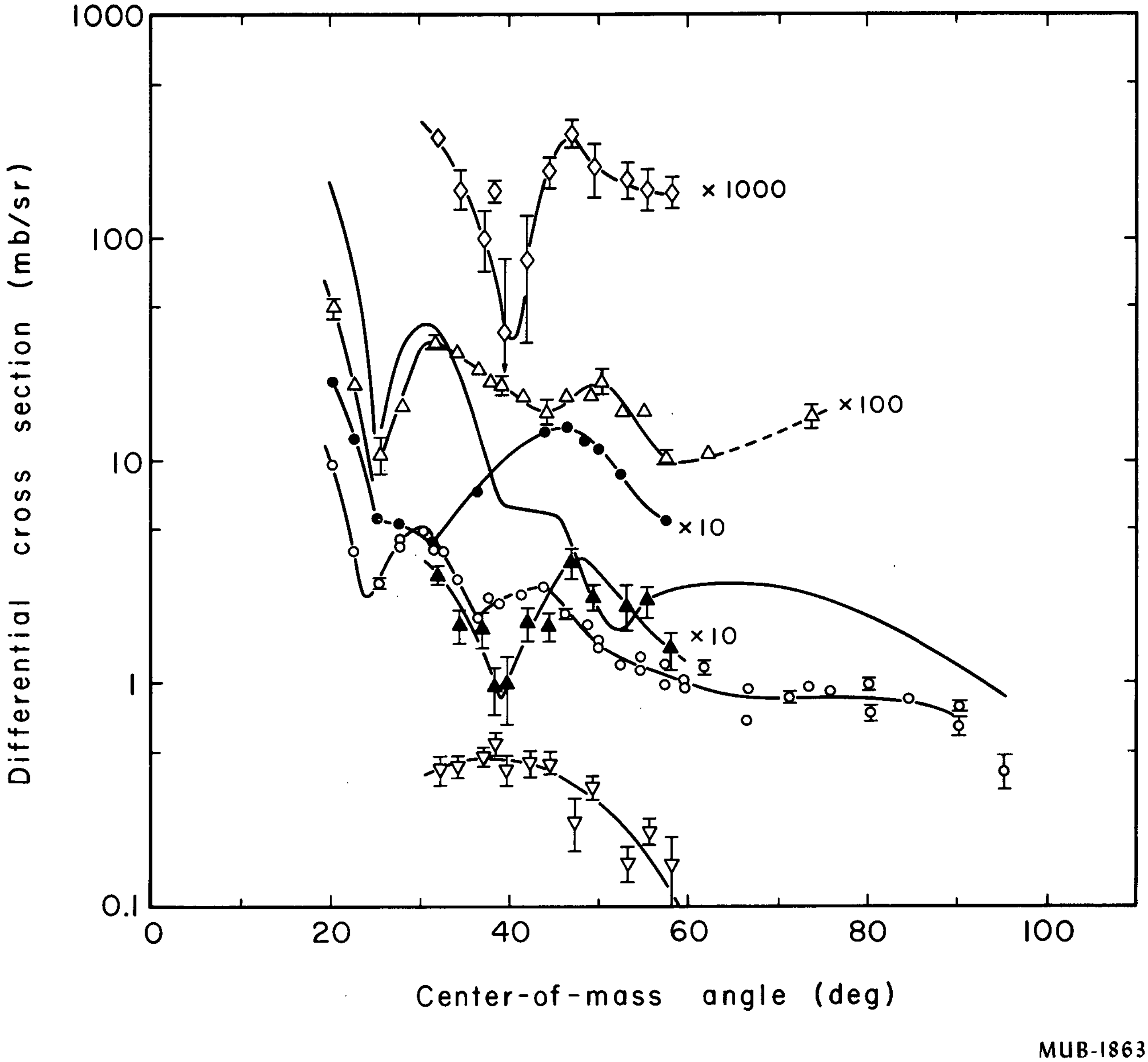
1000
100
10
1
0.1
0
20
40
60
80
100
Differential cross section (mb/sr)
Center-of-mass angle (deg)
× 1000
× 100
× 10
× 10
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Fig. 7