Elastic and Inelastic Scattering of Protons by Be^9 in the Energy Region from 6.1 to 7.3 Mev

Ryutaro ISHIWARI*

(Kimura Laboratory)

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The angular distributions of the elastic scattering and the inelastic scattering proceeding to the 3.04, 2.43 and 1.75 Mev states in Be^9 were measured at proton energies from 6.1 to 7.3 Mev. The background subtraction was carried out with special prudence to obtain reliable results for the 3.04 Mev state.

No remarkable energy dependence of the angular distributions is seen for the elastic scattering. All angular distributions of the inelastic scatterings show distinct forward peaking and change little with the proton energy. In the angular distributions for the 2.43 Mev state, however, gradual but definite energy dependence can be recognized.

These angular distributions were compared with the simple direct interaction theories. The present results are consistent with the negative parity of the 3.04 Mev state and the positive parity of the 1.75 Mev state.

The cross sections for the excitation of the 3.04, 2.43 and 1.75 Mev states are 22 mb, 106 mb and 5 mb respectively for 7.3 Mev protons.

The inelastic scattering proceeding to these states in Be^9 is considered to occur mainly *via* some kind of direct interaction process, and the contribution from the compound nucleus formation is small in the present energy region.

INTRODUCTION

The low lying excited states in Be^9 have been the subject of many experimental investigations[1~12]. Although the positions of the states have been well established, the character and the structure of them have not yet been fully determined. This is mainly due to the facts that the excited states in Be^9 decay predominantly by particle emission preventing the study by gamma-ray analysis, and that the nuclear reactions proceeding to the excited states in Be^9 are generally associated with the three-body breakup reaction due to the low neutron binding energy. Most experiments have been concerned with the energy or momentum spectra of the emitted particles[1~8], and only a few experiments have been reported on the angular distributions[9~12].

The momentum spectra of the inelastic scattering of protons, deuterons, and alpha-particles from Be^9, and of the $B^{11}(d,\alpha)Be^{9*}$ reaction have been observed by magnetic analysis[1~6]. The energy spectra of the protons from $Li^7(He^3,p)Be^{9*}$ have been also observed with scintillation counters[7][8]. These investigations have revealed that there exist four states at 1.75 Mev, 2.43 Mev, 3.04 Mev and 4.74 Mev in Be^9 below 6 Mev.

Among these the 2.43 Mev state is excited dominantly in all reactions. Summers-Gill[9] has measured the angular distributions of the inelastic scattering proceed-

* 石割隆太郎

ing to the 2.43 Mev state with 48 Mev alpha-particles, 24 Mev deuterons, and 12 Mev protons. The results have been analyzed by the simple direct interaction theory[13]. The angular distributions for alpha-particles and deuterons can be fitted to the expression $[j_2(qr)]^2$ with reasonable value of r, where j_2 is the spherical Bessel function, q is the momentum transfer, and r is the interaction radius. The angular distribution of the inelastic scattering of protons proceeding to this state have been also measured at 10 Mev by Rasmussen[10] and at 7 Mev by Seward[11]. The proton angular distribution shows forward peaking and varies little with the incident energy. However, it has been shown that this shape cannot be fitted to $[j_l(qr)]^2$ unless too small value was assumed for the value of r. It is currently considered that this state is most likely $5/2^-$.

It has been reported that 3.04 Mev state has the width of about 300 Kev[3)4]. Bockelman *et al.*[4] have deduced that this state has $J \leq 3/2$. No angular distribution of the nuclear reaction involving this state has been observed yet.

The 1.75 Mev state has been the subject of most investigations in which the momentum spectra were observed. It appears quite weakly and shows an anomalous spectral shape. It has been suggested that this is not a true level but an onset of a three-body breakup $Be^9(p,np')Be^8$ with a final state interaction between the neutron and Be^8 [3)4)5)6]. However, Miller[14] has pointed out that the large size of the S-wave scattering length (2×10^{-12} cm) required to explain the experiment implies the existence of a S-state in Be^9 near the neutron threshold. Thus the state seems to exist and be $1/2^+$. However, even in this model the assignment of the positive parity is not necessarily unique[15].

Theoretical studies of the Be^9 nucleus are rather ample. The intermediate coupling shell model[16] predicts that the lowest excited states are a pair of closely spaced states of $5/2^-$ and $1/2^-$ arising from $(1p)^5$ configuration. The order of these states depends on the choice of the intermediate coupling parameter. Since the 2.43 Mev state is most likely $5/2^-$, the 3.04 Mev state must be $1/2^-$ if the 1.75 Mev state is really positive parity. If the 1.75 Mev state is $1/2^-$, the 3.04 Mev state must be positive parity.

The alpha-particle model has been also applied to the Be^9 nucleus[17]. The most of the low lying states in Be^9 have been well described by this model. It has been also shown that the states belonging to the same rotational band as the ground state can be easily excited by inelastic collisions. The (α,α') data have been explained by this argument. Pinkston[15] has shown that such a sort of selection rule can be explained as well on the basis of the intermediate coupling shell model.

Recently an attempt has been made to explain several anomalies of the low lying states of the mirror pair of Be^9 and B^9 on the basis of the two-body cluster model, in which the clusters of the form of nucleon + Be^8 (ground 0^+, or 2.9 Mev 2^+) were assumed[6)18]. The spectral shape of the 1.75 Mev state has been well explained by this model. Whereas the 3.04 Mev state has been assigned to be $1/2^+$ or $5/2^+$.

Unfortunately, available experimental data are too little to examine closely the predictions of these theories. Especially, it seems necessary to investigate the angular distributions of the inelastic scattering leading to the states other than the 2.43 Mev state, and the cross sections for the excitation of these states. It is also of interest to see the energy dependence of the angular distributions from the standpoint of the reaction mechanism, since it has been known that the angular distributions of the proton inelastic scatterings from light nuclei show rather strong energy dependence at energies below 10 Mev[11)19)].

The present experiments were carried out with the following aims:

(1) to study the energy dependence of the angular distributions of the inelastic scattering proceeding to the 2.43 Mev state;

(2) to observe the angular distributions of the inelastic scattering proceeding to the 3.04 Mev state at several energies, and to obtain the cross-sections for the excitation of this state;

(3) to examine whether the 1.75 Mev state can be seen at any angles, and hence to examine the angular distributions and the cross-sections for the formation of this state;

(4) to search for the evidence of the excitation of the 4.74 Mev state as far as energetically possible.

During the measurements, the angular distributions of the elastic scattering were also measured to examine whether there is any irregular energy dependence or not in the energy region of the present experiment.

APPARATUS

The external proton beam of the 105 cm Kyoto University Cyclotron[20)] was used. Descriptions of the beam focussing system and of the 52 cm scattering chamber in which the measurements were carried out have been given in detail elsewhere[20)21)]. Since the general experimental procedures concerning the measurement of the beam energy, the integration of the beam current, the reduction of the beam energy, and the mounting of the detector on the turn table are the same as described by Kimura *et al.*[21)] and Kokame[22)], these will be touched here only briefly. The beam energy was determined by measuring the Bragg curve for the proton beam drawn out of the Faraday cup. The range-energy relation of Bichsel[23)] and the relation between the Bragg curve and the mean rage given by Mather and Segrè[24)] were used for this purpose. The beam current from the Faraday cup was integrated with a beam integrator of 100 % feedback type[25)]. The beam energy was reduced by inserting stacked aluminium foils of varying thickness into the incident beam.

The detector used was a scintillation counter with a thin CsI (T1) crystal. Two defining slits with rectangular apertures of $1.6 \times 7\ mm^2$ and $1 \times 5\ mm^2$ were prepared and the solid angle of each slit is 6.17×10^{-4} and 2.63×10^{-4} steradian. The larger slit was used in the usual cross section measurements and the smaller one was used with the absorber wheel described below. Electronics were conventional and pulses from the detector were amplified and fed into a RIDL model 3300 100-channel pulse height analyzer.

In order to separate the deuteron groups arising from the (p,d) reactions on tberyllium from the proton groups, a remotely controlled absorber wheel,* which permitted insertion of aluminium absorbers of variouss thickness, was provided between the defining slit and the counter window. A thin proportional counter of 1.5 cm in length was also used when the dE/dx of the scattered particles was measured. The counter pressure was 40 cm Hg$(A+CO_2\ (5\%))$.

The beam monitoring counter was also a scintillation counter with a thin crystal and was mounted externally to the scattering chamber at an angle of 90° to the incident beam.

EXPERIMENTAL PROCEDURE

The targets used were self-supporting beryllium foils of 3.38 mg/cm^2 and 2.46 mg/cm^2 in thickness. The target was mounted in the scattering chamber at an angle of 45° to the direction of the incident beam. These targets are fairly thick for the proton energies of the present experiment. The energy loss of the incident protons in each target is about 240 Kev and 160 Kev at 7.3 Mev, and about 280 Kev and 200 Kev at 6.1 Mev when the target is placed at an angle of 45° to the beam. The thickness of the target was rather favourable to distinguish the scattered protons from the deuterons and alpha-particles from the $Be^9(p,d)Be^8$ and $Be^9(p,\alpha)Li^6$ reactions.

The measurements of the angular distributions were made at the proton energies of 7.3, 6.9, 6.45 and 6.1 Mev. Henceforth, the energy value of the incident protons refers to the value in the laboratory frame at the median layer of the target foil.

Typical pulse height spectra obtained at several angles with 7.3 Mev protons are shown in Fig. 1. As shown in the figures, in addition to the prominent proton groups corresponding to the elastic scattering and the inelastic scattering proceeding to the 2.43 Mev state in Be^9, the proton group corresponding to the 3.04 Mev state has been clearly observed with considerable intensity at all angles where measurements were performed. Although the intensity is very weak, a definite grouping or a bump which corresponds precisely to the 1.75 Mev excitation in Be^9 can also be recognized at all angles smaller than 120° in the laboratory system. At larger angles, this group cannot be identified due to the lowering of the resolution of the detector for backward scattering.

When the angular distribution of the elastic scattering group was observed, at forward angles the deuteron group from the $Be^9(p,d_0)Be^8$ reaction proceeding to the ground state of Be^8 falls on it. These two groups were separated by inserting aluminium absorber before the counter.

As is also seen from Fig. 1, the inelastic proton groups, which are the main objects of the present experiment, are superposed upon the background continuum which is rising gradually as the energy decreases. Careful subtraction of the background is particularly required to obtain the reliable results concerning the 3.04 Mev state**.

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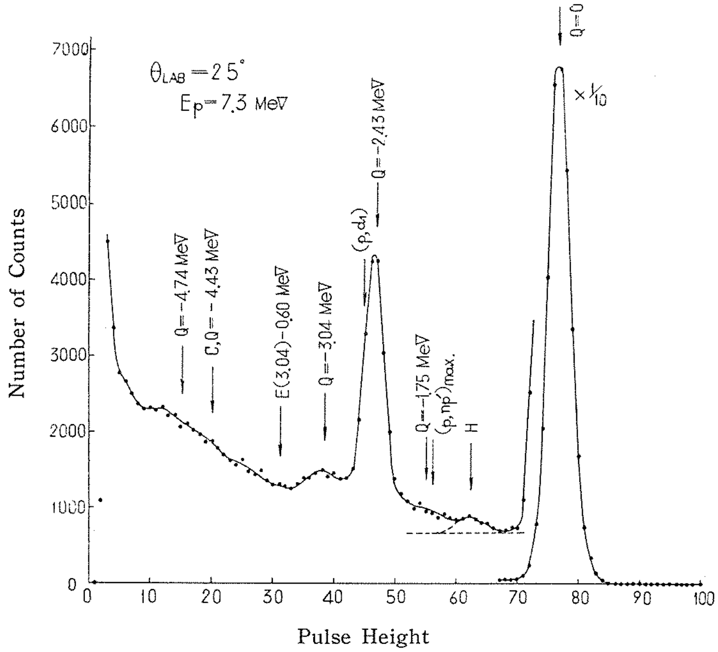
** In the works at heigher energies[9][10], the range analysis of the scattered particles were carried out instead of the pulse height analysis, so that the intense deuteron group from $Be^9\ (p,d_0)\ Be^8$ leading to the ground state of Be^8 were superposed on the proton group corresponding to the 3.04 Mev state.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×1/10
Q=-2.43 MeV
(p,d₁)
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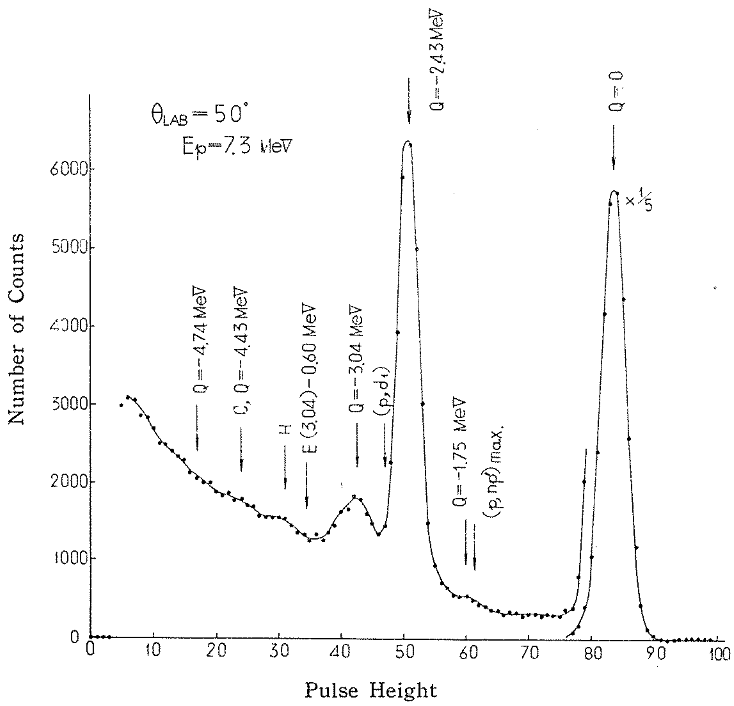
C,Q=-4.43 MeV
E(3.04)-0.60 MeV
Q=-3.04 MeV
Q=-1.75 MeV
(p,np')max.
H
Number of Counts
Pulse Height

Fig. 1 (a).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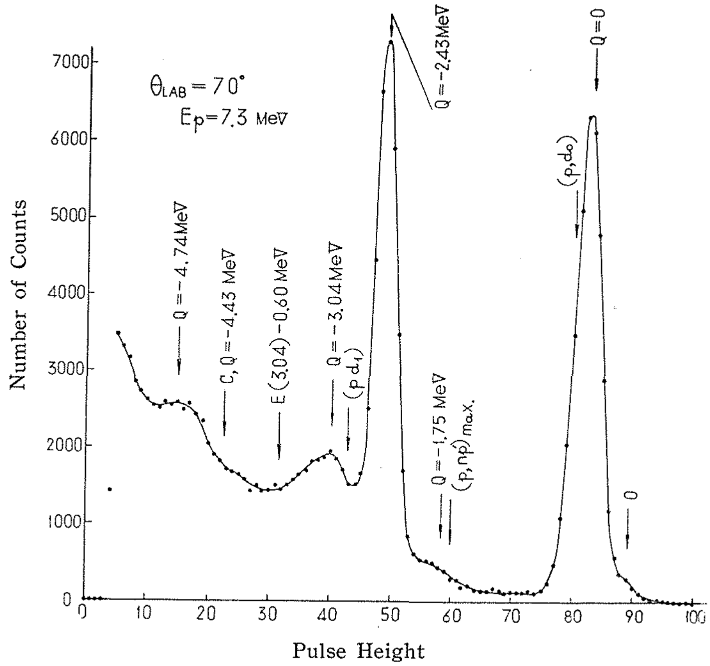
Q=0
×1/5
Q=-4.74 MeV
C, Q=-4.43 MeV
H
E (3.04)-0.60 MeV
Q=-3.04 MeV
(p,d₁)
Q=-1.75 MeV
(p,np')max.
Number of Counts
Pulse Height

Fig. 1 (b).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Number of Counts
Pulse Height
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C, Q=-4.43 MeV
E(3.04)-0.60 MeV
Q=-3.04MeV
(p,d1)
Q=-2.43MeV
Q=-1.75 MeV
(p,np)max.
(p,d0)
Q=0
0

Fig. 1 (c).

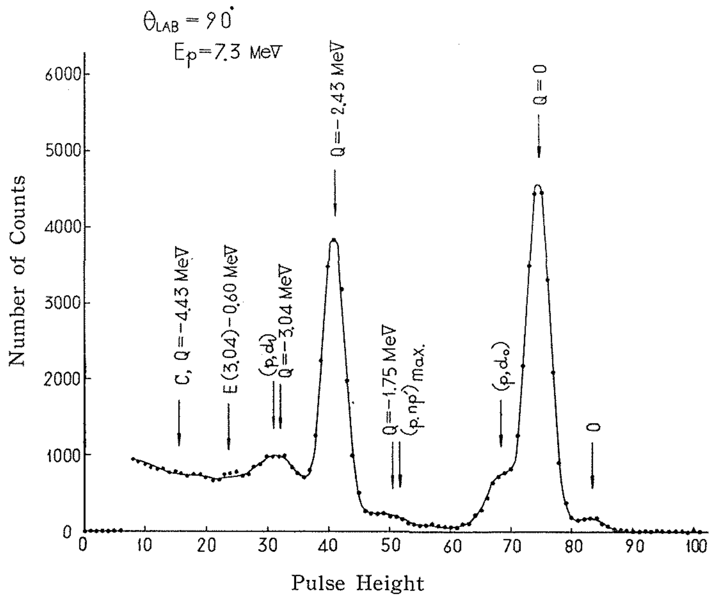

θ_LAB = 90°
Ep=7.3 MeV
Number of Counts
Pulse Height
C, Q=-4.43 MeV
E(3.04)-0.60 MeV
(p,d1)
Q=-3.04 MeV
Q=-2.43 MeV
Q=-1.75 MeV
(p,np)max.
(p,d0)
Q=0
0

Fig. 1 (d).

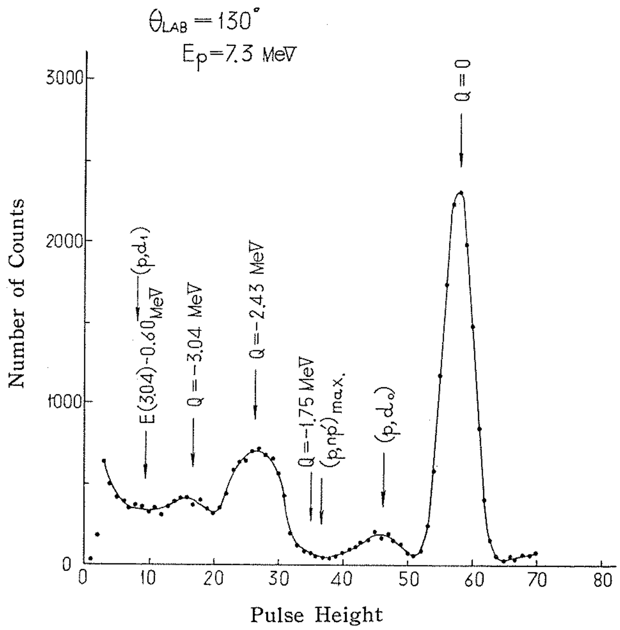


Fig. 1 (e).

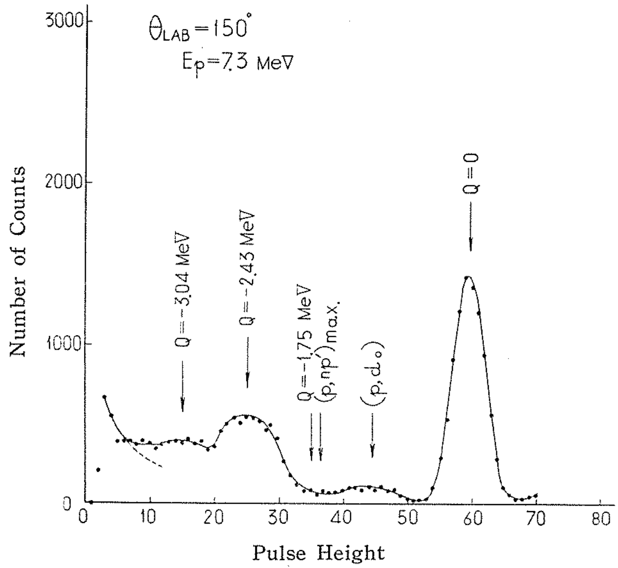


Fig. 1 (f).

Fig. 1. Typical pulse height spectra of the proton bombardment of beryllium obtained at laboratory angles of 25°, 50°, 70°, 90°, 130° and 150° with 7.3 Mev protons. (a), (b), (c) and (d) were obtained with the thin target and (e) and (f) were obtained with the thick target.

It is considered that this background continuum has four origins:

(1) The tail of the elastic proton group exists always. This effect, however, is very small.

(2) Alpha-particles arising from the $Be^9(p,\alpha)Li^6$ reaction will also fall on this region. These alpha-particles have the comparable energies to the elastically scattered protons. However, the fact that the response of the CsI(Tl) crystal to alpha-particles[26] is just one half of that to protons, and the fact that the target is very thick for these alpha-particles, will make the alpha-group spread out widely and merge into the continuum. The yield of this reaction is not yet known.

(3) The proton continuum arising from the three-body breakup $Be^9(p,np')Be^8$ will also contribute to the continuum. It is shown from the kinematics that the continuum from the the three-body breakup starts rising at the maximum available proton energy in the reaction which is slightly larger than the 1.75 Mev group and is indicated as $(p,np')_{max}$ in Fig. 1. Indeed, the observed continua begin to rise near this point.

(4) The deuteron group arising from $Be^9(p,d_1)Be^{8*}$ proceeding to the first excited state in Be^8 at 2.90 Mev, also falls on this energy region. Owing to the fact that the final excited state in Be^8 has a width as large as $1\sim2$ Mev[27] and the fact that the energy loss of the deuterons in the target easily amounts to about 1 Mev, the deuteron group will also spread out very widely. Therefore, it seems hardly that these deuterons appear as a distinguishable group in the present experimental conditions. The position indicated as (p,d_1) in Fig. 1 corresponds to the reaction occurring at the median layer of the target and leaving Be^8 at an excitation of exactly 2.90 Mev, and the energy loss in the target is of course taken into account.

At any rate, the latter two origins seem to account for the major portion of the background continuum. However, it is impossible to find out the exact shape of the background continuum at each angle, since at present there exist no available data of the differential cross section for the $Be^9(p,d_1)Be^{8*}$ reaction and of the the yield and the spectral shape of the protons from the three-body breakup. Only the existence of these reactions has been reported in literature[4][28].

Accordingly, in the present experiment, it was assumed for simplicity that the shape of the background could be approximated by a straight line, and then the validity of the assumption was examined experimentally.

In order to examine whether deuterons from the $Be^9(p,d_1)Be^{8*}$ reaction are really mixed in the pulse spectrum, a thin proportional counter previously mentioned was set before the main counter and the dE/dx of the scattered particles was measured. The pulses from the proportional counter were fed to the 100-channel pulse height analyzer, which was gated by the pulses from the main counter selected by a single channel pulse height analyzer so as to comprise the section of the pulse spectrum corresponding to the 3.04 Mev group or the 2.43 Mev group. In Fig. 2, the dE/dx curves obtained are shown. The figures show that indeed the mixing of deuterons amounts to about 40% at 40° as well as at 75°. The fact that nearly equal number of deuterons are contained in the 2.43 Mev section at 40°, indicates this deuteron group is very broad as was expected above.

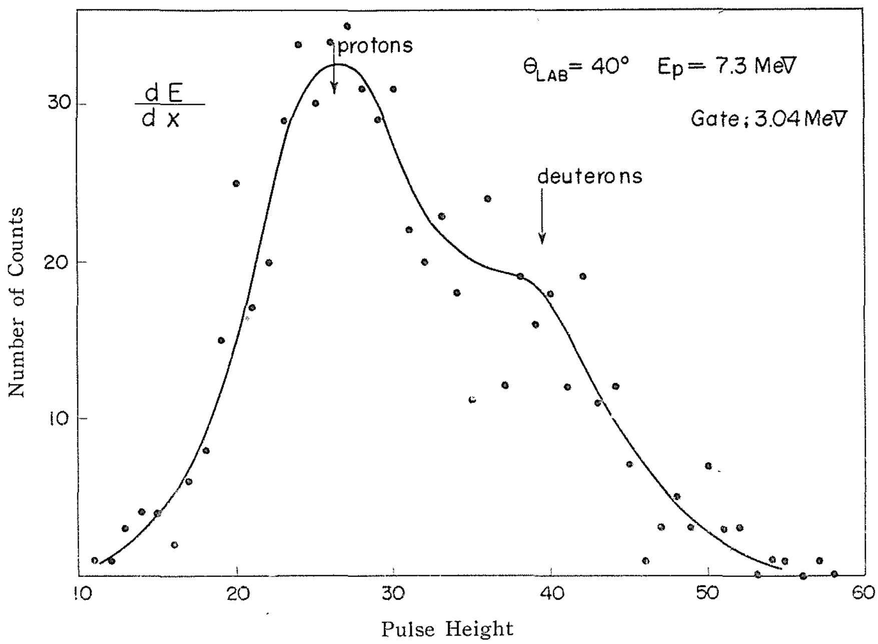

dE/dx
protons
θ_LAB = 40°
Ep = 7.3 MeV
Gate; 3.04 MeV
deuterons
Number of Counts
Pulse Height
10
20
30
40
50
60

Fig. 2 (a).

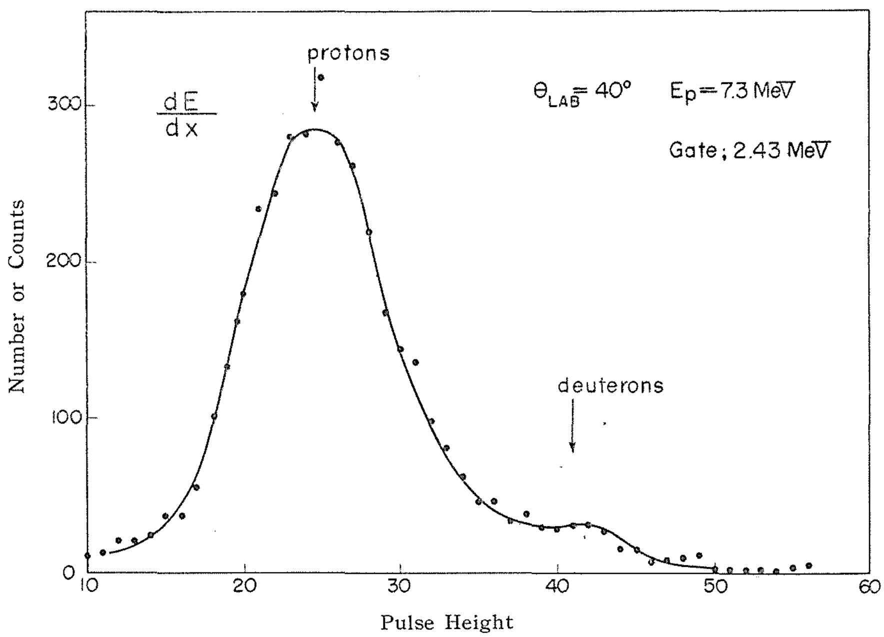

dE/dx
protons
θ_LAB = 40°
Ep = 7.3 MeV
Gate; 2.43 MeV
deuterons
Number or Counts
Pulse Height
0
100
200
300
10
20
30
40
50
60

Fig. 2 (b).

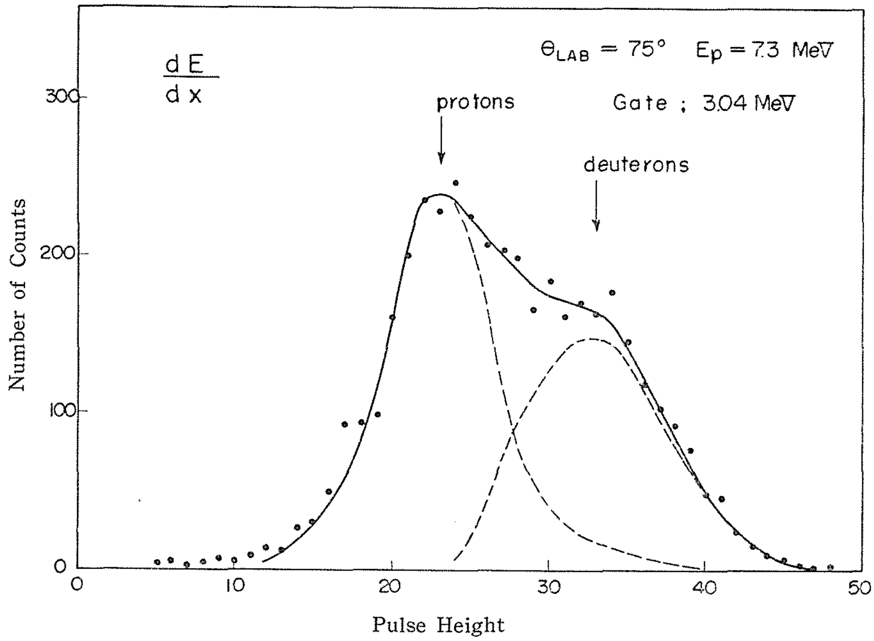


Fig. 2 (c).

Fig. 2. The dE/dx spectra for the scattered particles comprised in the section of the pulse spectrum corresponding to the 3.04 Mev group and the 2.43 Mev group.

Next, the relative pulse height of the deuteron group was shifted by inserting aluminium foils before the counter. The simplest method of background subtraction, the straight line, was applied to both cases with and without the absorbers, and the effect of the shift of the deuteron group was examined at the proton energy of 7.3 Mev. The thickness of the absorbers was so chosen that the median value (p, d_1) indicated in the figure was shifted to the value nearly equal to zero at each angle. A typical pulse height spectrum obtained with the absorber is shown in Fig. 3. In the figure the arrows are indicating the positions to which the respective groups are shifted by inserting the absorber foils.

An example of the background subtraction is shown in Fig. 4. For simplicity's sake, the intersection of the horizontal background level and $(p, np')_{max}$ was chosen as the point B shown in the figure. It was somewhat a delicate subject to choose the point A, since the yield of the 3.04 Mev group was very sensitive to this choice. It was necessary to establish a fixed rule of choosing the point A. After many trials at various angles, the intersection of the smooth curve drawn through the measured points and a line 0.60 Mev below the energy of the 3.04 Mev group was determined as the point A. By choosing the points A and B in this way, in the subtracted spectrum (Fig. 4 (b)) the 3.04 Mev group takes a natural and smooth form resembling that of the elastic and 2.43 Mev groups. The half-maximum width of the 3.04 Mev group thus obtained is consistent with the width of 300 Kev obtained by magnetic spectrometrs.

The results for both cases with and without the absorbers obtained by applying

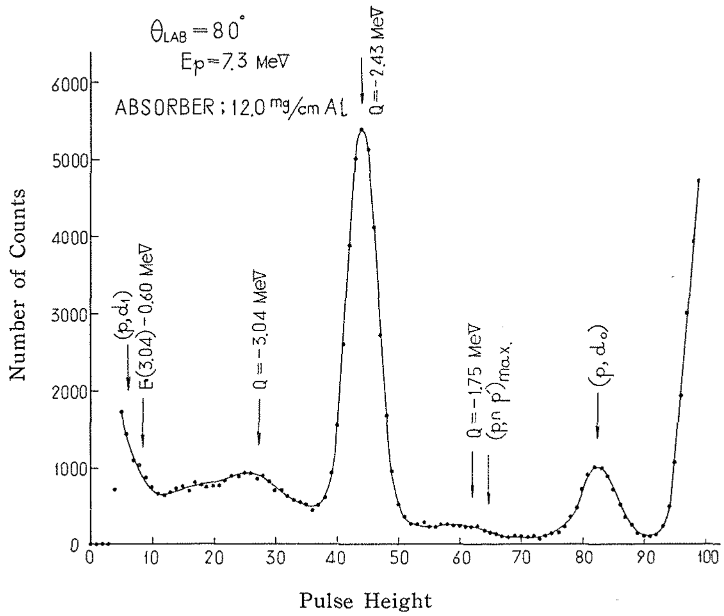


Fig. 3. Typical pulse height spectrum obtained with the absorber before the detector. The relative position of (p, d_1) is shifted markedly.

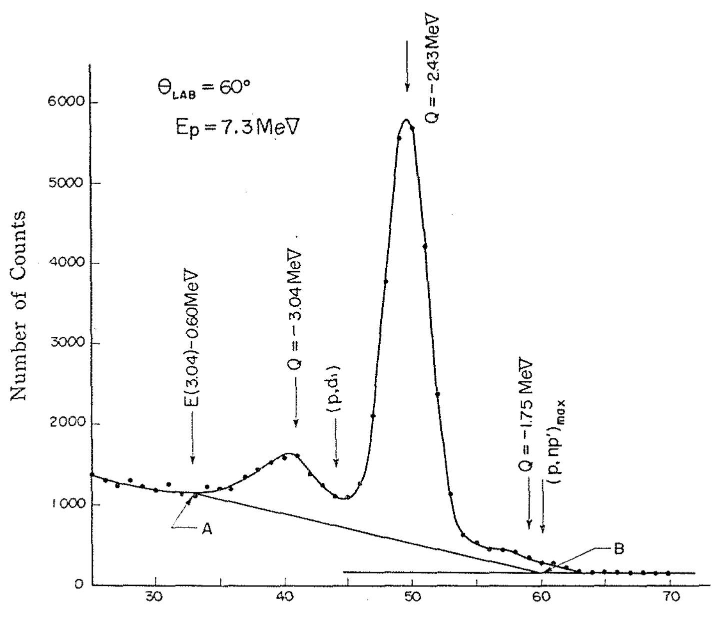
this rule is shown in Table 1, in which the relative yields normalized by the monitor counts are given. The statistical errors are 6 to 10% for the 3.04 Mev group and 1 to 2% for the 2.43 Mev group respectively. For the 3.04 Mev group, an additional uncertainty arising from the statistical fluctuations around the point A has considerable effect on the results.

Table 1 shows that only the background is markedly reduced by the insertion of the foils, whereas the sum of the inelastic groups remains completely unchanged. The variation of the sum of the inelastic groups is at most 5% and has not any statistical significance. While the decrease of the background by about 30% is significant with the uncertainty of about 10%. The relative variations between the 2.43 Mev and the 3.04 Mev groups, amounting to several percent, can well be explained by the statistical fluctuation and by the fact that the uncertainty in fixing the point A has much larger effect on the 3.04 Mev group than on the 2.43 Mev group.

The implications of Table 1 are: (a) The inelastic proton groups obtained in this way contain no deuteron contamination. (b) The deuteron group is actually very broad and has almost flat distribution so that the background subtraction by assuming a straight line yields the same result in both cases with and without the absorbers.

Thus it can be concluded that the above method of the background subtraction is a good approximation, so long as uncertainty of several percent is allowed for the 3.04 Mev group.

Since uncertainty accompanying a single determination of the yield of the 3.04 Mev group often came up to about 15%, measurements were repeated several



Eig. 4 (a).

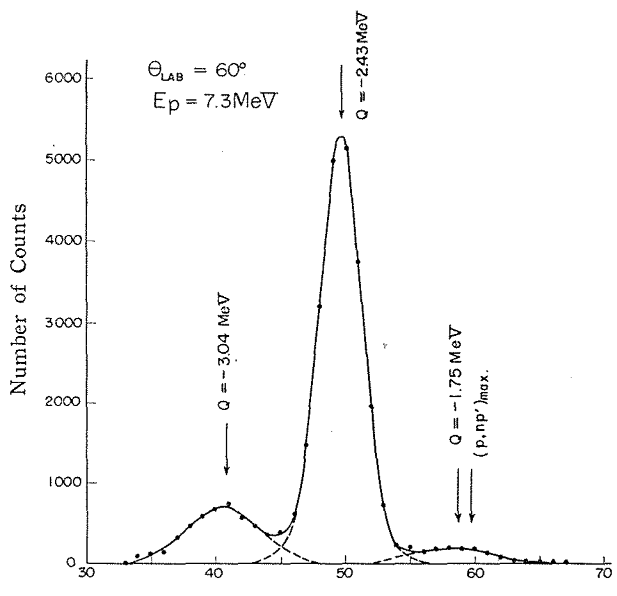


Fig. 4 (b).

Fig. 4. An example of the background subtraction assuming a straight line. The points A and B shown in (a) are discussed in the text. (b) shows the subtracted spectrum.

Table 1. The effect of the aluminium absorbers inserted before the counter.

θ_{LAB}	Absorber	3.04 Mev group	2.43 Mev group	1.75 Mev group	Sum of inelastic groups	Background
	no	726	3617		4343	5052
30°	yes	783	3496		4279	3428
		+7.9%	−3.3%		−1.5%	−32.2%
	no	608	3506	177	4291	3505
40°	yes	632	3380	180	4192	2624
		+4.0%	−3.6%	+1.7%	−2.3%	−25.1%
	no	502	2317	128	2947	1997
60°	yes	524	2180	108	2812	1270
		+4.4%	−5.9%	−16%	−4.6%	−36.4%
	no	509	1914	99	2522	1406
70°	yes	512	1962	72	2546	1030
		+0.6%	+2.5%	−26.8%	+1.0%	−26.8%
	no	387	1703	84	2174	1281
80°	yes	387	1640	55	2082	946
		0%	−3.7%	−19%	−4.2%	−26.2%
	no	364	1558	59	1981	1103
90°	yes	332	1510	58	1902	862
		−8.8%	−3.1%	−1.7%	−4.1%	−21.8%

times at the incident energies of 7.3 Mev and 6.9 Mev. The reproducibility of energy in the different runs was within 50 Kev, which was allowable as compared to the target thickness.

The targets used contained small amount of oxygen and hydrogen contaminations. The oxygen contamination is distinguished at the backward angles, but at the forward angles it must be subtracted from the elastic group. The hydrogen contamination appears at the forward angles and interferes the measurement of the 1.75 Mev group at 20°∼30°, the 2.43 Mev group at 40°, and the 3.04 Mev group at 50° in the laboratory system. The subtraction of the oxygen contamination was made by using the data obtained by Sempert *et al*[29]. and Kobayashi[30], but the correction required was only about one percent. The subtraction of the hydrogen was made by the data obtained by Rouvina[31]. The hydrogen contamination has significant effect only for the 1.75 Mev group at angles smaller than 30°. The carbon contamination may also exists. However, it is not distinguishable from oxygen at the backward angles, and the inelastic group from $C^{12}(p, p')C^{12*}$ leading to the 4.43 Mev state in C^{12} is also not recognized at angles where it may well appear if it really exists.

RESULTS AND DISCUSSIONS

(A) Elastic Scattering

The angular distributions of the elastic scattering measured at 7.3, 6.9, 6.45

and 6.1 Mev proton energies are shown in Fig. 5. Although a slight irregular dependence on the energy can be seen at backward angles, the general features of the patterns well accord with the results obtained at the higher energies[9)10)] and the lower energies of 4.85 and 5.49Mev[32)]. The shift of the positions of the first minimum and the second maximum with the energy also accords with the results at the higher and the lower energies. It seems that there is no anomalous energy dependence in the energy region between 5 and 12 Mev.

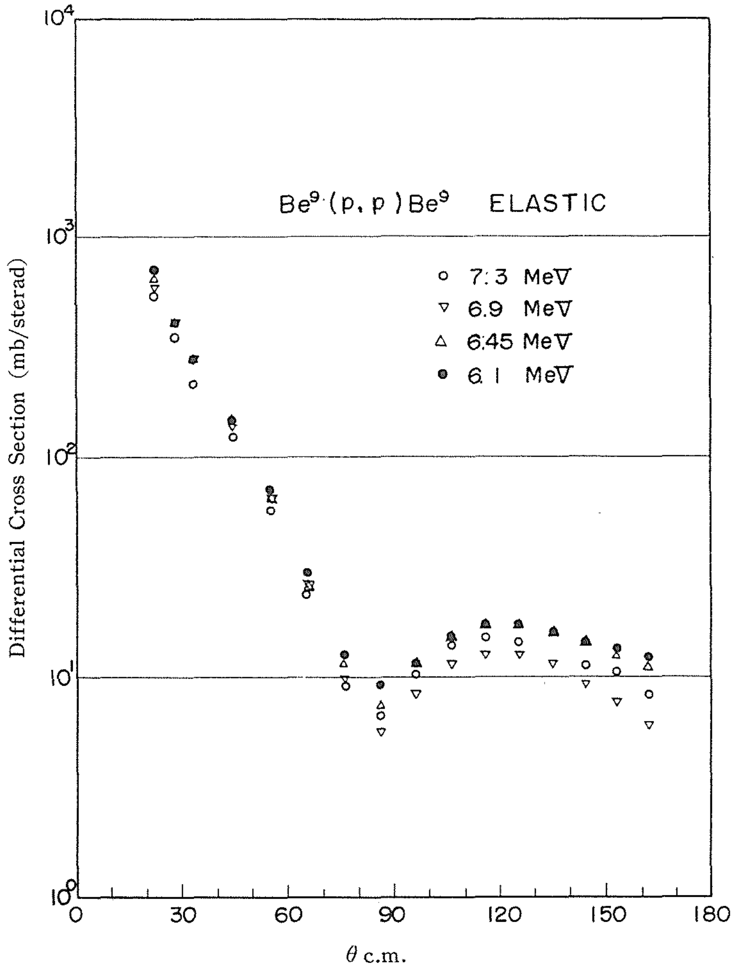
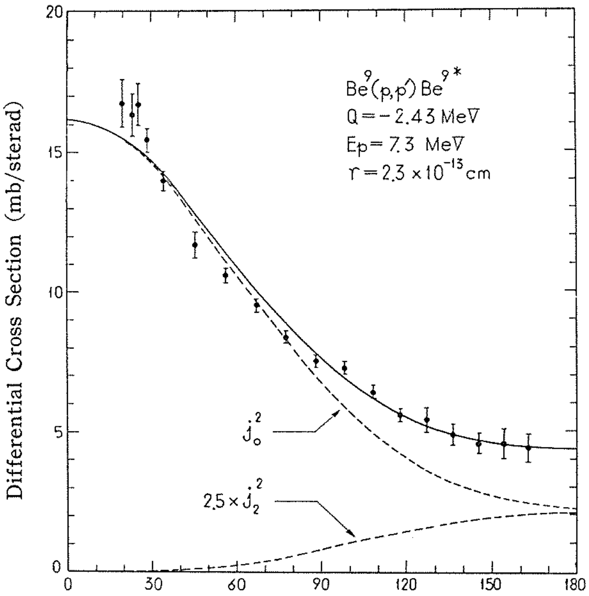


Fig. 5. The angular distributions of the elastic scattering of protons by Be^9 at 7.3～6.1 Mev proton energies.

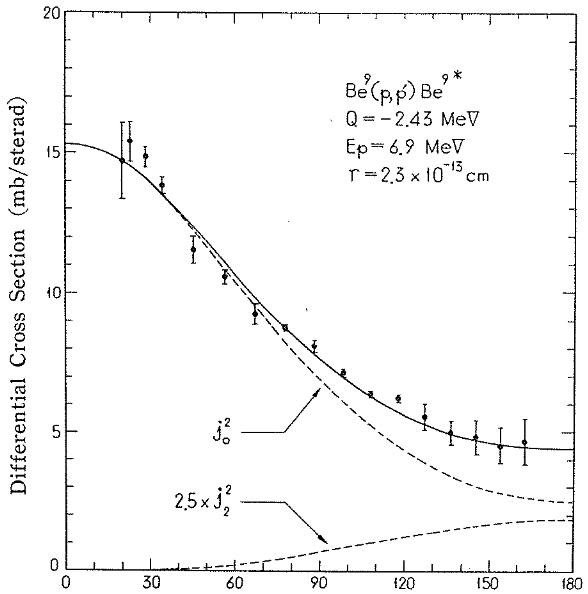
(B) Inelastic Scattering Proceeding to the 2.43 Mev State

Fig. 6 shows the angular distributions of the inelastic scattering proceeding to the 2.43 Mev state measured at 7.3, 6.9, 6.45 and 6.1 Mev proton energies. The error bars shown in the figures include the uncertainties due to the background subtraction. The patterns show distinct forward peaking, and gradual but definite energy dependence in which cross sections at forward angles decrease as the energy



θ c.m.

Fig. 6 (a).



θ c.m.

Fig. 6 (b).

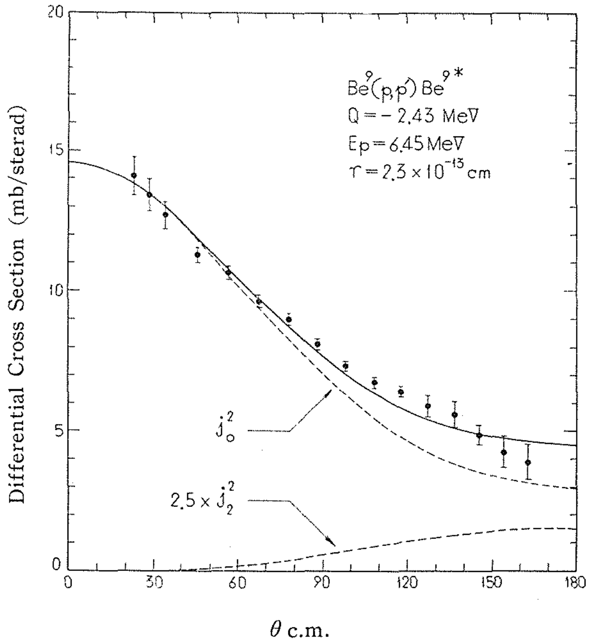


Fig. 6 (c).

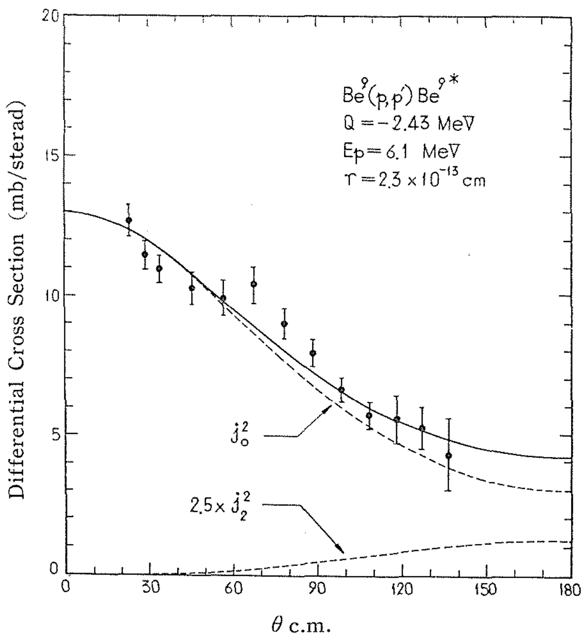


Fig. 6 (d).

Fig. 6 The angular distributions of the inelastic scattering of protons proceeding to the 2.43 Mev state in Be^9 at 7.3, 6.9, 6.45 and 6.1 Mev proton energies. The solid curves and the dashed curves are discussed in the text.

decreases. In Fig. 7, the present result at 7.3 Mev is compared with that of the other authors[9)~11)]. The result of Seward has been normalyzed at $\theta_{c.m.}=90°$. General features of the patterns are much alike one another, but the results of Rasmussen and Seward give lower cross sections at the forward angles. This is probably not a true energy dependence, but of only apparent nature due ot the method of background subtraction, since the present experiments cover the energy of the Seward's experiment. Also the good agreement between the present results and that of Summers-Gill should be accepted in the same sense. Therefore, it seems that there is no sharp energy dependence in the energy region between 6 and 12 Mev, but that a slowly varying dependence does exist as shown in Fig. 6. The result of Summers-Gill has been compared with the direct interaction theory of Austern, Butler and McManus[18)]. To obtain a good fit, it was necessary to take $l=0$ and $r=1.8\times10^{-13}$cm where l is the change of the orbital angular momentum and r is the interaction radius. Seward also took $l=0$ and $r=2.0\times10^{-13}$cm to compare his results with the theory. These values for r were considered too small as measures of the interaction radius.

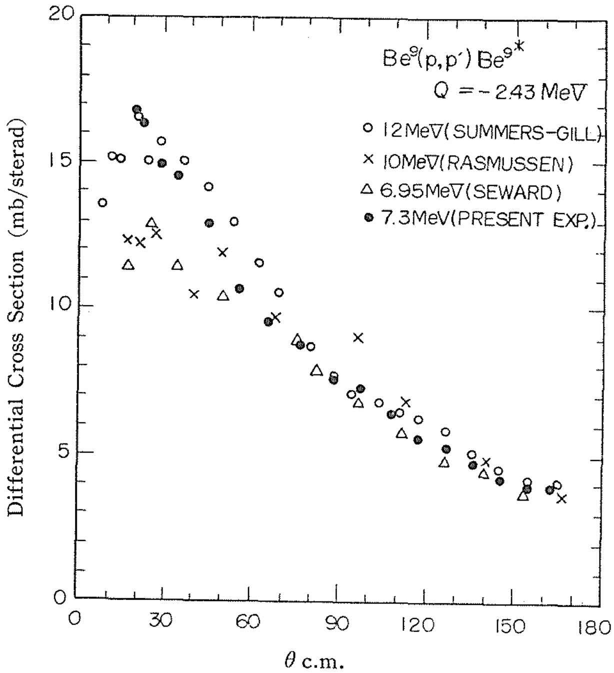


Fig. 7. The angular distributions of the inelastic scattering of protons proceeding to the 2.43 Mev state in Be^9. The present result at 7.3 Mev is compared with the results of other authors.

In the alpha-particle model of Be^9, the cross section for the inelastic scattering has been calculated by the direct interaction theory with plane wave approximation[17)]. The theory predicts a differential cross section of the Austern, Butler and McManus type,

$$\sigma(\theta) \backsim \sum_l B_l[j_l(q\xi)]^2$$

for the excitation by collision with the Be^8 core, where j_l is the spherical Bessel function, q is the momentum transfer, and ξ is the one half of the equilibrium distance between the two alpha-particles and chosen as $\xi = 2.3 \times 10^{-13}$cm.

It is of interest to note that this value of ξ is close to the value of r chosen by Summers-Gill and Seward. The present results were tentatively compared with this type of formula taking $\xi = 2.3 \times 10^{-13}$cm and $l=0$ and $l=2$. In Fig. 6 the dashed curves represent $[j_0(q\xi)]^2$ and $[j_2(q\xi)]^2$, and the solid curves represent $[j_0(q\xi)]^2 + 2.5[j_2(q\xi)]^2$ where the factor 2.5 was chosen appropriately to obtain good fits. The agreement is fairly good at all energies as shown in the figures.

For the inelastic scattering of portons in the present energy region, there are several complications[33], which were ignored in the theoretical calculations, but might have considerable effects on the cross section such as the distortion of the incident and final wave functions, the proton exchange effect, and the spin-dependent interactions. Indeed, assuming the 2.43 Mev state is $5/2^-$, spin-flip may be considered to take $l=0$. Therefore, the agreement shown in Fig. 6 cannot be simply interpreted as a proof of the alpha-particle model. However, it should be noted that equally good fits are obtaind with the same values of parameters for the results obtained at the energies from 6.1 to 7.3 Mev.

The integrated cross sections calculated from the solid curves in Fig. 6 are 106 mb for 7.3 Mev, 105 mb for 6.9 Mev, 104 mb for 6.45 Mev and 95 mb for 6.1 Mev respectively.

(C) Inelastic Scattering proceeding to the 3.04 Mev State

Fig. 8 shows the reproducibility of the results of the inelastic scattering proceeding to the 3.04 Mev state obtained in the different runs at proton energies 7.3 and 6.9 Mev. The errors attached to the representative points are the statistical errors. The data obtained with the thick or thin target are represented as points ● or × respectively. The angular distributions obtained by averaging these data are shown in Fig. 9 (a) and (b). The errors in these figures are including the uncertainties due to the background subtraction. In Fig. 9 (c) the angular distribution for 6.45 Mev protons are shown. In this case the measurement was not repeated and the statistical errors are multiplied by appropriate factors to include the errors due to the background subtraction.

The general features of the angular distributions show forward peaking and little energy dependence. The bumps observed near $\theta_{cm} = 70°$ at 6.9 Mev and 6.45 Mev proton energies may be probably of apparent nature. The median energy of the deuteron group (p, d_1) falls near the 3.04 Mev proton group around $\theta_{cm} = 70°$, so that the true background is expected to be slightly convex upward near this angle. This fact accounts for the tendency of causing too high values near 70° when the straight line approximation is applied. Although the validity of the method of background subtraction was verified at 7.3 Mev, if the choice of the point A discussed in the preceding paragraph was inadequate for lower energies the observed bumps might well be explained by this effect. However, the possibility that the bumps really exist, of bourse, cannot be ruled out.

The results obtained at 7.3 Mev and 6.9 Mev were compared with the formula

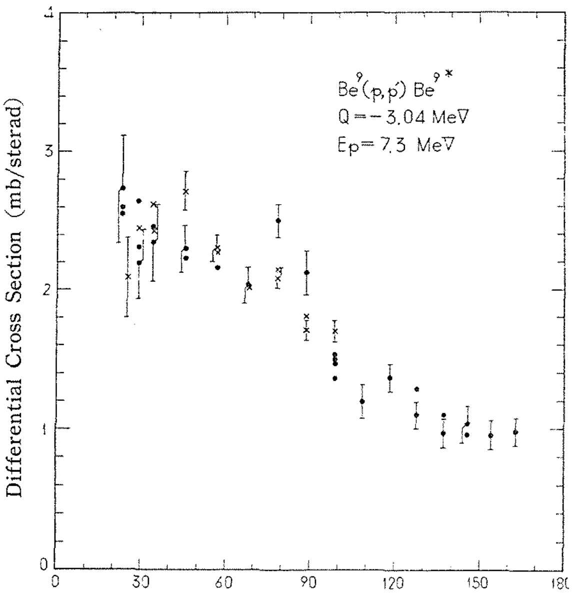


Fig. 8 (a).

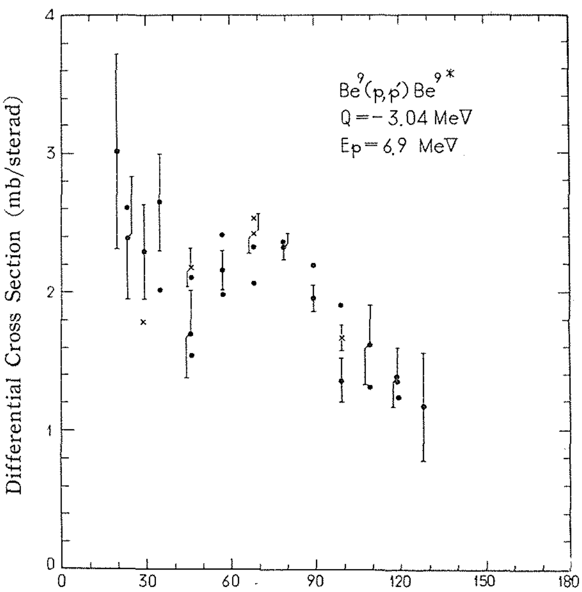


Fig. 8 (b).

Fig. 8. The reproducibility of the differential cross section measurements of the inelastic scattering of protons proceeding to the 3.04 Mev state in Be^9 at 7.3 and 6.9 Mev proton energies. The data obtained with the thick or thin target are represented as points ● or × respectively.

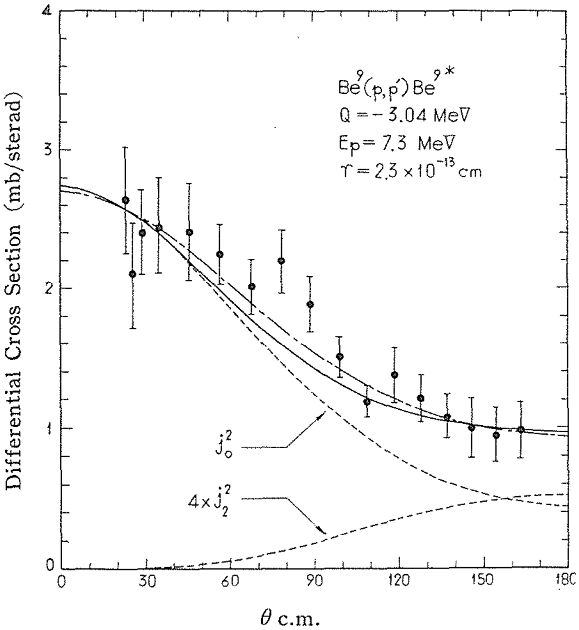

Be⁹(p,p′)Be⁹*
Q = − 3.04 MeV
Ep = 7.3 MeV
r = 2.3 × 10⁻¹³ cm
j_0^2
$4 \times j_2^2$
Differential Cross Section (mb/sterad)
θ c.m.

Fig. 9 (a).

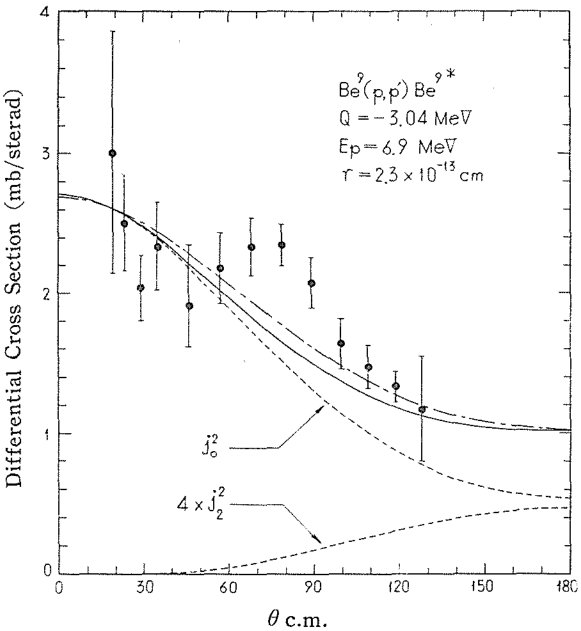

Be⁹(p,p′)Be⁹*
Q = − 3.04 MeV
Ep = 6.9 MeV
r = 2.3 × 10⁻¹³ cm
j_0^2
$4 \times j_2^2$
Differential Cross Section (mb/sterad)
θ c.m.

Fig. 9 (b).

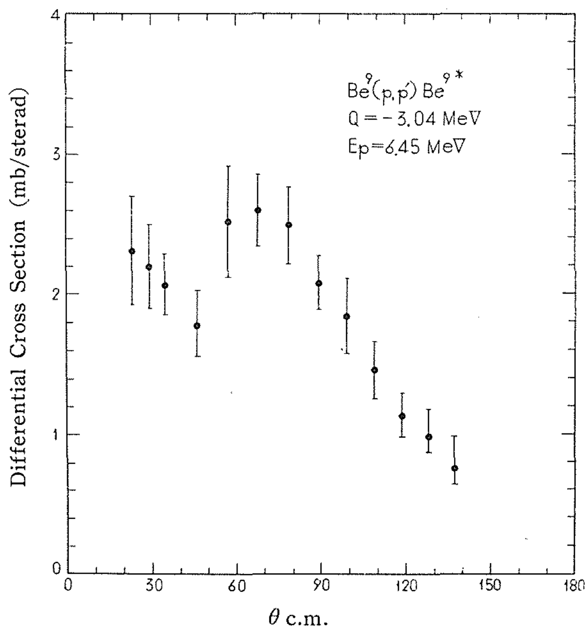


Fig. 9 (c).

Fig. 9. The angular distributions of the inelastic scattering of protons proceeding to the 3.04 Mev state in Be^9 at 7.3, 6.9 and 6.45 Mev proton energies. The curves in the figures are discussed in the text.

of the Austern, Butler and McManus type, taking likewise $r=2.3\times10^{-13}$cm and $l=0$ and $l=2$. In this case a combination of a single l value and an isotropic contribution from the compound nucleus formation was also examined. In Fig. 9 the dashed curves represent $[j_0(qr)]^2$ and $[j_2(qr)]^2$, the solid curves represent $[j_0(qr)]^2+4[j_2(qr)^2]$ where the factor 4 was appropriately chosen to fit to the data. The dash and dotted curves represent the combination of $l=0$ and an isotropic part of 0.6 mb/sterad. The latter curves show somewhat better fits. The implication of the agreement between the experimental data and the above formula with $r=2.3\times10^{-13}$cm is not immediately clear in the present stage. It is noteworthy as well that fairly good fits are obtined with the same values of parameters for both cases at 7.3 Mev and 6.9 Mev.

The present results are compatible with the negative parity of the 3.04 Mev state as predicted by the theories[16)17)], provided that the plane wave approximation is permissible for Be^9 in the energy region of the present experiment. However, the recent experiments on the $Be^9(\gamma, n)Be^8$ reaction[34)] seems to prefer the positive parity for this sate. If this state has spin 1/2, the term of $l=0$ implies the occurrence of spin-flip also in this case.

The integrated cross section proceeding to this state is about 22 mb at 7.3 Mev. The values at 6.9 and 6.45 Mev are almost the same as that of 7.3 Mev within the limit of experimental uncertainties.

(D) Inelastic Scattering proceeding to the 1.75 Mev State

Fig. 10 shows the angular distributions of the inelastic scattering proceeding

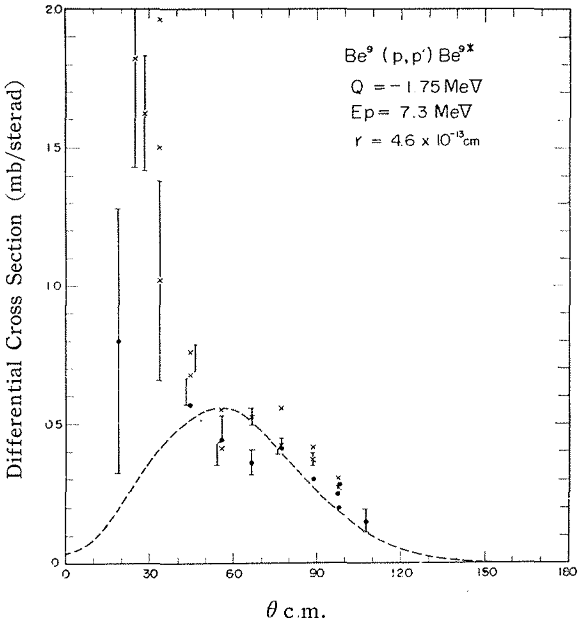


Fig. 10 (a).

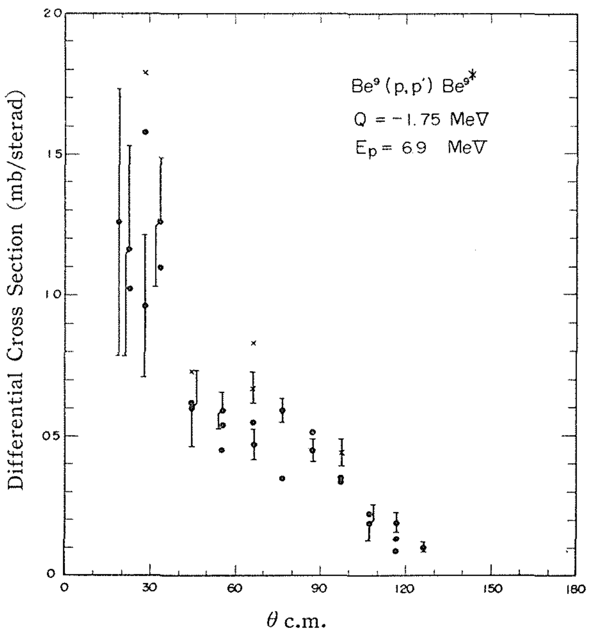


Fig. 10 (b).

Fig. 10. The angular distributions of the inelastic scattering of protons proceeding to the 1.75 Mev state in Be^9 at 7.3 and 6.9 Mev proton energies. The data obtained with the thick or thin target are represented as points ● or × respectively. The dashed curve is discussed in the text.

to the 1.75 Mev state obtained in the repeated measurements at 7.3 and 6.9 Mev proton energies. The data obtained with thick or thin target are represented as points ● or × respectively. The errors attached to the representative points are the statistical errors.

It should be noted here that judging from the method of the background subtraction the present results do not necessarily represent the differential cross sections for the excitation of the 1.75 Mev state in the strict meaning, but rather represent the peak corresponding to the difference of the both cases with and without the final state interaction in terms of the three-body breakup model. As is seen in Fig. 1 (a), the subtraction of the hydrogen contamination was carried out at the angles smaller than 30°. Because the estimation of the hydrogen content is accompanied with considerable ambiguity, the errors may be much larger if this ambiguity is taken into account. It is, therefore, somewhat doubtful whether the prominent forward peaking reallly exists or not. The fact that Summers-Gill has not found any trace of this peak with 12 Mev protons at the angle of 21° (Fig. 15 in Summers-Gill's paper), increases this doubt.

General features of the patterns obtained at 7.3 and 6.9 Mev are also very much alike each other. Although the data obtained at 6.45 Mev are not illustrated in the figure, it can be also recognized that general features persist at this energy. As shown in Fig. 1 (e) and (f), the group corresponding to this state is not distinguishable at backward angles. The upper limit of the differential cross section of this group at the backward angles may be estimated less than 0.1mb/sterad from the comparison with the yield of the 2.43 Mev group. Accordingly, the angular distribution for the excitation of this state is certainly asymmetric with respect to 90° showing that this process does not proceed through a compound nucleus of the usual sense, although it is not clear whether the distribution shows a marked forward peaking or has a maximum at 50°~60°. Since, at any rate, it is considered that this state is concerned with the single particle excitation of the loosely bound extra neutron in Be^9, the present results were compared with the theory of Austern, Butler and McManus taking $r=4.6\times10^{-13}$ cm this time. In Fig. 10 the dashed curve shows $[j_1(qr)]^2$ with $r=4.6\times10^{-13}$ cm. If the prominent peaking observed at forward angles is subject to very large errors, the agreement is satisfactory and this is compatible with the positive parity of the 1.75 Mev state. The integrated cross section for the formation of this state calculated from $[j_1(qr)]^2$ is about 3.5 mb and the upper limit is 5 mb, and the change with the energy is of course within the limit of errors.

(E) Inelastic Scattering proceeding to the 4.74 Mev State

It cannot be expected to observe clearly this state because of the low incident energy in the present experiment. In Fig. 1 the positions are indicated at which this group should appear. At 7.3 Mev proton energy this group was seen only at 60°, 70° and 80° (Fig. 1 (c)). Because of the large energy loss in the target and the presence of the background continuum, it is difficult to estimate the yield of this group. The differential cross section for the excitation of this state at 60°~80° seems to be of the same order of magnitude as the 3.04 Mev group considering the width of this state is very broad[8].

(F) Summary and Concluding Remarks

All angular distributions of the inelastic scattering proceeding to the 2.43, 3.04 and 1.75 Mev states show distinct forward peaking and change little with the incident proton energy. The most prominent group corresponding to the 2.43 Mev state shows slowly varying but definite energy dependence of the angular distribution. For the other states, experimental uncertainties cover the energy dependence if any.

The angular distributions corresponding to the 2.43 and 3.04 Mev states can be fitted by the simple direct interaction theory taking $r=2.3\times10^{-13}$cm, the postulation of the alpha-particle model, and $l=0$ and $l=2$, while that corresponding to the 1.75 Mev state is fitted fairly well by taking $r=4.6\times10^{-13}$cm and $l=1$. These results are consistent with the negative parity of the 3.04 Mev state and the positive parity of the 1.75 Mev state provided that the plane wave approximation is allowable for the present experimental conditions.

The integrated cross sections for the excitation of the 2.43, 3.04 and 1.75 Mev states are 106 mb, 22 mb and 5 mb respectively at 7.3 Mev. The excitation of the 4.74 Mev state is also discernible at 7.3 Mev proton energy.

Although the significance of the agreement between the observed data and the formula of the simple direct interaction theory is not directy obvious, the agreement does not seem to be a simple fortuitous occurrence. At any rate, it appears indubitable that some sort of direct interaction process plays an important role in the inelastic scattering of protons by Be^9 in the energy region 6.1 to 7.3 Mev and very likely in the region up to 12 Mev. The fact[11][32] that no distinguished resonance has been observed in the excitation function of the proton bombardment on Be^9 seems to make clear the characteristic features of the direct interaction in the inelastic scattering of protons.

It is in marked contrast with the case of the inelastic scattering of protons by the nearby nucleus B^{11} where remarkable energy dependence of the angular distribution has been observed in the same energy region as the present experiment[22], and also several resonance levels have been found in the excitation function[35]. It has been also reported that the energy dependence of the $Be^9(p,n)B^9$ reaction is much less than the $B^{11}(p, n)C^{11}$ reaction[36]. These facts awake our interest in the nature of the compound nucleus B^{10*}, the excitation of which is about 13 Mev for the proton energies of the present experiment.

The Be^9 nucleus is distinguishing in that the angular distributions of the inelastic scattering of protons of energies below 10 Mev show clearly the features of the direct interaction. More refined theoretical investigations which can account for the angular distributions and the cross sections for the excitation of each state as observed in the present experiment is desirable, together with further experimental studies in the more extended energy region of the incident protons.

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REFERENCES

(1) L. L. Lee and D. R. Inglis, *Phys. Rev.*, **99**, 96 (1955).
(2) C. R. Gossett, G. C. Phillips, J. P. Schiffer, and P. M. Windham, *Phys. Rev.*, **100**, 203 (1955).
(3) V. K. Rasmussen, D. W. Miller, M. B. Sampson, and U. C. Gupta, *Phys. Rev.*, **100**, 851 (1955).
(4) C. K. Bockelman, A. Leveque, and W. W. Buechner, *Phys. Rev.*, **104**, 456 (1956).
(5) R. W. Kavanagh and C. A. Barnes, *Phys. Rev.*, **112**, 503 (1958).
(6) R. R. Spencer, G. C. Phillips and T. E. Young, *Nuclear Phys.*, **21**, 310 (1960).
(7) C. D. Moak, W. M. Good, and W. E. Kunz, *Phys. Rev.*, **96**, 1363 (1954).
(8) C. D. Moak, A. Galonsky, R. L. Traughber, and C. M. Jones, *Phys.Rev.*, **110**, 1369 (1958).
(9) R. G. Summers-Gill, *Phys. Rev.*, **109**, 1591 (1958).
(10) S. W. Rasmussen, *Phys. Rev.*, **103**, 186 (1956).
(11) F. D. Seward, *Phys. Rev.*, **114**, 514 (1959).
(12) F. L. Ribe and J. D. Seagrave, *Phys. Rev.*, **94**, 934 (1954).
(13) N. Austern, S. T. Butler and H. McManus, *Phys. Rev.*, **92**, 350 (1953).
(14) D. W. Miller, *Phys. Rev.*, **109**, 1669 (1958).
(15) W. T. Pinkston, *Phys. Rev.*, **115**, 963 (1959).
(16) J. B. French, E.C. Halbert, and S.P. Pandya, *Phys. Rev.*, **99**, 1387 (1955) ; D. Kurath, *Phys. Rev.*, **101**, 216 (1956).
(17) *J. S.* Blair and E. M. Henley, *Phys. Rev.*, **112**, 2029 (1958) ; P. D. Kunz : *Ann. Phys. N. Y.*, **11**, 275 (1960).
(18) G. C. Phillips and T. A. Tombrello, *Nuclear Phys.*, **19**, 555 (1960).
(19) C. P. Browne and J. R. Lamarsh : *Phys. Rev.*, **104**, 1099 (1956) ; G. W. Greenlees, B. C. Haywood, L. C. Kuo and M. Petravic, *Proc. Phys. Soc.*, **A 70**, 331 (1957) ; H. A. Lackner, G. F. Dell, and H. J. Hausman, *Phys. Rev.*, **114**, 560 (1959) ; Y. Oda, M. Takeda, T. Yamazaki, C. Hu, N. Takano, K. Kikuchi, S. Kobayashi, K. Matsuda and Y. Nagahara, *J. Phys. Soc. Japan*, **15**, 760 (1960) ; S. Yamabe, *J. Phys. Soc. Japan*, **13**, 237 (1958) : M. Kondo and T. Yamazaki, *J. Phys. Soc. Japan*, **13**, 771 (1958) ; S. Yamabe, M. Kondo, T. Yamazaki and A. Toi, *J. Phys. Soc. Japan*, **13**, 777 (1958) ; Y. Oda, M. Takeda, C. Hu and S. Kato, *J. Phys. Soc. Japan*, **14**, 1255 (1959).
(20) K. Kimura *et al.*, to appear in this Bulletin.
(21) K. Kimura *et al.*, to appear in *J. Phys. Soc. Japan*.
(22) J. Kokame, to appear in *J. Phys. Soc. Japan*.
(23) H. Bichsel, *Phys. Rev.*, **112**, 1089 (1958).
(24) R. L. Mather and E. Segrè, *Phys. Rev.*, **84**, 191 (1951).
(25) W. A. Higinbotham and S. Rankowitz, *Rev. Sci. Instr.*, **22**, 688 (1951).
(26) R. A. Peck, H. P. Eubank and J. Lowe, *Rev. Sci. Instr.*, **30**, 703 (1959).
(27) F. Ajzenberg-Selove and T. Lauritsen, *Nuclear Phys.*, **11**, 1 (1959).
(28) J. R. Cameron, *Bull. Amer. Phys. Soc.*, **1**, 324 (1956).
(29) M. Sempert, H. Schneider and M. Martin, *Helv. Phys. Acta*, **27**, 313 (1954).

(30) S. Kobayashi, *J. Phys. Soc. Japan*, **15**, 1164 (1960).
(31) J. Rouvina, *Rhys. Rev.*, **81**, 593 (1951).
(32) F. H. Read and J. M. Calvert, *Proc. Phys. Soc.*, **77**, 65 (1961).
(33) C. A. Levinson and M. K. Banerjee, *Ann. Phys. N. Y.*, **2**, 471 (1957).
(34) M. J. Jakobson, *Phys. Rev.*, **123**, 229 (1961).
(35) M. Furukawa, Y. Ishizaki, Y. Nakano, T. Nozaki, Y. Saji and S. Tanaka, *J. Phys. Soc. Japan*, **15**, 2167 (1960).
(36) K. Hisatake, Y. Ishizaki, A. Isoya, T. Nakamura, Y. Nakano, B. Saheki, Y. Saji and K. Yuasa, *J. Phys. Soc. Japan*, **15**, 741 (1960).