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Analysis of ^{3}He + ^{4}He elastic scattering between 18 and 70 MeV with the resonating group method of Brown and Tang[1])

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Abstract. Differential cross-sections for the elastic scattering of ^{3}He from a ^{4}He gaz target have been measured at 44 energies between 18 and 70 MeV for center-of-mass angles between 18° and 160°. These measurements cover a range of excitation in ^{7}Be between 11.8 and 41.5 MeV. In this region we observe marked changes in the shapes of the angular distributions. A phase-shift analysis was performed and the results were compared to the resonating-group calculations of Brown and Tang.

The elastic scattering of ^{3}He by ^{4}He has been well described at least for low energy ^{3}He particles by the resonating-group method of Brown and Tang [1] in the one-channel approximation. Indeed phase-shifts calculated by this method have been found in good agreement with those determined from typical phenomenological analysis of ^{3}He + ^{4}He elastic scattering at least up to $E_{^3\mathrm{He}} = 31.5$ MeV [ref. 2]. The purpose of this experiment was to obtain data at higher energies to provide an extensive comparison with the resonating-group formalism which a priori should be less successful since an increasing number of reaction channels are expected to open as the energy increases. Another purpose of this experiment was to investigate the possible existence of high lying excited states of ^{7}Be. A recent ^{3}He + ^{4}He elastic scattering for incident ^{3}He particles between 27 and 43 MeV has indeed shown that the resonating-group method describes the data only in a rather general quantitative fashion [3].

The measurements were performed with ^{3}He-particle beams from the Berkeley 88-inch cyclotron using an analysis system [4] which provides a high-resolution beam ($\Delta E/E \simeq 0.02\%$). A set of seven Si(Li) detectors was used in the scattering chamber to obtain cross-sections at center-of-mass angles between 18° and 160°. The ^{4}He gaz target with a thin (7500 Å) nickel intrance foil was operated at a pressure of 0.1 Atm. The relative errors are typically less than $\pm 2\%$. Detection of both the scattered ^{3}He and the recoil alpha-particles makes it possible to get a complete angular distribution

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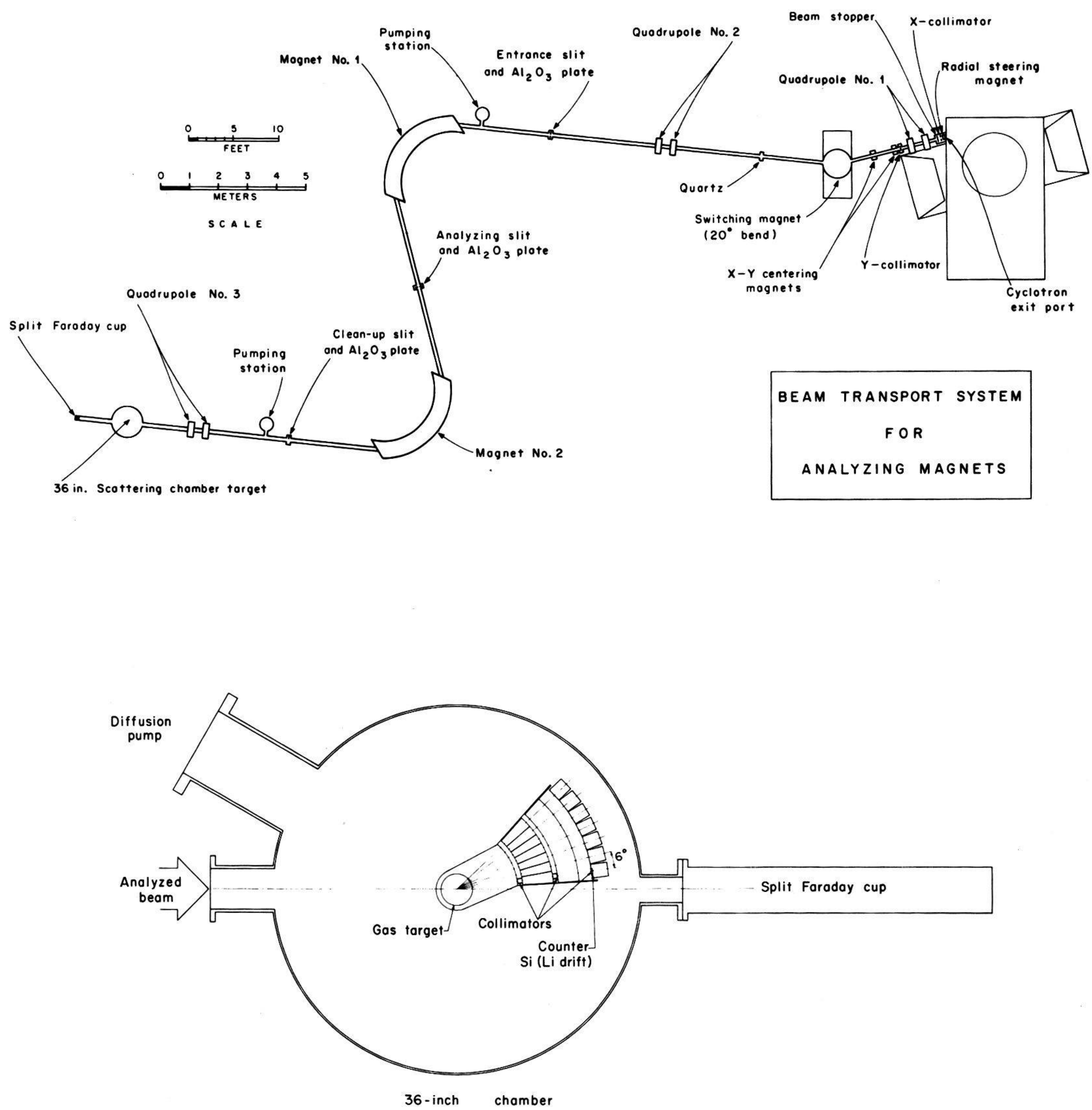
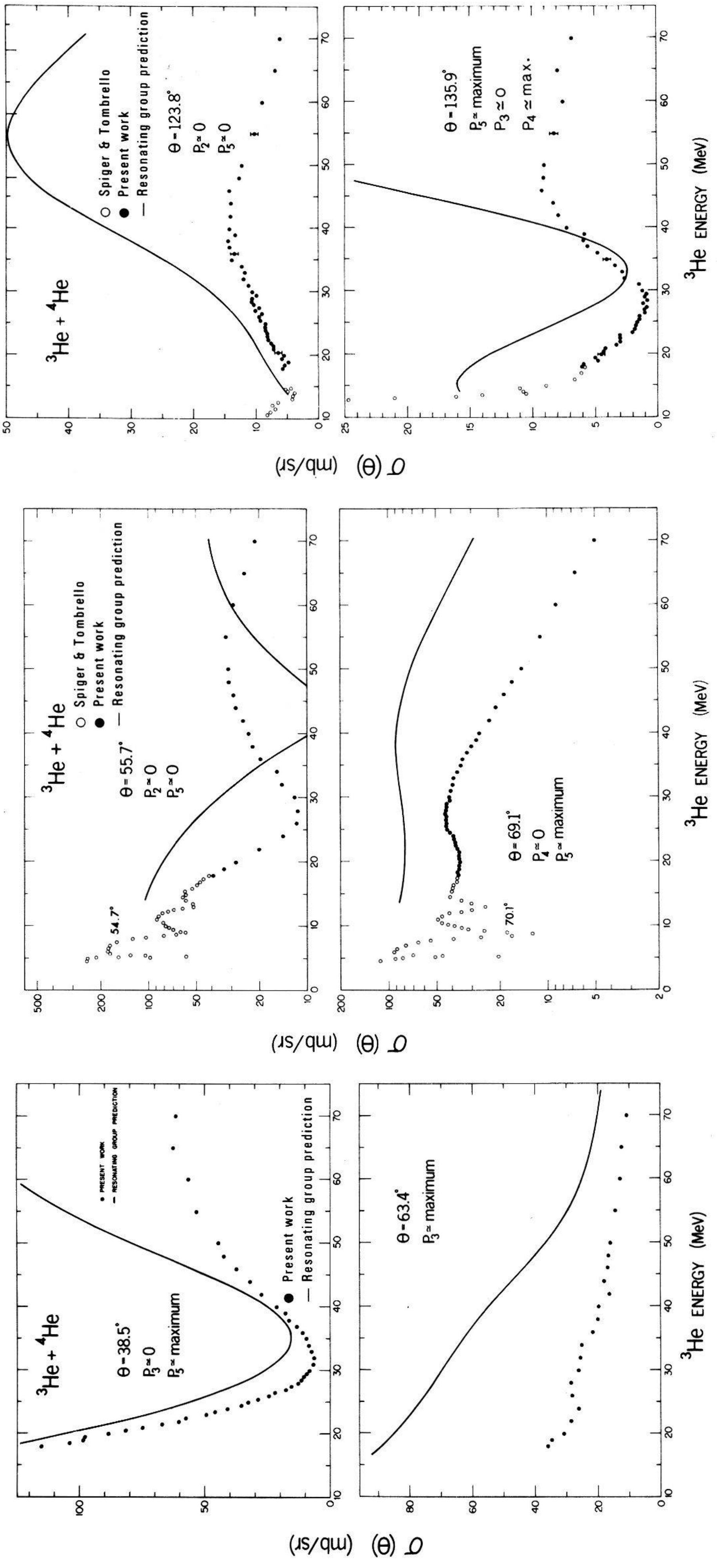


Figure 1

with only three angular setting of the detectors. The experimental set-up is presented in Figure 1. Since a split Faraday cup was used during the experiment the beam centering could be continuously controlled and monitored.

In this paper we present the differential cross-section of the ^3He + ^4He elastic scattering at certain angles and for 44 energies between 18 and 70 MeV. The range of excitation energies of ^7Be covered is between 11.8 and 41.5 MeV. Most of the low-lying states in ^7Be have already been observed in low energy ^3He + ^4He elastic scattering. For $l \leqslant 4$ only f-wave phase shifts show resonance structure for $E(^3He) < 18$ MeV corresponding to the 4.57 MeV ($7/2^-$), the broad 6.73 MeV ($5/2^-$) and the 9.27 MeV ($7/2^-$) states in ^7Be [refs. 2, 5]. The 7.21 MeV ($5/2^-$) level has not been seen in elastic scattering. Besides these levels and states at 9.9 MeV ($3/2^-$) and 11.01 MeV ($3/2^-$) which have been obtained through various reactions [2, 5], no other levels in ^{7}Be have yet been clearly assigned. Recently [6] however a broad resonance structure at $E(^3\mathrm{He}) = 34$ MeV has been seen in rough agreement with the resonating-group prediction [7]. Resonating-group calculations [8] employing an l-dependent phenomenological imaginary potential reproduce the cross-section data over a wide range of energy and predict a broad $l = 2$ level at 11.6 MeV and both $l = 4$ and $l = 5$ levels near 25 MeV excitation. In this paper we will compare the resonating-group calculations with the excitation functions obtained at some particular angles, such as the zeros or maxima of the Legendre polynomials which contribute to the partial wave expansion. Since we are dealing with a spin 1/2 particle elastically scattered on a spin zero target it is important to recall that for any level of given spin and parity only one partial wave contributes. We observe indeed marked changes in the shape of the angular distribution which are best reflected, as we shall see, in the behaviour of the excitation functions. Figure 2 presents the excitation function at several angles corresponding to zeros or maxima of the Legendre polynomials which are compared to the resonating-group calculations. The left part of this figure shows the behaviour at 38.5° ($P_3 = 0$, P_5 = maximum) and $\theta = 63.4°$ (P_3 = maximum) compared to the resonating-group calculations. The increase in the cross-section in the upper one suggests that the $l = 5$ wave could be involved, however the slow decrease in the lower one rules out the possibility of a significant contribution from the $l = 3$ wave. The middle of Figure 2 shows also the behaviour at 55.7° ($P_2 = 0$, $P_5 \sim 0$) and 69.1° ($P_4 = 0$, P_5 = maximum). Points from previous low energy work of Spiger and Tombrello [2] are also shown on this figure. The predicted cross-sections are quite different although the shape seems similar, but displaced along the energy scale. One could attribute the increase in the upper of these curves to the $l = 4$ wave, while the bump in the lower one would then come from the $l = 5$ wave. We are therefore in agreement with recent suggestion of possible broad $l = 4$ and $l = 5$ levels around $E(^3\mathrm{He}) = 25$ MeV. The $l = 5$ coulld be therefore located around $E(^3\mathrm{He}) \simeq 30$ MeV and the $l = 4$ near $E(^3\mathrm{He}) \simeq 50$ MeV. Finally this figure presents also the results at $\theta = 123.8°$ ($P_2 \simeq P_5 = 0$) and for $\theta = 135.9°$ ($P_3 \sim 0$, $P_4 \simeq P_5 \simeq$ maximum) compared to the resonating-group predictions. The upper figure shows an increase probably due to the $l = 4$ wave, while the bottom one at 135.9 suggests that an increase of $l = 5$ might be involved.

Several interesting conclusions can therefore be drawn from this analysis. First of all, if the shape of the excitation function is in good agreement with the resonating-group calculation, at least at some angles, the magnitude of the prediction is off sometimes by a factor of four or five. This conclusion is in agreement with the recent calculation for the lower energy elastic scattering of Schwandt et al. [3]. However this should not be too surprising since these calculations were done by considering the elastic channel only, and that at these high energies many reaction channels are expected to be open. Thus this analysis is expected to give only a qualitative indication. Considering now the possible existence of new levels in ^{7}Be, a look at the excitation functions would tend to rule out $l = 2$ and $l = 3$ levels while there are strong indications for very broad levels suggested from $l = 4$ and $l = 5$ waves, around $E(^3\mathrm{He}) \simeq 30$ and 50 MeV respectively. Phase-shift analysis was also performed for these data. The results are generally in agreement with the recent polarized ^{3}He particles scattering by ^{4}He between 18 and 32 MeV, although our data extend to 70 MeV [10]. Therefore no curve will be shown and only the conclusions from these calculations will be presented here. Such an analysis is of course rather complicated



³He + ⁴He
θ = 123.8°
P₂ ≈ 0
P₅ ≈ 0
○ Spiger & Tombrello
● Present work
— Resonating group prediction
θ = 135.9°
P₅ ≈ maximum
P₃ ≃ 0
P₄ ≃ max.
³He + ⁴He
θ = 55.7°
P₂ ≈ 0
P₅ ≈ 0
○ Spiger & Tombrello
● Present work
— Resonating group prediction
54.7°
θ = 69.1°
P₄ ≈ 0
P₅ ≈ maximum
70.1°
³He + ⁴He
θ = 38.5°
P₃ ≈ 0
P₅ ≈ maximum
● Present work
— Resonating group prediction
θ = 63.4°
P₃ ≈ maximum
σ (θ) (mb/sr)
³He ENERGY (MeV)

Figure 2

and the outcome doubtful due mainly to the opening of many reaction channels like (p, ^{6}Li), (d, ^{5}Li), (n, ^{6}Be) for which the threshold are 5.606 MeV, 9.05 MeV and 10.67 MeV respectively. Moreover reaction cross-sections which should help considerably in reducing the multiplicity of solutions are to the best of our knowledge not yet available. A standard χ^2 minimization search routine was employed to determine phase-shifts including $l = 6$ at the higher energies. The $l = 0$ phase-shift (δ_0) follows very closely a simple line while the corresponding reflection coefficient η_0 remains well bounded, the $l = 1$ phase shift indicates a possible $l = 1$ level around 20 to 30 MeV (which could be $3/2^-$ or $1/2^-$) while the corresponding η_1 follows also a reasonable resonant behaviour in that region. This is in agreement with the very recent suggestion from polarized ^{3}He particles elastically scattered from ^{4}He for a new level assigned as $J^\pi = 1/2^-$ at 16.7 MeV excitation energy in ^{7}Be [10]. The $l = 2$ and $l = 3$ curves are featureless as we would expect. On the other hand the rise of the $l = 4$ and $l = 5$ phase-shift above 30 MeV suggest the possible existence of levels in ^{7}Be which is also reflected in the behaviour of the reflection coefficient η_L. With the notable exception of the p-wave phase δ_1, the best phase-shifts generally follow the trend of the resonating-group predictions.

In conclusion, we can say that the resonating-group predictions follow generally the behaviour of the excitation functions, at least for the shape of these functions. These calculations are also in relatively good agreement with the phase-shift with the exception of the p-wave δ_1. From our analysis and experiment, we can suggest the existence of a possible $l = 1$ level around 20–30 MeV and most certainly broad $l = 4$ and $l = 5$ levels above 30 MeV in agreement with recent theoretical calculations [8]. The resonating-group method describes the ^{3}He + ^{4}He elastic scattering for ^{3}He energies between 18 and 70 MeV only in a rather general qualitative fashion. The real phase-shift predicted by the simple model as well as recent polarization measurement using either a polarized ^{3}He beam [9, 10] or a polarized ^{3}He target [11], will provide the possibility of a complete and unique phenomenological analysis of the scattering data, especially when the polarization data will be extended to higher energies.

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