A MICROSCOPIC APPROACH FOR p+^{9}Be AT ENERGIES BETWEEN 1.7 TO 15 MeV/NUCLEON

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Elastic scattering data for p+^{9}Be, recently obtained in inverse kinematics, together with data from the literature measured in direct kinematics, were previously considered and evaluated via a Coupled Reaction Channels approach (CRC). This set of data for energies between 1.7 and 15 MeV/nucleon, free from normalization inconsistencies, is analyzed in this work using the microscopic approach of the Jeukenne, Lejeune and Mahaux interaction (JLM). The results show that even at these low energies the data can be well-described within this framework.

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A considerable amount of elastic scattering data for protons incident on a ^{9}Be target at low energies has appeared in the literature during the past forty years. A recent measurement in inverse kinematics at three energies between 1.7 to 5.7 MeV/nucleon [1] motivates the present research in the following context. The previous measurements and analyses were carried out under quite different conditions giving occasionally contradictory results with respect to the absolute normalization of the cross sections. Inconsistencies were traced and removed via a coherent coupled reaction channels (CRC) analysis evaluating results at energies between 1.7 to 15 MeV/nucleon in Ref. [1]. Therefore, these results, free from normalization problems, may be used for systematic theoretical investigations.

The microscopic optical potential due to Jeukenne, Lejeune and Mahaux (JLM) [2] has been found to be successful in interpreting proton and neutron scattering results for energies above 10 MeV/nucleon and various targets with atomic numbers between $A = 9$ to 206 [3]. The JLM potential is based on a free nucleon–nucleon potential, and the scattering in nuclear matter is calculated by solving the Bethe–Goldstone equation. The starting point for computing JLM potentials is the Brueckner–Hartree–Fock approximation and the Reid hard core nucleon–nucleon interaction, which provides, for energies up to 160 MeV, the energy and density dependence of the isoscalar, isovector and Coulomb components of the complex optical model potential in infinite matter. The optical potential of a finite nucleus is obtained by applying the local density approximation (LDA).

The JLM potential was successfully applied in Refs. [4–6] to medium- and heavy-mass stable nuclei at energies above 10 MeV/u with only slight necessary adjustments to the imaginary part. It should be noted that Jeukenne, Lejeune and Mahaux parameterized their numerical results for the real and imaginary parts of the optical potential in an analytical form. For that, they took into consideration calculated values over the energy interval $10 \leq E \leq 160$ MeV. In Ref. [7] by Lejeune, a modification of the formula for proton and neutron scattering suitable for energies below 10 MeV/u was suggested but has never been validated experimentally. On the other hand, the standard formula was tested for low-energy (between 7 and 21 MeV/u) data for neutron scattering from lead by Dietrich *et al.* in Ref. [8] and found to give adequate agreement.

Moreover, the application of the JLM potential to nucleon scattering from light nuclei constitutes a severe test of the assumptions underlying the LDA since such nuclei are surface dominated. It was found to give a reasonable description of proton scattering from ^{6,7}Li targets at $E_p = 20$ to 50 MeV [9]. However, it proved unsuccessful in describing similar data for ^{6,7}Li$+p$ measured in inverse kinematics by our group at rather low equivalent proton energies [10, 11], while the data were described very well within a Continuum Discretized Coupled Channels approach.

In the present work, we apply the Jeukenne, Lejeune and Mahaux model [2] to the consistent set of $p+^9$Be elastic scattering data evaluated in Ref. [1]. The potential was calculated using the code developed by Dietrich with the "standard" normalization for light nuclei ($\lambda_V = 1.0$ and $\lambda_W = 0.8$). The ^{9}Be density was derived from the Hartree–Fock calculations performed by Trache *et al.* [12]. Our calculations are compared with the experimental data in Figs. 1, 2 and 3, and it is obvious that they describe the data adequately well, at least at the most forward angles. Better agreement with the data was obtained if the normalization for the imaginary part was taken to be close to unity ($\lambda_W = 1.0$) for the higher energies, while at the lower energies, lower values ($\lambda_W = 0.7$) gave the best description. The effect of using other densities was also investigated but only small changes were observed in the angular distributions, mainly affecting the minimum.

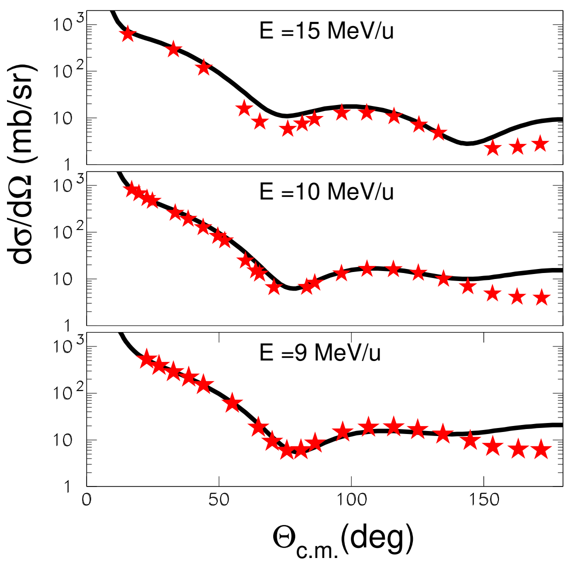

Fig. 1. Elastic scattering angular distributions for $p+^9$Be at 15, 10 and 9 MeV/nucleon. Data are from [13, 14] evaluated in [1].

For a more complete test, calculations were also performed for the analyzing powers for energies where polarization data exist. Comparisons between theory and experiment are presented in Figs. 4 and 5. Adequate agreement is observed which worsens at some of the lower energies. Slightly better agreement is found for normalization with $\lambda_W = 1.0$ and for potentials calculated with a ^{9}Be density derived from electron scattering measurements [15] using method B of Ref. [16].

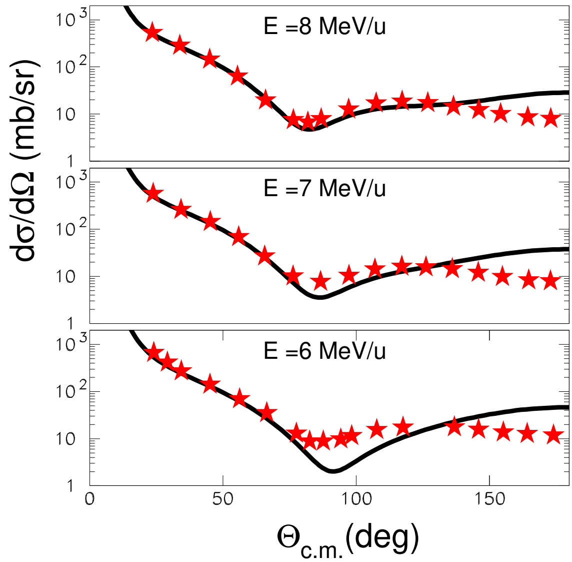

Fig. 2. Elastic scattering angular distributions for $p+^9$Be at 8, 7, and 6 MeV/nucleon. Data are from [13] evaluated in [1].

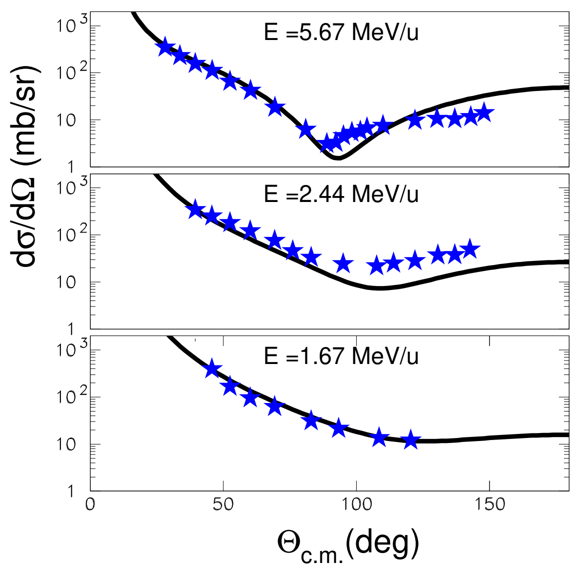

Fig. 3. Elastic scattering angular distributions for $p+^9$Be at 5.67, 2.44, and 1.67 MeV/nucleon. Data are from [1].

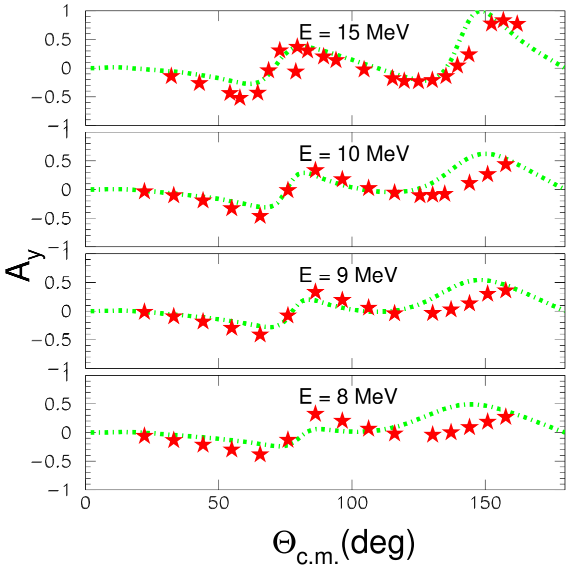

Fig. 4. Analyzing power angular distributions for 15, 10, 9, and 8 MeV protons incident on ^{9}Be. Data are from [13, 14] evaluated in [1].

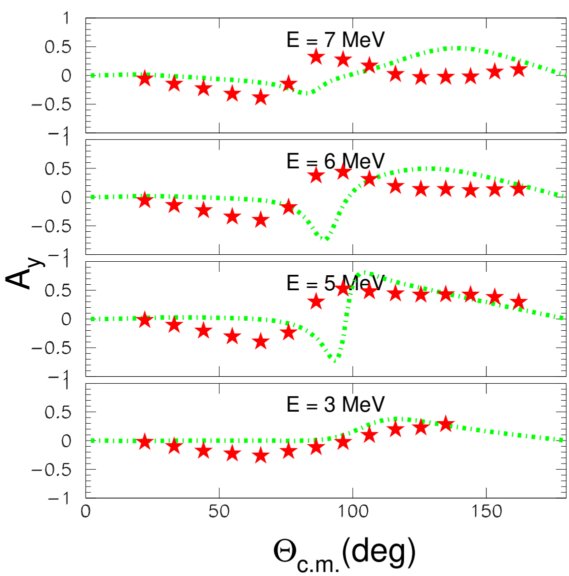

Fig. 5. Analyzing power angular distributions for 7, 6, 5, and 3 MeV protons incident on ^{9}Be. Data are from [13, 14] evaluated in [1].

The present analysis provides independent support for the normalization choices made in Ref. [1], since the data are adequately described by the consistent JLM calculations. It also supports the conclusion of Ref. [1] of little or no contribution from compound elastic processes at these energies. While it would be desirable to confirm this by explicit calculation of the compound elastic contribution, this is not straightforward, especially for light systems. A typical example of a case where this contribution was taken into account is for a much heavier system, $p+^{24,25}$Mg [17], and only under the assumption that the interference term between direct and compound contributions is negligible. The compound part was calculated using the Hauser–Feshbach (HF) theory and incoherently summed with the direct part. Since the HF calculations require the fitted optical model parameters as input, an iterative procedure is necessary to obtain the final direct+compound elastic scattering result. In the present case, this will not help the agreement between data and calculation, as the compound part will contribute mainly at the backward angles where our JLM calculations overestimate rather than underestimate the experimental results. With light targets, there is also the question of the possible low density of states of the compound nucleus, particularly at low incident proton energies, which may call into question the suitability of the HF theory.

In summary, we have analyzed a set of elastic scattering data for ^{9}Be+p in the energy range from 1.7 to 15 MeV/nucleon using the JLM microscopic approach. It should be underlined that this data set was previously evaluated in a CRC approach and is, therefore, free from normalization inconsistencies. Despite the weakly bound nature of the ^{9}Be nucleus, where breakup might be expected to have a strong effect on the elastic scattering, the adopted interaction proved to be adequate to describe the data even at the lower energies. The worst agreement occurs for the energy at 2.46 MeV/nucleon. However, below 5 MeV/nucleon, as already noted in Ref. [1], we enter the region of ^{10}B resonances and possible compound nucleus contributions. In fact, according to the compilation of Krat *et al.* [18], the energy of our data at 2.46 MeV/nucleon matches almost exactly a pronounced resonant peak, responsible for the apparent worse agreement of the present JLM calculations and the CRC calculations of Ref. [1] with the data at this energy. On the other hand, taking the above into account, we may conclude that the apparent failure of JLM to describe in total the ^{6,7}Li data [10, 11] at similar energies to those investigated here stems from strong compound contributions, perhaps due to resonances at specific energies. In this case, the JLM calculations underestimate the data at backward angles and a compound contribution may have an influence on the results. The reaction Q values rule out strong neutron pickup coupling effects for ^{6}Li and ^{7}Li, and the breakup thresholds do not provide any obvious clue so that this seems the most likely explanation. The excellent description of the ^{6,7}Li data by the Continuum Discretized Coupled Channels (CDCC) [10, 11] approach could be due to the exact mapping of the potentials for each constituent cluster and the target. This procedure may have "absorbed" possible strong compound contributions. More elaborate calculations in the direction of compound couplings should be pursued in the future for addressing the above problems under the same footing for both lithium and beryllium projectiles.

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