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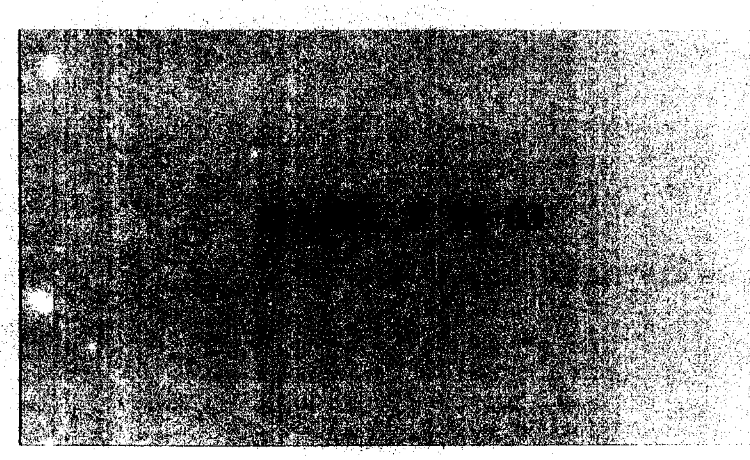

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Abstract: The elastic scattering of ^{6}He, ^{10,11}Be secondary beams on a $(CH_2)_3$ target and the charge exchange reaction p(^{6}He,^{6}Li)n have been measured. Very good agreement was found for the ^{6}He+^{12}C data with a four-body eikonal scattering model. A microscopic optical potential was used to reproduce the proton-nucleus elastic scattering data. Finally no clear signature of a halo structure was found in the present data for the charge exchange reaction.

1 Introduction

The nucleon-nucleus and nucleus-nucleus elastic scattering has gained a new interest with the availability of unstable nuclear beams, especially in the case of halo nuclei where this type of study is expected to provide information on the nuclear densities of dripline nuclei and on the components of interactions which depend on the isospin. Several experiments have already measured elastic scattering angular distributions of projectiles such as ^{8}He, ^{11}Li, ^{12,14}Be, ^{8}B on various targets [1-6]. However, very often in these first studies, the statistics remained rather low and the energy resolution was not good enough to separate the ground state from the first excited states. As a consequence, the conclusions extracted from these data are sometimes not without ambiguities and even contradictory. To clarify the situation, the first thing to do is to obtain high quality data, with good statistics and energy resolution.

The (p,n) charge exchange reaction has been a privileged tool to explore nuclear structure and nuclear interactions. This reaction is highly selective since only isobaric analog states (IAS) and Gamow-Teller (GT) resonances are strongly populated. The transition to the IAS is a $\Delta T=1$, $\Delta S=0$ non spin flip Fermi transition (F), whereas the excitation of GT resonances proceeds via a $\Delta T=1$, $\Delta S=1$ spin flip transition, induced respectively by the V_τ and $V_{\sigma\tau}$ components of the nucleon-nucleon interaction. In particular, these studies provide information on the spectroscopic strength of the states involved in these reactions, on the fraction of the sum rule exhausted by these transitions, and on the interactions V_τ and V_σ [7].

Both the ground state of ^6He and its isobaric analog state in ^6Li are expected to behave like halo states [8-11], therefore two reasons motivated us for the study of the $p(^6He,^6Li)n$ reaction: one is the possibility to get information on the interactions V_τ and $V_{\sigma\tau}$ in a low density region, the other is the sensitivity of the transition leading to the IAS with respect to the differences between the neutron and proton density distributions, as this was shown for example for a series of Sn isotopes [12]. Taking into account the significant effect observed for very small differences of radii in the Sn case, we would expect very strong effects in the case of the halo nuclei considered here.

2 Experimental procedure

The secondary beams were produced by fragmentation of a 75 MeV/nucleon primary ^{13}C beam, delivered by the GANIL accelerator, on a 1155 mg/cm^2 carbon production target, located between the two superconducting solenoids of the SISSI device [13,14]. The position of SISSI at the exit of the second cyclotron and at the entrance of the beam analysing α–spectrometer allows for an improved collection of the produced secondary beams and for a better transmission to the different experimental areas. The total momentum acceptance of the system SISSI+α-spectrometer was of the order of 0.6% and the angular acceptance was about 100 mr in the horizontal and vertical planes. This results in roughly one order of magnitude increase in beam intensity with respect to an ion-optical system without the SISSI device.

In this work, the magnetic rigidity of the alpha spectrometer was set at 2.82 T.m. At this rigidity, the total intensity of the secondary beams was of the order of 10^7 pps in the acceptance of the system for a primary intensity of 2×10^{12} pps. The intensity for the neutron-rich nuclei ^6He and ^{11}Be was of the order of a few percent of the total intensity, whereas the intensity for the nuclei closer to the stability valley such as ^7Li and ^{10}Be was around 1/5 of the total intensity.

The elastic scattering and charge exchange reactions were studied using the energy loss spectrometer SPEG [15]. The reaction target was a 100μm thick polypropylene foil, $(CH_2)_3$. All the scattered particles were unambiguously identified in the focal plane of the spectrometer with an ionisation chamber and a plastic scintillator. The momentum and scattering angle were measured with two position sensitive drift chambers [16] placed 70 cm apart and located near the focal plane of the spectrometer. The elastic and inelastic scattering of the secondary beams were measured on ^1H and ^{12}C in the range θ_{lab}=0.7°-6.0°, while the charge exchange reactions on ^1H and ^{12}C were obtained from θ_{lab}=0.0° to 4.0°. In the latter case, the measurement down to 0° was possible due to the large difference in the magnetic rigidity between the beam and the ejectiles.

3 Nucleus-nucleus elastic scattering: the $^6He+^{12}C$ system at 41.6 A.MeV

Although the angular range covered by the data is relatively restricted, an interesting result could be obtained in the case of the $^6He+^{12}C$ system. The data were compared to the theoretical cross section calculated within a few body eikonal model [17]. This model requires three inputs: the ^6He three-body wave function plus the $\alpha+^{12}C$ and $n+^{12}C$ optical potential at the relevant energy per nucleon. Once these are chosen the calculation is completely parameter-free. The wave functions used were those of Zhukov et al. [18] calculated within the coordinate space Faddeev approach with a realistic NN interaction and Woods-Saxon for the αN interaction. The $\alpha+^{12}C$ optical potential at 41.6 A.MeV was obtained from a fit of the data existing at 166 MeV [19]. The $n+^{12}C$ potentials were derived from a

Schrödinger equation [20] of the global Dirac nucleon optical potential parametrisation of Cooper *et al.* [21].

Fig. (1) shows the measured angular distribution plotted against the result of the four-body calculation (solid curve). The agreement between the calculation and the data is perfect in this case, whereas for the case of $^{11}Li+^{12}C$ quasielastic scattering, all attempts to describe the small angle behaviour of the cross section within few-body models [17,22], and also semi-microscopic models [23] have failed. A common feature of all these calculations is the presence of a sharp minimum at 4°, whereas the measured cross section has a much shallower minimum at around 5°. No such discrepancy between theory and data exist for $^{6}He+^{12}C$ scattering. Since both ^{11}Li and ^{6}He are assumed to have two-neutron halos surrounding an inert core, this leads us to speculate that it may well be the ^{9}Li core that requires a better treatment. The effects of core excitation and spin-dependence may well need to be included in future models of ^{11}Li. Whereas ^{6}He, with its inert and spinless α core, appears not to require such considerations. In order to progress in these studies, besides theoretical developments, high quality data for $^{9}Li+^{12}C$ and $^{11}Li+^{12}C$ elastic scattering are urgently needed.

The sensitivity of the cross section to the ^{6}He wave function, and in particular to the strength of the valence neutron correlations was also studied. For the case of maximally correlated valence neutrons, a two-body wave function based on the dineutron model, was used for ^{6}He. Here the two neutrons are treated as a single structureless entity, and the result is shown by the dashed line in Fig. (1). In the other extreme case of no correlation between the valence neutrons, the NN interaction was switched off and the αN interaction increased in strength to retrieve the correct binding energy. The cross section obtained using this uncorrelated wave function for ^{6}He was almost identical, over the angular region shown, to the solid curve and was thus not plotted. Clearly, the elastic cross section is not very sensitive to the strength of the valence neutron correlations in ^{6}He. Whereas in the corresponding study of ^{11}Li scattering [17] using similar model wave function, these correlations appeared to influence more strongly the angular distribution.

The present data also allow to test some models which have been used to describe elastic scattering with stable nuclei. For example the dotted line represents the result obtained with the double folded model, using a DDM3Y interaction [24]. This interaction has been used extensively in the past and has been successful in describing elastic scattering of light systems such as $^{12}C+^{12}C$ between 10 and 100 A.MeV [25]. We used the ^{6}He density obtained by Sagawa *et al.* [26] and a 2-parameter Fermi density for ^{12}C [27]. The parameters of the imaginary potential were taken from the systematics given in Ref [25]. The fit obtained is very good on the maximum at 4°, but the deep minimum in the dotted curve at 7° may be due to ambiguities in the imaginary potential in this kind of calculation. Therefore the present data do not extend far enough to distinguish unambiguously between the different calculations.

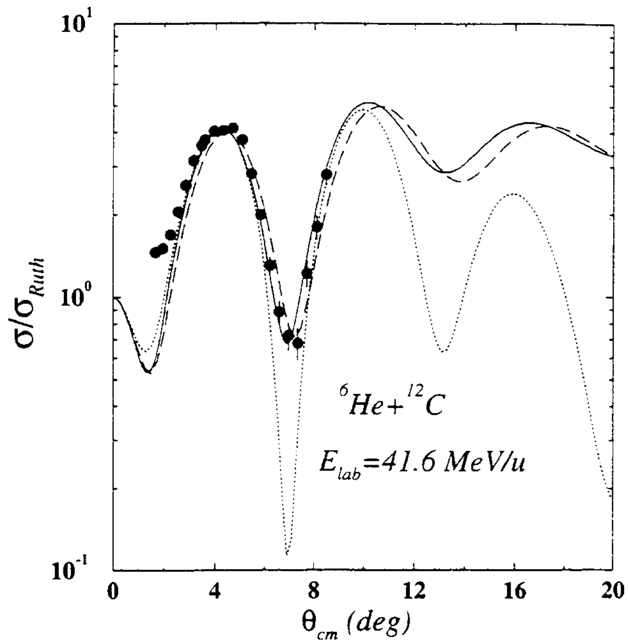

Fig 1: Elastic scattering angular distribution for $^{6}He+^{12}C$ at 41.6 A.MeV. The solid curve is calculated from the parameter-free four body-eikonal model with a Faddeev wave function for ^{6}He. The dashed curve is calculated from a three-body eikonal model using a dineutron wave function. The dotted curve was obtained using a density-dependent double folding model.

4 Proton-nucleus elastic scattering

The experimental angular distributions for the elastic scattering of the ^{6}He, ^{7}Li, ^{10}Be and ^{11}Be are presented in Fig. (2). We have analysed these data by using the nucleon-nucleus optical model potential calculated by Jeukenne *et al.* (JLM) [28]. The JLM central potential has been extensively studied by S.Mellema *et al.* [29] and J.S. Petler *et al.* [30]. It has been particularly successful in describing elastic neutron and proton scattering from stable nuclei, provided the imaginary potential is adjusted downward by a normalisation factor of the order of $\lambda_W \approx 0.8$.

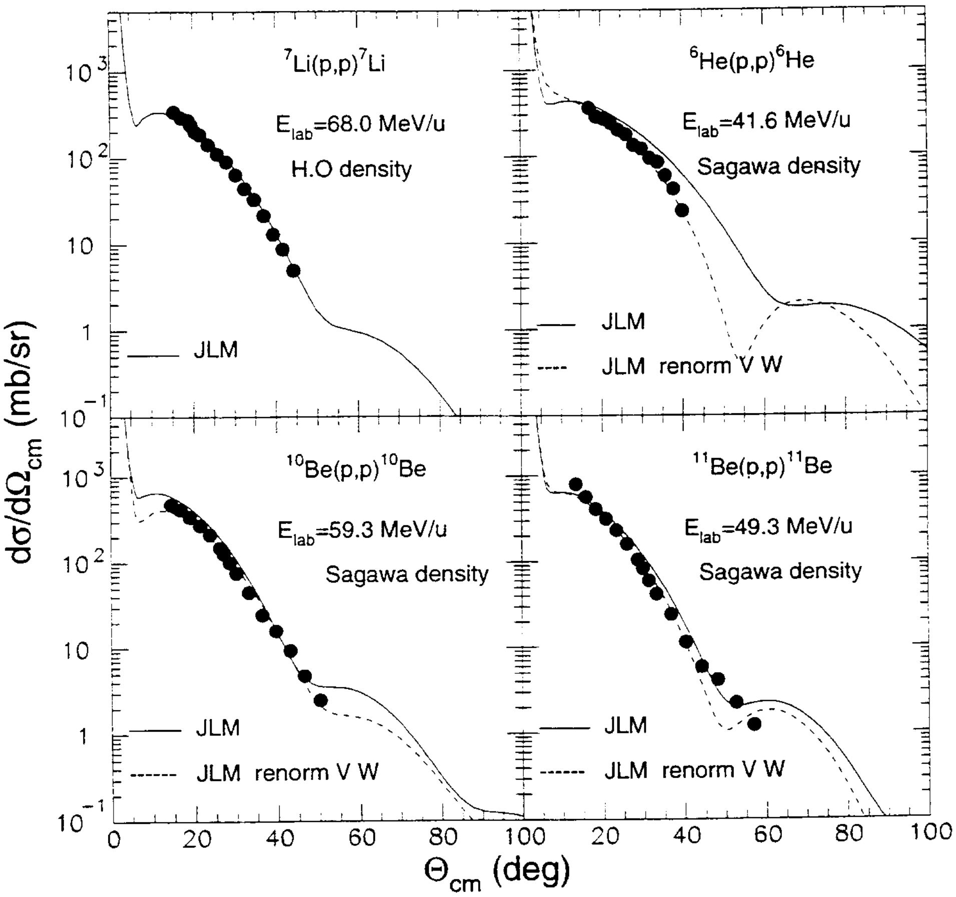

Fig. (2): Elastic scattering angular distributions measured for ^{6}He, ^{7}Li, ^{10,11}Be on proton

The solid curves on Fig. (2) present the results obtained with the JLM potential with no renormalisation of the real part (λ_V= 1.0) and a renormalisation of 20 % of the imaginary part (λ_W = 0.8). The agreement obtained in the case of the stable ^{7}Li secondary beam is excellent with these standard normalisation factors. However the calculated angular distribution overpredict the data for the neutron-rich nuclei. For these nuclei, the normalisation factors λ_V and λ_W were allowed to vary in order to obtain a best fit of the data, based on χ^2 minimisation. The optimum values are plotted on Fig.(3) for the four beams used in the present data, and also for the ^{9}Li and ^{11}Li data of Ref. [4].

The normalisation factors obtained in the case of ^{7}Li and ^{9}Li are the same as those found in previous studies with stable nuclei, whereas all other cases require a decrease of the real potential and an increase of the imaginary potential. This is exactly what can be expected from a dynamic polarisation potential representation of the break-up effects [31].

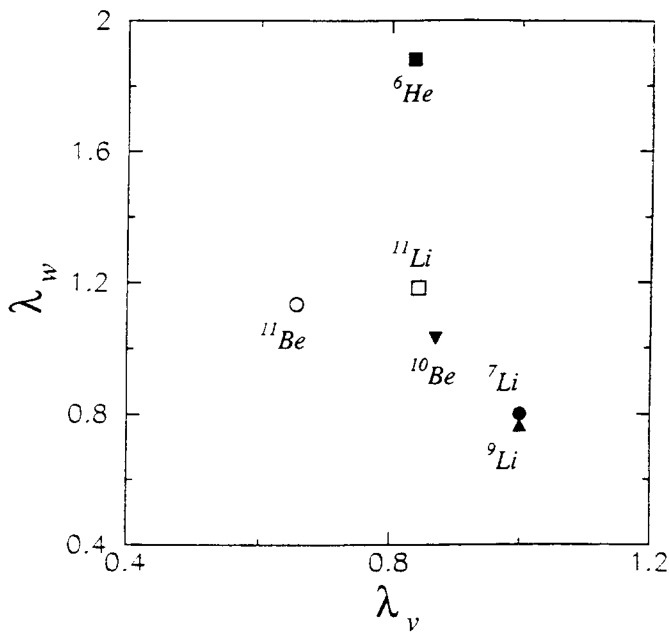

Fig. 3: Normalisation factors applied to the real (λ_V) and imaginary part (λ_W) of the JLM potential to best fit the data

5 Charge exchange reaction: p(^{6}He,^{6}Li)n

The charge exchange reaction cross section can be compared to β decay strength. This comparison for Fermi and GT transitions provides an essentially model independent means to extract the V_τ and $V_{\sigma\tau}$ interactions or more precisely their volume integral. A detailed review of this aspect can be found in ref. [7].

The expected (experimental) cross-sections for the Fermi and GT transitions can be written, following ref. [7], as a product of three factors

$$\sigma = \hat{\sigma}_\alpha\ (E_p,A)\ F_\alpha(\mathbf{q},\omega)B(\alpha) \qquad (1)$$

where α stands for F or GT. $\hat{\sigma}$ is a " unit cross section", depending on incident energy E_p and target mass A. $F_\alpha(q,\omega)$ is a kinematical factor depending on the three-dimensional momentum transfer **q** and on the energy loss $\omega=E_X-Q_{gs}$, while B(α) is the β-decay transition strength, obtained from beta decay lifetimes.

Even without considering detailed features of the angular distributions, valuable information can be extracted from the ratio of the cross sections for the Fermi and GT transitions at 0°. Indeed, the ratio R defined by the relation

$$R^2 = \widehat{\sigma_{GT}} / \widehat{\sigma_F} \quad (2)$$

is closely related to the ratio of the volume integral J_τ and $J_{\sigma\tau}$ of the interactions V_τ and $V_{\sigma\tau}$. It can be expressed as:

$$R = \left|\frac{J_{\sigma\tau}}{J_\tau}\right| \left(\frac{N_{\sigma\tau}}{N_\tau}\right)^{1/2} \approx \left|\frac{J_{\sigma\tau}}{J_\tau}\right| \quad (3)$$

where N_τ and $N_{\sigma\tau}$ are distortion factors defined by the ratio of the plane wave to distorted wave amplitudes. At the present energy, the ratio $N_{\sigma\tau}/N_\tau$ is close to 1.

As shown is ref. [7], R can be determined experimentally and it is related to the 0° cross sections by the relation:

$$R^2 = \frac{\sigma_{GT}(0^\circ)(N-Z)}{\sigma_F(0^\circ)B(GT)} \quad (4)$$

A compilation of the ratio R obtained using equation (4) for N=Z+2 nuclei is shown on Fig. (4). The data corresponding to ^{7}Li, ^{14}C, ^{18}O, ^{26}Mg(p,n) reactions are from ref [32-35], and the calculation used the B(GT) values from Taddeucci et al [7]. The linear energy dependence of R is a well established behaviour observed for many stable nuclei [7] and has been attributed to the energy dependence of the V_τ potential. Brown, Speth and Wambach [36] have shown, using a meson exchange model, that this energy dependence arises essentially from a two pion exchange contribution to the V_τ potential.

The ratio R was also computed for the transitions measured in the present experiment, by applying equation (4). The value of B(GT) which is necessary to compute R was obtained from β decay lifetime measurements and is given in ref. [7] for the inverse β decay transition ^{6}Li--->^{6}He. To be compared with the present experiment, it must be corrected by the spin factor $\frac{(2J_f+1)}{(2J_i+1)}$, where $J_i(J_f)$ refers to the initial (final) total angular momentum in the ^{6}Li(n,p)^{6}He reaction.

It is known that the volume integral of the spin-isospin term $J_{\sigma\tau}$ measured for ^{6}Li(n,p)^{6}He ground state (GT) transition is in good agreement with the values obtained for other systems [37], as well as with the theoretical predictions of Nakayama and Love [38]. The ratio R, or $\left|\frac{J_{\sigma\tau}}{J_\tau}\right|$ measured in the present experiment is in agreement with the systematic behaviour established for T=1 nuclei. This means that the isospin term J_τ also shows no deviation from the values obtained for stable nuclei. A deviation could have been expected due to the halo structure of the states which are involved in these transitions.

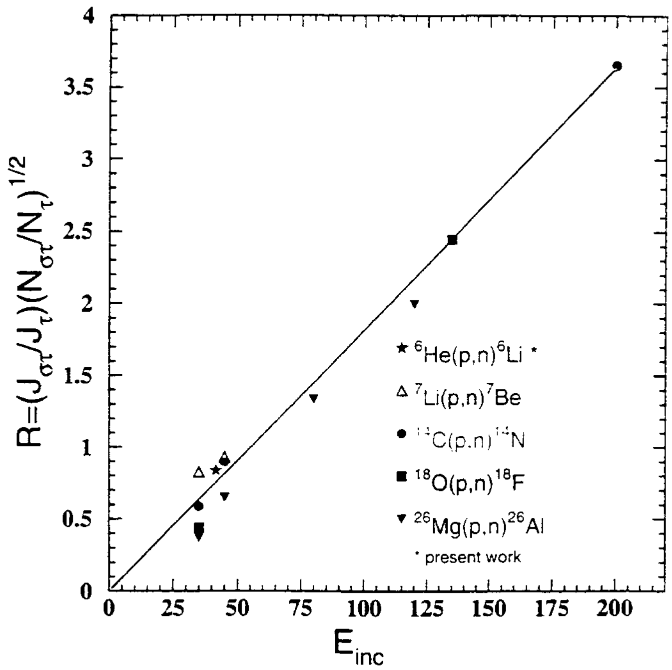

Fig. (4): Compilation of the reduced transition strength ratio R of Gt and Fermi charge exchange transitions in light nuclei as a function of the incident energy of the proton

6 Conclusions

We have shown that the combined use of SISSI and SPEG offers new opportunities for measuring elastic scattering cross sections of neutron-rich nuclei to high accuracy. These are the first data on nucleus-nucleus elastic scattering with exotic beams without contribution from inelastic scattering. For the limited range covered by the present data, a three-body model for ^{6}He of α+n+n describes the data very well, whereas in the same angular domain, it was not possible to fit the ^{11}Li data, using the same model. It would be also extremely interesting to obtain new data at larger angles, both on ^{12}C and proton targets, to discriminate between new data at larger angles, both on ^{12}C and proton targets, to discriminate between the various models available, and to try to extract information on the nuclear matter density distributions. Several sets of data will also be necessary for the same system at different energies in order to disentangle the break-up effects in these loosely bound systems.

It seems well established that the ^{6}He ground state is a halo state, and there are also some indications that its isobaric analog has the same characteristics. The fact that the $J_{\sigma\tau}$ as obtained from the (n,p) reaction of previous studies is in good agreement with the systematics, indicates that the transition strength between a standard ground state (^{6}Li) and a halo ground state (^{6}He) shows no anomaly. From the analysis of the (p,n) reactions, we conclude that the J_{τ} volume integral of the nucleon-nucleon effective interaction does not show any deviation from the systematics in this mass region. This indicates that the transition between two halo states also has standard strength, if we accept as granted that ^{6}He and its IAS are halo states. Therefore, with this assumption, the presence or absence of a halo structure does not influence the transition strength in a (p,n) reaction. Possible explanations may be either th... this assumption is wrong, or that the increase of the imaginary potential in such a system counterbalances the effect of the halo structure.

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