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ABOUT A POSSIBILITY TO STUDY THE ^{3}He STRUCTURE IN THE BREAK-UP REACTIONS USING POLARIZED ^{3}He BEAM

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1. Brief review of the experimental situation

In the last few years considerable progress in the investigation of few-nucleon systems, in particular the three- nucleon systems, have been achieved. But a number of problems remains unsolved. For example:

- The difference between binding energy of ^3He and ^3H is still not fully explained; it is not just due to the 3-body force.
- As in the case of the deuteron[1], the elastic electromagnetic form factor for both ^3H and ^3He is not really explained for momentum transfer $q > 4fm^{-1}$, even by the most-refined calculations employing realistic meson-exchange models (such as Paris and Bonn potentials); taking into account $3 - N$ forces[2] does not repair this situation.
- The empirical momentum distributions of fragments (d and p) extracted from the ^3He breakup reactions is interpreted in different ways. To make a choice between them one needs new experimental information.
- The origin of the "hole" at small distances [3], obtained for point-like nucleons distribution in ^3He and ^4He nuclei, remains unexplained.

The ^3He break-up reactions in various channels have been investigated both with electromagnetic and nuclear probes. Two experiments with nuclear probe are of particular interest here: exclusive measurements of the $^3He(p,2p)d$ and $^3He(p,pd)p$ reactions at $TRIUMF$[4], and inclusive measurements of the $A(^3He,d)$ and $A(^3He,p)$ reactions at zero angle at Dubna[5].

The data of ref.[5] are presented in fig.1 as a function of the fragment momentum in the nuclear rest frame, q, and in fig.2 the same data are shown as function of the light cone variable k [6], which is related to the fragment momentum q by the following formulas:

$$\begin{aligned}
\alpha &= \frac{\sqrt{m_s^2 + q^2} + q_{\|}}{M} \\
M_{sf}^2 &= \frac{q_\perp^2 + m_s^2(1-\alpha) + m_f^2\alpha}{\alpha(1-\alpha)} \\
k_{\|} &= (\alpha - \frac{1}{2})M_{sf} - \frac{m_s^2 - m_f^2}{2M_{sf}} \\
k_\perp &= q_\perp \\
k &= \sqrt{k_\perp^2 + k_{\|}^2}
\end{aligned}$$

where m_s is the mass of the spectator, m_f is the mass of the second fragment, M is the mass of the projectile and α is the part of the momentum carried away by the spectator in the longitudinal direction in the infinite-momentum frame.

There are various reasons to prefer the variable k as an inner momentum of a fragment in the nucleus. The difference between $k_{\|}$ and $q_{\|}$ ($k_{\|} > q_{\|}$) becomes appreciable when $q_{\|} > 0.2 GeV/c$, and increases as $q_{\|}$ increases. One can see that $k \simeq q$ when $q_{\|} << q_{\perp}$ (TRIUMF's kinematic). Therefore there is no need for any transformations to present the TRIUMF data as a function of k (originally they were presented versus q). The largest difference between q and k takes place when $q_{\perp} << q_{\|}$ (Dubna's and Saclay's kinematic). The TRIUMF and Dubna data are presented in fig.3 versus k. The data of the two experiments agree rather well and overestimate the impulse approximation (IA)[7] estimate. Taking into account the very different kinematical conditions of these experiments, it is rather difficult to explain an enhancement of spectra over calculations simply as a deviation from Impulse Approximation (IA). In ref. [9] it is pointed out that the SLAC $^3He(e,e')$ data[8] agree well with predicted momentum distribution[7], if multiplied by a factor :

$$1 + (k/285 MeV/c)^{2.5}$$

As seen in fig.3, the same factor has been found necessary to get agreement between hadronic data and IA. A similar situation occurs when one compares spectra extracted from the deuteron break-up reactions (fig.4). The momentum spectra extracted from the inclusive experiment $d(e,e')$ [10] (SLAC) and from inclusive $A(d,p)$ at zero angle [11, 12] (Dubna, Saclay) agree with each other, but overestimate predicted distributions at $q > 200 MeV/c$[13]. The spectrum extracted from $d(e,e'p)n$ the Saclay cross-section data[14] by A.Kobushkin[15] agrees well with the spectra mentioned above

In fig. 5 it is shown that the momentum spectrum extracted from the $^3He(e,e'p)d$ Saclay experiment[16] and predicted distribution are in agreement at small $k < 150 MeV/c$, but disagree at higher k.

We see the following possibilities to explain the difference between the deuteron- and ^3He break-up data on the one hand, and the IA predictions on the other hand:

- non-nucleons degrees of freedom (multiquark states and their projections onto the $\Delta\Delta$ and N^*N^*... configurations).
- various methods to take into account relativistic effects (we use one of them by selecting the light cone variable k as wave function argument).
- intermediate and final state interactions, as well as meson exchange currents for the electron data;
- need to use a modified fragment momentum distribution derived from updated NN-potentials (or perhaps searching for the "most realistic" NN- potential among "realistic" ones by fitting 3-body data).

Each of these points achieves some degree of success at explaining the observed effects in cross-sections. The measurement of spin observables proposed here would help greatly to determine the correct explanation for the discrepancies outlined above.

2. Review of existing investigations of ^3He structure

It is often claimed that he electron the best probe to study the structure of light nuclei; the reasons usually given to justify this position are as follows:

- electrodynamics is well known;
- the electromagnetic interaction produces only a small distortion of the investigated system.

Of course the nuclear distortion in the final state is usually as important in electromagnetically induced reactions as in hadron induced reactions, as it involves the strongly interacting fragments of the targets. But even if the reaction mechanism is well known, one needs to have good electromagnetic nucleon form factors to make reliable calculations and be able to extract structure information from experimental results. Meanwhile a sufficiently accurate characterization of the electric neutron form factor remains the central problem of hadron electrodynamics. There is also the additional problem of modelling the proton form factor far off-shell; popular off-shell prescription (de Forrest for example), are just that, prescriptions.

To interpret reliably measurements of the neutron electric form factor $G_{En}(Q)$ using a polarized ^3He target, one need to know: the reaction mechanism and the spin structure of ^3He.

To disentangle the empirical data from both electron scattering and electrodisintegration of light nuclei will require using not only deuteron but also ^3He. Several such experiments are being planned or are being carried out currently. For example, an experiment with a polarized ^3He target is underway at Bates at $Q^2 = 0.2(GeV/c)^2$, for different orientations of target spin relatively the direction of 3-vector k. Also, the $^3He(e,e'p)X$ and $^3He(e,e'd)X$ reactions will be investigated in a wide kinematical region in experiments proposed at CEBAF. It is important to note that polarization observables of these reactions will not be available very soon; but without polarization measurements one hardly will be able to resolve questions such as off-shell and, or 3-N forces effects, FSI or consequence of using an "insufficiently realistic potential", and so on.

The comprehensive program of investigation of ^3He using the electron probe might just mirror the fact many physicists prefer the electromagnetic probe; our position is that the electron probe alone will not solve all problems. In fact, we predict that it is only after detailed comparison of electron and hadron induced reactions on the light nuclei, that real progress in the field will occur. The comparison of various spectra presented in the first chapter supports this contention. The task of investigating the structure of light nuclei can only be brought to a fruitful end if **nuclear** reactions are included in the data base.

The main advantage of using nuclear probes is of course a much higher cross section for the reaction. It is well known that in the case of the deuteron investigated (including polarization characteristics) both at Dubna and Saclay very interesting characteristics of the deuteron have been found, as discussed recently in refs.[11, 12, 17, 18].

An experiment with a polarized ^3He target and polarized protons at TRIUMF[19] has recently been completed. The results indicate although the analyzing powers A_{0n}, A_{n0} and A_{nn} are close to the IA prediction for the $(p, 2p)$ channels, they are not for (p, pn). This discrepancy cannot be explained at the present time.

3. Impulse Approximation for polarization effects in $(^3He, d)$ and $(^3He, p)$ reactions.

The $^3He \to p + d$ vertex , in contradiction with the $d \to n + p$ vertex, is not symmetrical among the final state particles. Therefore the $^3He \to p + d$ vertex must be described in general by a set of two wave functions, taking into account whether it is the proton or the neutron which is virtual. That is why the full reconstruction of the ^3He spin structure needs to be investigated in both $(^3He, d)$ and $(^3He, p)$ reactions.

The amplitude of the $^3He \to d + p$ transition can be written in general as

$$\chi_2^+ \left[(\vec{\sigma}\vec{U})u_i + (\vec{\sigma}\vec{n})(\vec{U}\vec{n})w_i\right] \chi_1 \qquad (1)$$

where $\vec{U}$ is the 3-vector of the deuteron polarization, $\vec{n}$ is the unit vector along the fragment momentum (in the ^3He rest frame), χ_1 and χ_2 are the two-component spinors of the ^3He and the proton,u_i and w_i are the s- and d-components of the wave function, i is equal to 1 if the deuteron is virtual, and equal to 2 in the other case.

Based on (1) one can obtain the following formula for the proton polarization vector $\vec{P}_1$ of the reaction $A(^3He, p)X$:

$$\vec{P}_p = \frac{-\vec{P}_0(u_1 + w_1)^2 + 2\vec{n}(\vec{n}\vec{P}_0)(u_1^2 + 2u_1w_1)}{2u_1^2 + (u_1 + w_1)^2}, \qquad (2)$$

where $\vec{P}_0$ is the ^3He polarization vector.

In the case of transverse ^3He polarization, $(\vec{n}\vec{P}_0) = 0$, we will have

$$\vec{P}_p = -\vec{P}_0 \frac{(u_1 + w_1)^2}{2u_1^2 + (u_1 + w_1)^2}, \qquad (3)$$

i.e. $\vec{P}_p$ and $\vec{P}_0$ are always antiparallel for any u_1,w_1 functions. The deuteron vector polarization $\vec{P}_d$ in the $A(^3He, d)$ reaction is defined by the following formulae:

$$\vec{P}_d = \frac{\vec{P}_0 u_2^2 + u_2 w_2(\vec{P}_0 - \vec{n}(\vec{n}\vec{P}_0))}{2u_2^2 + (u_2 + w_2)^2} \qquad (4)$$

in general and

$$\vec{P}_d = \vec{P}_0 \frac{(u_2^2 + u_2 w_2)}{2u_2^2 + (u_2 + w_2)^2} \qquad (5)$$

when $(\vec{n}\vec{P}_0) = 0$.

Finally the tensor polarization ρ_{20} of the deuteron in the $A(^3He, d)$ reaction with **unpolarized** ^3He is defined by following formula

$$\rho_{20} = -\sqrt{2} \frac{2u_2 w_2 + w_2^2}{2u_2^2 + (u_2 + w_2)^2} \qquad (6)$$

The latter expression has been obtained earlier by C. Wilkin. **In this case the only vector suitable as an axial symmetry axis (i.e. the quantization axis) is the momentum of the deuteron-fragment. In other words the deuteron-fragment will be tensor polarized along the momentum direction.**

The predictions for polarization transfer coefficient, κ, **based on calculations[7] and using formulas given above are presented in figs.6,7.**

4. What will be learned from the suggested experiment

An investigation of polarization effects in the ^3He break-up reaction at SATURNE would be very important for progress in understanding the structure of ^3He. Experimental results are essential for the full exploitation of neutron form factor measurements which use polarized ^3He as a target of "polarized neutrons". The measurements of κ in the $(^3He, p)$ reactions in the vicinity of $q = 0$ will help to clear up this question. In this case the IA is valid and the S-wave part of ^3He dominates. Very different values of κ are expected, depending whether the remaining (np) part of ^3He is in a singlet or a triplet state. A value of κ at $q = 0$ will thus determine the percentage of singlet and triplet state in this case.

The complementarity of such polarization observables as T_{20} and κ (for the $(^3He, d)$ reaction) extracted from the experiment proposed here for SATURNE, will help map an expected and progressive deviation from the Impulse Approximation; this is the kind of data base which is needed for a detailed understanding of the reaction, and is a prerequisite for the extraction of structure information. An analysis of these observables in the case of the deuteron breakup reaction, recently made by Kuehn, Perdrisat and Strokovsky[20], has showed that very interesting conclusions might be reached from such an analysis.

Comparison of the expected data with the TRIUMF polarization results on polarization observables will help establish which argument of wave function in momentum space is the correct one. As mentioned in the first part, different kinematical conditions were used in the TRIUMF and Dubna differential cross

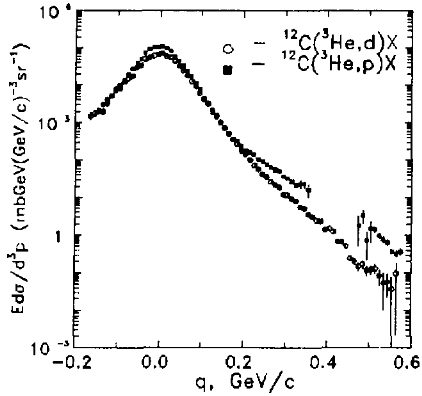

Fig.1 The data of V.G.Ableev et al for the differential cross section in the reactions $^{12}C(^3He,d)X$ and $^{12}C(^3He,p)X$ versus q, the momentum of the spectator in the ^3He rest frame.

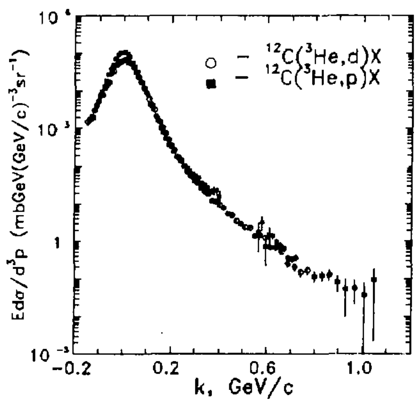

Fig.2 The same as in fig.1 versus k, (see text).

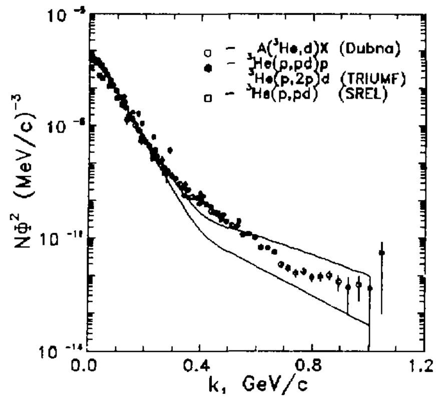

Fig.3 The momentum distribution of deuterons in ^3He, extracted from the $TRIUMF$ and $SREL$ exclusive data and from the $Dubna$ $A(^3He, d)$ data versus k.

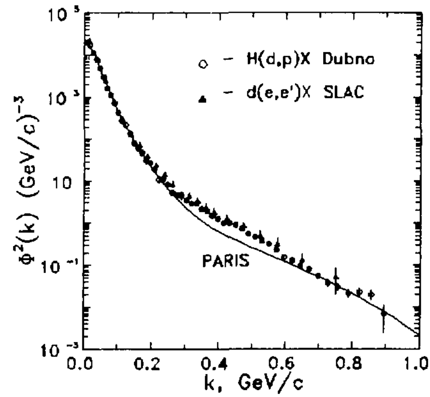

Fig.4 The momentum distribution of protons in deuteron, extracted from $p(d,p)$ and $d(e,e')$ data versus k.

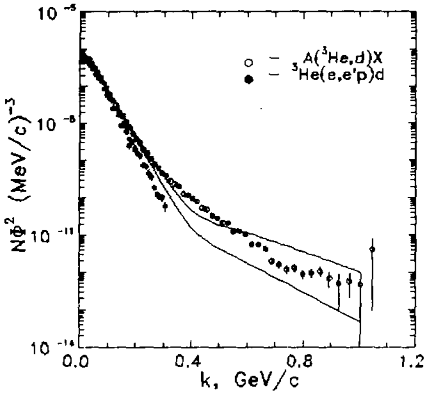

Fig.5 The momentum distribution of deuterons in ^3He, extracted from the Saclay $^3He(e,e'p)d$ data and the Dubna $A(^3He,d)$ data.

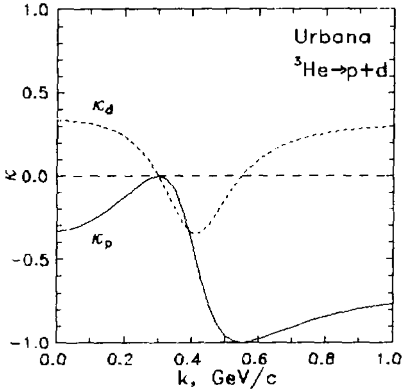

Fig.6 The predicted polarization transfers of $^3He \to d$ and $^3He \to p$ reactions (in framework of IA) for the $(d+p)$ vertex of ^3He (using calculation and formulas from text).

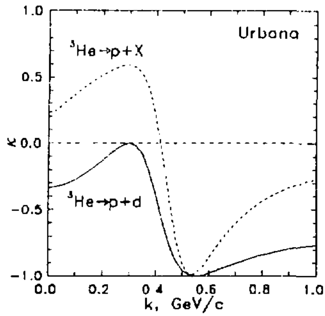

Fig.7 The polarization transfer of the $^3He \to p$ reaction (in framework of IA) for the $(d+p)$ vertex and in general (using calculations).

section measurements, but distribution extracted from these two independent sets of data agree rather well when the internal momentum k define above is used.

We suggest that ultimately the comparison of ^3He and deuteron breakup data, including the data generated by the experiment proposed here, will lead to definite conclusions concerning the structure of the two lightest nuclei which will surpass the boldest forecasts.

5. Conclusions

Assuming that the problem of accelerating polarized ^3He in Saturne can be resolved, measurements of the polarization transfer coefficient, κ, in the $(^3He, d)$ and $(^3He, p)$ reactions will be no more difficult, technically, than the measurements of this observable in the deuteron break-up reaction[18] which was performed at SATURNE in 1990 (experiment 202), using $SPES1+POMME$.

It is possible to measure tensor polarization of secondary deuterons using unpolarized ^3He beam, but a liquid hydrogen target must be installed in POMME to have sufficient tensor analyzing power of the second scattering. We would like to stress here that one must overcome definite difficulties to stage this experiment because azimuthal asymmetry of second scattering is absent when secondary deuterons aligned along the beam axis.

Of course, if a polarized ^3He beam can be produced, the list of possible experiments becomes much longer. Among them we would like to mention backward elastic $^3He + p$ and $^3He + d$ scattering experiments, which might be carried out using the same experimental set-up. These two reactions can provide useful information about the ^3He wave function; as in the case of the results of the deuteron structure studies, it would be interesting to compare data on cross sections, analyzing powers and spin transfer coefficients of both the elastic and the breakup reactions.

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