Nuclear data acquisition for proton-nucleus reactions above 20 MeV: requirements and conceivable experiments.

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1 INTRODUCTION

In the 20-200 MeV energy region, the optical model validation suffers an important lack of data in proton-nucleus reactions for non-spherical nuclei. The improvement of the data in this energy region is particularly necessary for all the recent studies concerning transmutation of long life nuclear waste. In the different scenarii elaborated, a prediction is required on the emission energy spectra from spallation targets bombarded by proton beams. For proton up to 200 MeV incident energies one needs to have reliable cross section calculations using optical potential for all the proton-nucleus systems that could be considered.

As a consequence, new measurements have to be performed at different proton energies, so that the energy dependence of the optical potential can be precisely defined. The purpose of this paper is to make an overview of the data needed and to discuss the different experimental possibilities.

Different kinds of data need measurements. At first, experimental elastic angular distributions are required in order to adjust the energy dependence of the real and imaginary part of the optical potential. Direct total reaction cross section measurement would also be very useful since they have proven to be crucial to help distinguish between different sets of optical potential parameters that fit equally well elastic angular distributions, particularly for the imaginary potential. The latter also needs to be tested with inelastic angular distributions.

The second point is to establish a list of nuclei to be experimentally studied, in order to improve the range of data in poorly explored mass regions and if possible to work with nuclei fully concerned by the problem of transmutation. A first review was done by J.P.Delaroche [1], leading to a set of nuclei : ^{238}U, ^{232}Th, ^{184}W, ^{152,154}Sm, ^{100}Mo, ^{27}Al, chosen because they are spallation target candidates, fission products or structure materials.

In the next section, the experimental characteristics of the various measurements will be discussed.

2 Experimental characteristics

2.1 Inelastic and elastic angular distribution measurements

The experimental set-up for elastic scattering is strongly dependent on the proton incident energy and on the precision needed for the measurement. Indeed, this last point has to be clearly defined since it is going to determine the energy resolution required. The proposed nuclei are deformed so their first excited states are at less than 100 keV for most of them. The contribution of the low energy states at the cross section is problably not negligible in particular at large angles. Thus it might be important to be able to discriminate the elastic cross section from the inelastic.

Let's consider two extreme cases in the energy range 20-200 MeV. Figure 1 shows the angular distribution obtained for the elastic scattering on ^{208}Pb of protons between 35 and 65 MeV extracted from reference [2].

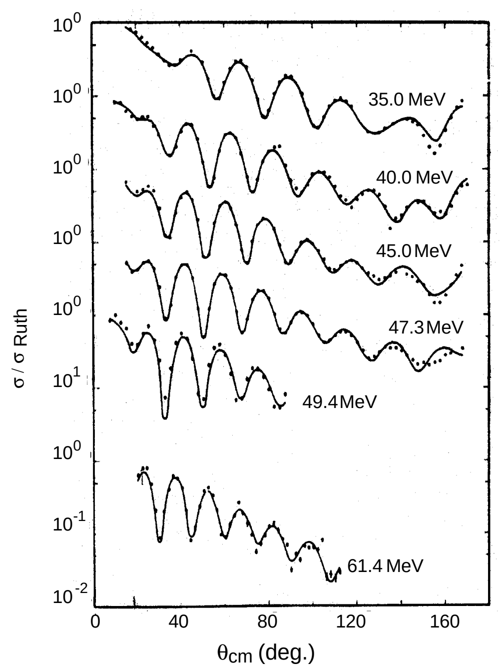

Figure 1: *Elastic angular distribution for protons on ^{208}Pb from ref. [2]*

In this case, the angular range that needs to be measured (in the center of mass and here also in the laboratory frame) is 20-160 degrees, thus the data can be obtained with a relatively light set-up that would be an ensemble of charged particle detectors placed all around the target. A set of Si telescopes could be used for protons with energy lower than 30 MeV. For higher energy protons, one can use one of the Si(Li), CsI or NaI arrays existing in different laboratories. For example, detectors with 2 cm diameter, located at 50cm from the target, would lead to a 2 degrees angular resolution. In order to increase the granularity while maintaining a large solid angle, one can consider using a silicon strip multi-detector. MUST [3], the french silicon-strip ensemble would be very well suited since its Si(Li) and CsI detectors placed behind the strips allow to locate and to identify protons up to 100MeV. But the set-up described above cannot be used at energy above 30 MeV if a energy resolution of less than 100 keV is needed.

Let's now discuss the case of incident protons at energies around 200 MeV. Figure 2 shows the angular distribution obtained for the elastic scattering on ^{208}Pb of protons between 156 and 185 MeV [2].

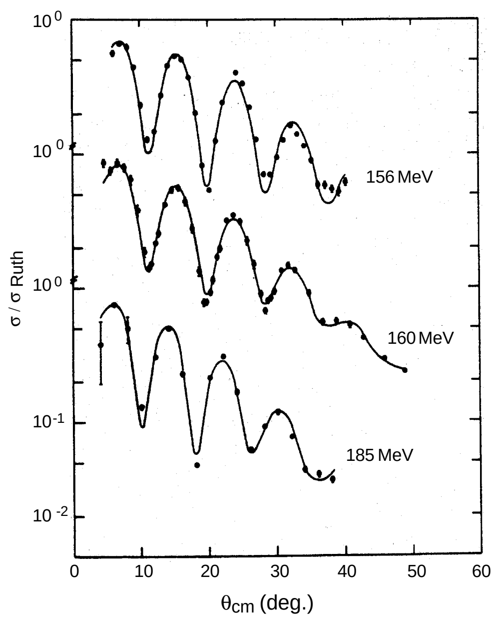

Figure 2: *Elastic angular distribution for protons on ^{208}Pb from ref. [2]*

In this case, the angular domain to be explored, starting at very small angles, obliges to use a spectrometer. In that case a typical angular resolution would be .2 degrees, and a typical energy resolution would be 100keV at 200MeV. One limitation is that most spectrometers are not built to be rotated to angles larger than 90 degrees. For example, BBS, the spectrometer available at KVI, is limited to a 45 degrees rotation.

If we consider an intermediate case, for example for 70 MeV protons, it is impossible to obtain a good energy resolution with charged particle detectors. So a spectrometer could be used as in the precedent case, and the energy resolution would be about 30 keV. But in that case the angular domain will be limited to the spectrometer angular range and thus much under what be required.

It is clear that at some energies or at some angles, it will be impossible to discriminate the elastic scattering from the first excited states of the inelastic. As those states are well known (or can be measured at some energies), it should be possible to include in the calculations their contribution. This analyse will need to be tested on nuclei where it is possible to do also a separate measurement for elastic and inelastic.

A possibility that can be used in all the 20-200 energy domain would be to couple the two set-up, i.e. a spectrometer and its detection system that can be moved as far as possible, and particle detectors that could cover the angular domain from 20 to 180 degrees.

The interest of such a set-up is to take the best of each measurement and to have a redundance that can allow to compare the results of the different analysis obtained with or without the resolution. This will give a test of the method cited above for deformed nuclei at least for a few energies and for a few angles.

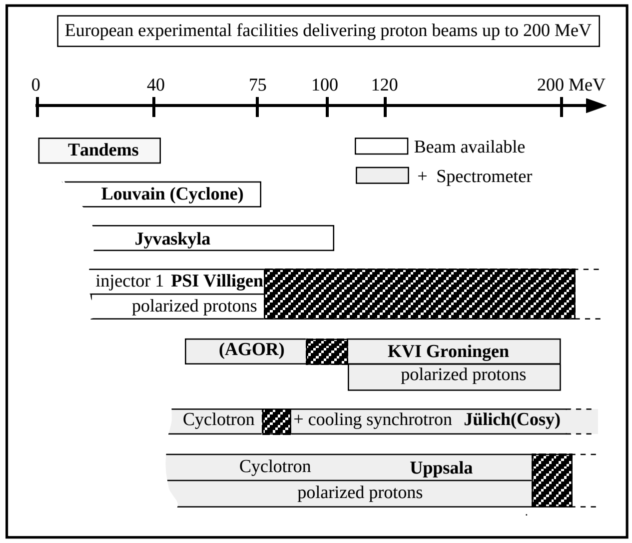

Figure 3: *Europeans facilities delivering proton beams*

Figure 3 shows a summary of the european facilities delivering protons beams with the domain in energy covered. If the energy resolution is not crucial, at energy lower than 100 MeV, there are various possibilities to host the experiments. According to figure 3, for almost all measurements, the AGOR cyclotron would be a good candidate with its new spectrometer BBS [4]. One can also think of using the primary cyclotron of the cooling synchrotron of Jülich or Uppsala, that both have a spectrometer. One can notice that polarized measurements can be performed at different facilities if necessary. It might be interesting to have data with polarized protons, at least at some energies, in order to evaluate the additional constraints they may impose on the optical potential, in particular for the spin-orbit component.

In summary, the elastic and inelastic scattering measurement is a classic experiment than can be performed with existing set-up. A new interest for these measurements is born these last years with the possibility of investigating nuclei far from stability, leading some laboratories to invest in new and performing equipment, like silicon-strips detectors. Thus the classic techniques used for tenth of years should be improved and allow to do experiments in better conditions with reasonable beam time.

For each particular case, it will be very important to define clearly the requirement for the precision, the resolution (in energy and angle) and the angular domain to be investigated. All these parameters will allow to choose a specific designed set-up.

2.2 Reaction cross section measurements

The reaction cross section data existing for protons were almost all obtained in the sixties and they appeared to need experiments requiring particular care. In the energy domain concerned, it is impossible to sum the partial cross sections of all the reactions that may take place.

The attenuation methods seem to be well adapted for measurement between 20 and 200 MeV. The attenuation of a beam of particles passing through matter is given by $I = I_o exp(-nx\sigma)$ where I_o and I are respectively the intensities of the incident beam and the attenuated beam, n is the number of nuclei per unit of volume in the target, x is the target thickness, and σ is the attenuation cross section. If the quantity $nx\sigma$ is small compared to the unity, it can be written: $\sigma = \frac{I-I_o}{nxI_o}$

In order to determine precisely σ for a number or incident protons I_o, one first needs to know nx with at least the precision required for σ. The second problem is to measure $I - I_o$, that is the substraction of two large numbers of nearly equal value, specially if you use rather thin targets in order to keep a good precision on the protons energy. The third problem is that the measured value of σ includes the elastic cross section. So in order to deduce the reaction cross section σ_R, it is necessary, either to know very well the value of the elastic cross section σ_{el}, either to measure it, either to use a measurement technique where its contribution is discriminated.

Most experiments performed in the sixties made measurement of beam attenuation by monitoring the intensity of the beam with the target in and with the target out. But these data suffers the uncertainty of the beam intensity measurements [5]. Since then, the performance of the equipment have considerably been improved, thus this method, with appropriated upgrade, should give much better results. Recently, people interested in measuring the reaction cross section of radioactive beams on proton target have started to propose experiments with this method using also a spectrometer in order to discriminate and measure the elastic cross section. They hope to measure σ_R with a precision of less than 5% [6].

An interesting method, very much used also with exotic beams, is to measure the attenuation of the beam in a detector, but this is of limited use since the target you can study has to be a substance that can be used as a detector.

The method that seems the most efficient according to Carlson and coll., [7, 8, 9] is the attenuation technique first developed by Gooding [10]. Figure 4 shows a schematic diagram of the corresponding set-up.

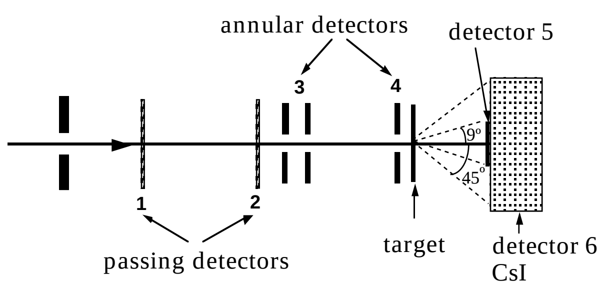

Figure 4: *Schematic diagram of the total reaction cross-section apparatus from ref.[7]*

The principle of this system is to measure the energy of the beam in a stopping detector after the target. All particles that had no reactions in the target retain approximately the beam energy and are eliminated. An incoming event is a particle that was detected in 1 and 2 and that was not detected in the annular detectors 3 and 4 in order to remove the events scattered by detector 2. An attenuation event is a particle that has an energy below a certain threshold in thick detector 6. The detector 5 covers a 9 degree cone around the beam axis. It is used to remove most of the false events due to elastic events that could have reactions in detector 5 and thus have an energy below the threshold. All the events detected by detector 6 are counted like non-attenuation events. The precision obtained with this method, including many corrections detailed in reference [7] was between 2 and 3 % which is very good.

This method allows to measure directly the reaction cross section, but it assumes that 98% of the reaction events are outside the 9 degrees cone. Before using this method in a specific case, one should check and eventually adapt the validity of this assumption according to the kinematics.

To conclude this part, it is important to note that direct reaction cross section measurement is still a very subtil work that probably deserves special technical development.

3 CONCLUSION

It is important to consider that all the work needed for new cross section data up to 200 MeV requires a close collaboration between experimentalists and theoriticians. They have to weigh and decide together the limits of the different measurements to be performed in order to optimize them. This is very crucial because for example a difference of 10 degrees in an angular domain can transform a straightforward experiment in a long and delicate one. Conversely, if a measurement does not allow to have data in a specific domain where the models are particularly sensitive, it is also useless to spend time and energy.

In conclusion, it is possible through a limited number of well chosen experiments to improve our knowledge of (p,p') optical potentials. Some experimental methods have been proposed in this paper. An important work is necessary in order to prepare and optimize the measurements that need to be performed.

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